Supernova Relic Neutrinos at Super-Kamiokande

Kirk Bays
University of California, Irvine
### Super-Kamiokande (SK)

SK is a 50 kton water Cherenkov detector in the Kamioka mine, Japan (2700 mwe). It began operation in 1996. The data is divided into segments: SK-I, II, III, and IV. This study focuses on SK-I/II/III.

<table>
<thead>
<tr>
<th>Period</th>
<th>Live time</th>
<th># ID PMTs / % coverage</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK-I</td>
<td>1497 days</td>
<td>11146 / 40%</td>
<td>Experiment start</td>
</tr>
<tr>
<td>SK-II</td>
<td>791 days</td>
<td>5182 / 19 %</td>
<td>After accident</td>
</tr>
<tr>
<td>SK-III</td>
<td>562 days</td>
<td>11129 / 40%</td>
<td>After repair</td>
</tr>
<tr>
<td>SK-IV</td>
<td>running now</td>
<td>11129 / 40%</td>
<td>New electronics</td>
</tr>
</tbody>
</table>
The SN1987A neutrinos are the only neutrinos ever detected from outside the solar system!

Supernova Relic Neutrinos (SRNs) are a diffuse neutrino signal from all past supernovae.

At Super-Kamiokande (SK), we can look for SRNs without waiting for a galactic supernova. The main interaction mode for SRNs in SK is charged current quasi-elastic interaction (inverse $\beta$ decay).
• SRN rate in SK is low (few a year expected), and difficult to search for among the numerous backgrounds

• Most backgrounds can be fully eliminated:
  – Spallation
  – Solar neutrinos
  – Radioactive backgrounds

• Some must be modeled:
  – Atmospheric ν backgrounds
  – World’s current best flux limit from 2003 SK study

• This study is now improved

2003 final data sample. SRN events were searched for using a χ² fit, in an energy window of 18-82 MeV, with two modeled atmospheric backgrounds
Spallation cut improvement

- Cosmic ray muon spallation occurs $< \sim 21$ MeV; more as E lowers
- Spallation determines lower energy threshold
- Must be spall ‘free’
- Cut highly improved
- E threshold now lowered from $18 \rightarrow 16$ MeV
- Efficiency of 2003 data: $64\% \rightarrow 91\%$

**Improvements:**
New method of tracking spallation along muon track! (with dE/dx info)
New tuning, better fitters, muon ID
Other improvements in event selection:

- More data
  - (1497 → 2853 live days)
- Lower energy threshold
  - (18 MeV → 16 MeV)
  - SK-II E thresh: 17.5 MeV
- More improved cuts:
  - Solar neutrino cut
  - Radioactivity cut
  - New pion cut
  - Many more

![Signal efficiency graph](Image)

<table>
<thead>
<tr>
<th>Cut</th>
<th>SK-I</th>
<th>SK-II</th>
<th>SK-III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise Reduction</td>
<td>99% (1%)</td>
<td>99% (1%)</td>
<td>99% (1%)</td>
</tr>
<tr>
<td>Spall + Solar</td>
<td>88% (1%)</td>
<td>87% (1.4%)</td>
<td>89% (1%)</td>
</tr>
<tr>
<td>Incoming event Pion</td>
<td>98% (0.5%)</td>
<td>95% (0.3%)</td>
<td>96% (0.3%)</td>
</tr>
<tr>
<td>Cherenkov angle</td>
<td>95% (0.4%)</td>
<td>88% (3%)</td>
<td>94% (0.3%)</td>
</tr>
<tr>
<td>Other cuts</td>
<td>98% (2%)</td>
<td>98% (2%)</td>
<td>98% (2%)</td>
</tr>
<tr>
<td>Total</td>
<td>78.5% (2.5%)</td>
<td>69.2% (4.0%)</td>
<td>76.7% (2.5%)</td>
</tr>
</tbody>
</table>

Final efficiencies (based on LMA MC)
Remaining Backgrounds

- Final sample still mostly backgrounds, from atmospheric $\nu$ interactions; modeled w/ MC
  
- 1) $\nu_\mu$ CC events
  - muons from atmospheric $\nu_\mu$'s can be sub-Cherenkov; their decay electrons mimic SRNs
  - modeled with decay electrons

- 2) $\nu_e$ CC events
  - indistinguishable from SRNs

- 3) NC elastic
  - low energy mostly

- 4) $\mu/\pi$ events
  - combination of muons and pions remaining after cuts

Backgrounds 1) and 2) were considered in the 2003 study.

Backgrounds 3) and 4) are new!
Fitting method

• 2003 study used a binned $\chi^2$ method to extract a SRN signal from the final data, assuming backgrounds
• We discovered the binning can have significant effect on result
• Moved to unbinned maximum likelihood method
• Now we model and search for many different SRN models, each with our four remaining backgrounds

$$L = \prod_{i=1}^{N_{\text{events}}} \left( \sum_{j=1}^{5} c_j F_j(E_i) \right) e^{\left( -\sum_{j=1}^{5} c_j \right)}$$

**Where:**
- $F$ is the PDF for a particular channel;
- $E$ is the event energy;
- $c$ is the magnitude of each channel;
- and
- $i$ represents a particular event, and $j$ represents a channel:
- $1$ = SRN model
- $2$-$5$ = background channels

**systematics considered:**
- cut inefficiency systematic error
- energy scale and resolution
- background spectrum errors (conservative)
• SRN events expected (98% SK-I) in the central, signal region (38-50°)
• ‘Sidebands’ previously ignored
• Now that we consider new background channels, sidebands useful
  – NC elastic events occur at high C. angles
  – $\mu/\pi$ events occur at low C. angles
• We now fit all three C. angle regions simultaneously
• Sidebands help normalize new backgrounds in signal region

<table>
<thead>
<tr>
<th>number of events</th>
<th>$\mu/\pi$ region</th>
<th>signal region</th>
<th>not used</th>
<th>NC region</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK-I final sample</td>
<td>$\nu_\mu + \nu_e$ CC</td>
<td>$\mu/\pi$ CC</td>
<td>NC elastic</td>
<td></td>
</tr>
</tbody>
</table>
SK-I finds no evidence for SRNs
SK-II and SK-III give positive fit for SRNs (no significance)

Likelihoods (as fxn of SRN events) combined for a total result (limit)
### New Results: flux limits ($\nu$ cm$^{-2}$s$^{-1}$, 90% cl)

<table>
<thead>
<tr>
<th>$E_{e^+} &gt; 16$ MeV</th>
<th>SK-I</th>
<th>SK-II</th>
<th>SK-III</th>
<th>Combined</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMA (03)</td>
<td>&lt;2.5</td>
<td>&lt;7.7</td>
<td>&lt;8.0</td>
<td>&lt;2.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Cosmic gas Infall (97)</td>
<td>&lt;2.1</td>
<td>&lt;7.5</td>
<td>&lt;7.8</td>
<td>&lt;2.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Heavy Metal (00)</td>
<td>&lt;2.2</td>
<td>&lt;7.4</td>
<td>&lt;7.8</td>
<td>&lt;2.8</td>
<td>0.4 - 1.8</td>
</tr>
<tr>
<td>Failed Supernova (09)</td>
<td>&lt;2.4</td>
<td>&lt;8.0</td>
<td>&lt;8.4</td>
<td>&lt;3.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Chemical Evolution (97)</td>
<td>&lt;2.2</td>
<td>&lt;7.2</td>
<td>&lt;7.8</td>
<td>&lt;2.8</td>
<td>0.6</td>
</tr>
<tr>
<td>6 MeV (09)</td>
<td>&lt;2.7</td>
<td>&lt;7.4</td>
<td>&lt;8.7</td>
<td>&lt;3.1</td>
<td>1.5</td>
</tr>
</tbody>
</table>
## COMPARISON TO PUBLISHED LIMIT

<table>
<thead>
<tr>
<th>Description</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Published limit</td>
<td>1.2</td>
</tr>
<tr>
<td>Cross section update to Strumia-Vissani</td>
<td>$1.2 \rightarrow 1.4$</td>
</tr>
<tr>
<td>Gaussian statistics $\rightarrow$ Poissonian statistics in fit</td>
<td>$1.4 \rightarrow 1.9$</td>
</tr>
<tr>
<td><strong>New SK-I Analysis:</strong></td>
<td></td>
</tr>
<tr>
<td>$E_{\text{THRESH}}$ 18 $\rightarrow$ 16 MeV</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon = 52% \rightarrow 78%$ (LMA)</td>
<td></td>
</tr>
<tr>
<td>(small statistical correlation in samples)</td>
<td></td>
</tr>
<tr>
<td>Improved fitting method takes into account NC</td>
<td></td>
</tr>
<tr>
<td><strong>New SK-I/II/III combined fit</strong></td>
<td>$1.7 \rightarrow 2.0$</td>
</tr>
<tr>
<td><em>(2.9 &gt; 16 MeV)</em></td>
<td></td>
</tr>
</tbody>
</table>
Limit Re-parameterization

- Elements of models now well known (very low error on cosmic star formation rate, initial mass functions, etc.)
- Elements are sufficiently known to recast new models into only 2 free parameters:
  - SN average $\nu$ luminosity
  - Temperature of a F-D spectrum
- Older models may use outdated parameters (i.e. incorrect star formation rate), care must be taken comparing with new results

Positron spectra seen in SK resulting from F-D $\nu$ E spectrum
LMA = Ando et al (LMA model)
HMA = Kaplinghat, Steigman, Walker (heavy metal abundance)
CGI = Malaney (cosmic gas infall)
FS = Lunardini (failed SN model)
CE = Hartmann/Woosley (chemical evolution)

$\frac{4}{6}$ MeV = Horiuchi et al $\nu$ temp
Outlook

• New SRN SK study ready
• Many improvements, now detailed, fully considered
  – better efficiency
  – more data
  – lower E threshold
  – new backgrounds considered
  – new fit, systematics
• Paper out soon
• SK-II/III shows excess; no statistical significance. Hint of a signal? Statistical fluctuation?
• How to get certainty? Gd

Adding gadolinium to Super-K’s water would make neutrons visible, allowing:

- Rapid discovery and measurement of the diffuse supernova neutrino flux → determine total and average SN ν energy, rate of optically failed SN
- High statistics measurement of the neutrinos from Japan’s power reactors → greatly improved precision of $\Delta m^2_{12}$
- De-convolution of a galactic supernova’s ν signals → 2X pointing accuracy
- Sensitivity to very late-time black hole formation following a galactic SN
- Early warning of an approaching SN ν burst (up to one week) from Si fusion
- Proton decay background reduction → about 5X, vital for future searches
- Matter- vs. antimatter-enhanced atmospheric ν samples → CPT violation?
Following seven years of above ground studies in the US and Japan, we are now building a dedicated Gd test facility in the Kamioka mine, complete with its own water filtration system, 240 50-cm PMT’s, and DAQ electronics. This 200 ton-scale R&D project is called EGADS – Evaluating Gadolinium’s Action on Detector Systems. By 2012, EGADS will have demonstrated conclusively whether or not gadolinium loading of Super-Kamiokande will be safe and effective. If it works, then this is the likely future of water Cherenkov detectors.
Latest EGADS News

• Egads test tank construction, water system complete
  – EGADS pure water transparency > SK

• Gd removal system ready
  – $10^6$ removal in single pass

• Gd introduced in system
  – dissolved into water system, no problems
  – Gd water system circulation 99.97% efficient
  – Preliminary Gd water transparency good

• PMTs prepped, installed soon

• Electronics and DAQ by end of 2011

• Full experimental program on track for 2012
• Thanks for your attention!
BACKUPS
List of models and references

• Cosmic Gas Infall – Malaney - R. A. Malaney, Astroparticle Physics 7, 125 (1997)
• Chemical evolution - D. H. Hartmann and S. E.Woosley, Astroparticle Physics 7, 137 (1997)
• Large Mixing Angle - S. Ando, K. Sato, and T. Totani, Astroparticle Physics 18, 307 (2003) (updated NNN05)
• Failed Supernova - C. Lunardini, Phys. Rev. Lett. 102, 231101 (2009) (assume Failed SN rate = 22%, EoS = Lattimer-Swesty, and survival probability = 68%).
Spallation Cut

- 4 variable likelihood cut
- The 4 variables:
  - \( d_{\text{Longitudinal}} \)
  - \( d_t \)
  - \( d_{\text{Transverse}} \)
  - \( Q_{\text{Peak}} \)
- Use new, better \( \mu \) fitters
- Tuned for each muon type (i.e. single, multiple, stopping \( \mu \))
- Improvements allow lowering of energy threshold to 16 MeV!

New Cut (SK-I/III):
- \( 16 < E < 18 \) MeV: 18% signal inefficiency
- \( 18 < E < 24 \) MeV: 9% signal inefficiency

Old cut (likelihood + 150 ms hard cut)
- \( 18 < E < 34 \): 36% signal inefficiency

\( Q_{\text{Peak}} \) = sum of charge in window
spallation expected here

\( d_{\text{Longitudinal}} \)
\( d_{\text{Transverse}} \)

Relic Candidate

\( \mu \) track

\( \mu \) entry point

\( dE/dx \) Plot

\( p.e.'s \)

distance along muon track (50 cm bins)

TAUP 2011
spallation distance variables
- Solar $^8$B and hep neutrino are a SRN background (hep at 18 MeV, and both at 16 MeV, because of energy resolution)
- Cut criteria is optimized using $^8$B/hep MC
- New cut is now energy dependent, tuned in 1 MeV bins
Coulomb multiple scattering is estimated (‘arigood’); more scattering, more deviation from solar direction. Each energy bin is broken into ‘arigood’ bins; cut in each bin tuned using ‘significance’ function to maximize signal/background$^{1/2}$.
Systematics: NC elastic

- Keep spectra the same
- Change normalization in signal region by 100%
  - $+1\sigma = \text{double (14.8\% SK-I)}$
  - $-1\sigma = 0\%$
- Because of physical bound, apply error asymmetrically ($-1\sigma$ to $+3\sigma$)
- Instead of standard Gaussian weighing function (appropriate for symmetric case), use a weighted Gaussian function
- Maintain necessary properties:
  - expectation value $= 0$
  - variance $= \sigma^2$

<table>
<thead>
<tr>
<th>SK-I NC elastic normalization</th>
<th>20-38°</th>
<th>38-50°</th>
<th>78-90°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.6%</td>
<td>7.4%</td>
<td>87%</td>
</tr>
</tbody>
</table>

Weighing function applied (weighted Gaussian)
Systematics: $\nu_e$ CC

- For $\nu_e$ CC case, keep normalization, distort spectrum
- Use large error of 50% at 90 MeV (0 distortion at 16 MeV, linear between)
- Use same range (-1 to 3 $\sigma$) and weighing function as NC case
- -2 $\sigma$ would bring spectrum to 0 at 90 MeV, which is unphysical
**Systematics: Inefficiency**

- Define:
  - $r =$ # relic events we see in data
  - $R =$ # relic events actually occurring in detector
  - $\varepsilon =$ efficiency (SK-I/II/III dependent)
  - assume $\varepsilon$ follows a probability distribution $P(\varepsilon)$
  - assume $P(\varepsilon)$ is shaped like Gaussian w/ width $\sigma_{\text{ineff}}$
  - then we alter likelihood:

  $$L'(R) = \int_{\varepsilon=0}^{1} L(\varepsilon R) \varepsilon P(\varepsilon) d\varepsilon$$

  then the 90% c.l. limit $R_{90}$ is such that

  $$\int_{0}^{R_{90}} L(R) dR = 0.9$$

  $\sigma_{\text{ineff}}$
  - SK-I: 3.5%
  - SK-II: 4.7%
  - SK-III: 3.4%
Systematics: energy scale, resolution

- **Method:**
  - Use MC, parameterize effects
  - ie for e-res, parameterize:
    \[ f_{\text{e-resolution}}(E) = (E_{\text{true}} + (E_{\text{recon}} - E_{\text{true}}) \times \text{error}) \]
  - \[ \delta(E) = (f_{\text{e-scale}}(E)^2 + f_{\text{e-resolution}}(E)^2)^{1/2} \]

\[ \rho(E_i) \longrightarrow \rho(E_i, \varepsilon) = c(1 + \delta(E_i)\varepsilon)\rho(E_i) \]

\[ L(\varepsilon) = \prod_{i=1}^{N_{\text{events}}} \left( r\rho(E_i, \varepsilon) + m\mu(E_i) + e\zeta(E_i) \right) \]

\[ L' = N \int_{-\infty}^{\infty} e^{-\varepsilon^2/2} L(\varepsilon) d\varepsilon \]

- **e-scale e-res**
  - SK-I: 1% 2.5%
  - SK-II: 1.5% 2.5%
  - SK-III: 1% 2.5%

TAUP 2011
Cosmic Gas Infall (Malaney, 1997)
Chemical Evolution (Woosley & Hartmann, 1997)
Failed Supernova (Lunardini, 2009) (failed SN rate = .22 survival P = .68)
Low Mixing Angle (Ando et al, 2003) (NNN05 corrected)
Heavy Metal Abundance (Kaplinghat et al, 2000)

Flux (/cm\(^2\)/sec) for E>16 MeV

SK Limit

Model Prediction

TAUP 2011