Searching for Supernova Relic Neutrinos

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University of Birmingham – HEP Seminar
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Outline

● Introduction: A Brief History of Neutrinos
● Theory
  • Supernova Neutrino Emission
  • Supernova Relic Neutrinos
● Super-Kamiokande Detector
● Data Reduction
● Analysis and Results
● Conclusions and Future
Enter The Neutrino

**1910s - 1920s:** Studies of nuclear $\beta$ decays

$N_1 \rightarrow N_2 + e^-$

Did not appear to conserve energy!

**1930:** Wolfgang Pauli postulated Neutrinos in order to save energy conservation

$N_1 \rightarrow N_2 + e^- + \nu$

“*I have done a terrible thing. I have postulated a particle that cannot be detected*”

$\nu$ has no charge, no mass, very feeble interaction, just a bit of energy

**1956:** $\nu$ finally discovered by Cowan and Reines.

*Used nuclear reactor as source of neutrinos.* Nobel prize 1995
In The Mine, But Looking At The Stars

- First solar neutrino detector:
  - Homestake mine, South Dakota
  - Ray Davis, Brookhaven
  - 615 tons of C₂Cl₄ (cleaning fluid!)
- "Radiochemical" detector:
  \[ \nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar}^* + e^- \]

**Good News:**
First discovery of solar \(\nu\)!

**Bad News:**
Far fewer than anticipated!
Supernova Neutrinos: The Plot Thickens

- On 23-Feb-1987, a burst of $\nu$ came from Sanduleak -69° 202 in Large Mag. Cloud. (now known as Supernova 1987a)

- 19 (or 20) SN neutrinos seen in two water Cherenkov experiments:
  - 11 (or 12) at KamiokaNDE
  - 8 at the competing IMB

- Hundreds of papers written analysing these few neutrinos!

- Between solar and supernova $\nu$ detections, the field of neutrino astronomy was born!

- In 2002, Ray Davis and Masatoshi Koshiba shared Nobel Prize for this accomplishment (along with discovery of x-ray astronomy).
Supernova Progenitors

Main Sequence

H core
Supernova Progenitors

Main Sequence

H core

Red Giant

He core + H shell
Supernova Progenitors

Main Sequence

- H core

Red Giant

- He core
  + H shell

Supergiant

- C & O core
- He & H shells
Supernova Progenitors

Main Sequence

H core

Red Giant

He core + H shell

Supergiant

C & O core

He & H shells

m > 8 M?
Supernova Progenitors

- **Main Sequence**
  - H core
  - He core + H shell

- **Red Giant**

- **Supergiant**
  - C & O core
  - He & H shells

- **Accreting White Dwarf**

$m > 8 \ M$?
Supernova Progenitors

Main Sequence

H core

Red Giant

He core + H shell

Supergiant

C & O core
He & H shells

Accreting White Dwarf

Carbon deflagration
supernova

m > 8 M?
Supernova Progenitors

Main Sequence
- H core

Red Giant
- He core + H shell

Accreting White Dwarf
- Carbon deflagration supernova

Supergiant
- C & O core
- He & H shells

m > 8 M?

“Onion” Shells
- (H, He, C, O, Ne, Si, Fe)
Supernova Progenitors

- Main Sequence
  - H core
- Red Giant
  - He core + H shell
- Supergiant
  - C & O core
  - He & H shells
- Accreting White Dwarf
  - Carbon deflagration supernova
  - m > 8 M?
  - “Onion” Shells (H, He, C, O, Ne, Si, Fe)
  - Core Collapse!
Supernova Classification

Classify by spectral lines:

Got Hydrogen?
Supernova Classification

Classify by spectral lines:

- Got Hydrogen? [YES]
  - Type II Supernova
- Got Hydrogen? [NO]
  - Type I Supernova
Supernova Classification

Classify by spectral lines:

- Got Hydrogen? [YES]
  - Type II Supernova
- Got Silicon? [NO]
  - Type I Supernova (Got Silicon?)
Supernova Classification

Classify by spectral lines:

- **Type II Supernova**: Got Hydrogen? *YES*
  - **Type I Supernova (Got Silicon?)**: Got Helium? *NO*
  - **Type Ia Supernova**: Got Helium? *NO*
Supernova Classification

Classify by spectral lines:

- **Got Hydrogen?**
  - **YES** → Type II Supernova
  - **NO** → Type I Supernova (Got Silicon?)

Type I Supernova

- **Got Helium?**
  - **YES** → Type Ia Supernova
  - **NO** → Type Ib Supernova

Type Ib Supernova

- **Got Helium?**
  - **YES** → Type Ic Supernova
  - **NO** → [Diagram not showing the next step]
Supernova Classification

Classify by spectral lines:

- **Type II Supernova**
  - Got Hydrogen? **YES**

- **Type I Supernova**
  - Got Hydrogen? **NO**

- **Type Ia Supernova**
  - Got Hydrogen? **NO**
  - Got Helium? **YES**

**NOTE:** Spectral class ≠ Mechanism

- **Type Ib Supernova**
  - Got Helium? **NO**

- **Type Ic Supernova**
  - Got Helium? **YES**
Supernova Classification

Classify by spectral lines:

- **Type II Supernova**
  - Got Hydrogen? **YES**

- **Type I Supernova** (Got Silicon?)
  - Got Hydrogen? **NO**
  - Got Helium? **NO**

- **Type Ia Supernova**
  - Got Hydrogen? **NO**
  - Got Helium? **YES**

- **Type Ib Supernova**
  - Got Helium? **NO**

- **Type Ic Supernova**
  - Got Helium? **NO**

**NOTE:** Spectral class ≠ Mechanism
Supernova Neutrino Emission: 
Start of the Collapse

1. Start of collapse

Electrons captured on nuclei produce $\nu_e$ via:

$$e^- + A(N,Z) \rightarrow \nu_e + A(N+1,Z-1)$$

- Mean free path of neutrinos > core size
- Neutrinos escape promptly
Supernova Neutrino Emission: Neutrino Trapping

2. Neutrino trapping

Core density increases as collapse continues
Mean free path of neutrinos shrinks w/ increasing density
ν trapped by coherent scattering off nuclei:

\[ \nu + A(N,Z) \rightarrow \nu + A(N,Z) \]
Supernova Neutrino Emission: 
Shock Wave Formation

3. Shock wave formation (t = 0)

- Inner core reaches nuclear densities
- Neutron degeneracy halts gravitation attraction
- Inner core rebounds, causing shock wave
- Shock wave propagates through outer core
- \( \nu \)-sphere larger; \( \nu \) still emitted from outer core
Shock slows infall and dissociates nucleons

Shock loses 8 MeV per dissociated nucleon

Electrons captured on dis. protons produce $\nu_e$ via:

$$e^- + p \rightarrow \nu_e + n$$
Supernova Neutrino Emission: **Neutrino Cooling**

5. Neutrino cooling ($t = 1 - 10 \text{ s}$)

- $E_{\text{grav}} \rightarrow E_{\text{therm}} (\sim 10^{53} \text{ erg})$
- $T \approx 40 \text{ MeV}$
- Proto-neutron star cools:
- Neutron star (or black hole?) left behind

\[
e^- + p \rightarrow \nu_e + n
\]
\[
e^+ + n \rightarrow \bar{\nu}_e + p
\]
\[
e^- + e^+ \rightarrow \nu + \bar{\nu}
\]
\[
e^\pm + N \rightarrow e^\pm + N + \nu + \bar{\nu}
\]
\[
N + N \rightarrow N + N + \nu + \bar{\nu}
\]
\[
\gamma (+ e^\pm) \rightarrow \nu + \bar{\nu}
\]
Supernova Neutrino Energy Spectra

$\nu_\mu$ and $\nu_\tau$ do not experience CC $\rightarrow$ smaller $\nu$-sphere $\rightarrow$ higher E

More n than p in proto-neutron star $\rightarrow$ $\nu_e$ decouples before $\nu_e$

Average $\nu$ Energies:

$< E_{\nu e} > = 13$ MeV

$< E_{\bar{\nu}e} > = 16$ MeV

$< E_{\nu_x} > = 23$ MeV

Supernovae Relic Neutrinos

- To date, only SN $\nu$ burst seen on 23-Feb-1987 (Sanduleak -69° 202)
- Diffuse backgrnd of SN relic $\nu$ should exist! (Called 'SRN')
- All 6 types of $\nu$ emitted in SN but we only search for $\bar{\nu}_e$
- Inverse $\beta$ x-section dominant:
  $$\bar{\nu}_e + p \rightarrow e^+ + n$$
  \[E_e = E_\nu - 1.3 \text{ MeV}\]

Theoretical Models

- Predictions generated from SN model, cosmology, etc.
- SRN detection provides info on SN rate, SFR, galaxy ev.
- Low thresh → probe high Z
- Flux predictions:
  \[ F_{SRN} = 2 - 54 \ \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1} \]

Population synthesis (Totani et al., 1996)
Constant SN rate (Totani et al., 1996)
Cosmic gas infall (Malaney, 1997)
Cosmic chemical evolution (Hartmann et al., 1997)
Heavy metal abundance (Kaplinghat et al., 2000)
LMA \( \nu \) oscillation (Ando et al., 2002)
The Super-Kamiokande Detector

- 50,000 ton water Cherenkov detector
- Located 1,000 m underground
- 11,146 inward-facing 50 cm PMTs view fiducial volume (22,500 t)
- 1,885 outward-facing 20 cm PMTs monitor incoming events
- 5 MeV energy threshold
Detection Method

Solar: $\nu_e + e^- \rightarrow \nu_e + e^-$

SN: $\bar{\nu}_e + p \rightarrow e^+ + n$

$E_e = 35$ MeV
The LINAC Calibration System

- Position of LINAC electrons known to within few mm
- LINAC used to calibrate absolute energy scale, & detector resolutions (angular, vertex and energy)

Single mono-energetic electrons injected into SK
Momentum can be tuned between 5.1 and 16.3 MeV/c
Energy Calibration for $E > 18$ MeV

Use $\mu$-$e$ decay for E-scale
$\mu^+$ gives basic Michel spec.
$\mu^-$ can be captured on $^{16}$O

Ave. $\mu$-$e$ event has $E = 37$ MeV
Systematics: $1.23\% \pm 0.24\%$
SRN Data Reduction

We cannot 'tag' SRN events! Understanding BG vital!

**Reducible**
- $\mu$ induced spallation
- Atmospheric $\nu_{\mu}$
- Nuclear de-excitation $\gamma$
- Solar neutrinos

**Irreducible**
- Atmospheric $\nu_e$
- Atm. $\nu_{\mu} \rightarrow \mu \rightarrow$ Decay-$e$
  [Muon is "invisible"]

**Strategy:** Remove 'reducible' BG with cuts
Differentiate 'irreducible' BG from SRN signal by shape
Spallation Cut

- Cosmic ray $\mu$ spall $^{16}$O nuclei → emit $\beta$ particles
- $E_\beta = 3-21$ MeV; $\tau_\beta > 8.5$ msec
- Apply spallation cut to data w/ $E < 34$ MeV (due to $E_{\text{res}}$ of SK)
- Cut all events with $\Delta T < 0.15s$. Likelihood func. uses $\Delta T$ & $\Delta L$ to cut long-lived spallation
- Ability to remove spallation sets lower threshold (18 MeV)
Sub-Event Cut

- Cut designed to remove $\mu$ with:
  - $p_\mu < 350$ MeV/c
- $\mu$ created from low energy atmospheric $\nu_\mu$
- Search for decay electron in same event (two timing peaks)
- 34% of $\mu$ eliminated
Cherenkov Angle Cut: 
**Basic Idea**

- Remaining $\mu$ tagged by Cherenkov angle
- Look for a collapsed ring: $\cos(\theta_c) = 1 / (n \cdot \beta)$
Cherenkov Angle Cut: Reconstruction Method

\[ R^2 = \sin(\theta_{\text{open}}) \]
Cherenkov Angle Cut: Electron Reconstruction

Peak expected at $\sim 42^\circ$

(Ee = 59 MeV)
Cherenkov Angle Cut: Muon Reconstruction

Peak expected at < 42°

(E_µ = 68 MeV)
Cherenkov Angle Cut: Cut Results

- Cut events w/ $\theta_c < 38^0$ to remove $> 97\%$ of $\mu$
- Cut events w/ $\theta_c > 50^0$ to remove nuclear de-excitation events
Cherenkov Angle Cut: Multi-$\gamma$ Reconstruction

Peak near 90° (E = 20 MeV)
Solar Direction Cut: Motivation

- **Solar neutrinos:**
  created by nuclear fusion in the Sun

  \[ 4p \rightarrow ^4\text{He} + 2\ e^+ + 2\ \nu_e \]

- Flux & spectra calculated by the Standard Solar Model

**Flux:**
[Units are \((10^{10}\ \text{cm}^{-2}\ \text{sec}^{-1})\)]

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Flux</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>5.96</td>
<td>(1.00±0.01)</td>
</tr>
<tr>
<td>pep</td>
<td>1.40x10^{-2}</td>
<td>(1.00±0.015)</td>
</tr>
<tr>
<td>hep</td>
<td>9.3x10^{-7}</td>
<td>(1.00±???)</td>
</tr>
<tr>
<td>(^7\text{Be})</td>
<td>4.82x10^{-1}</td>
<td>(1.00±0.10)</td>
</tr>
<tr>
<td>(^8\text{B})</td>
<td>5.05x10^{-4}</td>
<td>(1.00 $^{+0.20}_{-0.16}$)</td>
</tr>
</tbody>
</table>

http://www.sns.ias.edu/~jnb
Solar Neutrino Detection

\[^{8}\text{B} \text{ flux :} \]
\[2.35 \pm 0.02 \pm 0.08 \times 10^{6} /\text{cm}^{2}/\text{sec}\]
\[0.465 \pm 0.005^{+0.016}_{-0.015} \times \text{SSM}\]

22,385 solar \( \nu \) events
(14.5 events/day)
18 MeV threshold is below hep cut-off → SSM predicts 1.06 events

Potential contamination from $^8$B due to smearing

Remove all events that point back to $30^\circ$ of Sun AND have $E < 34$ MeV
Reduction Summary

- Before sp. cut (E = 18 – 82 Mev): 1602 events
- After spallation cut (E < 34 MeV): 992 events
- After sub-event cut: 828 events
- After $\theta_c$ cut: 278 events
- After solar $\nu$ cut (E < 34 MeV): 271 events
Final Efficiencies
For $E \leq 34$ MeV,
$\varepsilon = 47% \pm 0.4%$
For $E > 34$ MeV,
$\varepsilon = 79% \pm 0.5%$
Final Data Sample
Signal & BG Shapes: Monte Carlo

**SRN Signal:**
- Signal falls sharply with increasing energy;
- BG shape rises.

**Decay-e:**

**Atm. Ve:**

→ Use shape difference to extract SRN signal.
Fitting the Final Data

\[ \chi^2 = \sum_{l=1}^{16} \frac{[(\alpha \cdot A_l) + (\beta \cdot B_l) + (\gamma \cdot C_l) - N_l]^2}{\sigma_{\text{stat}}^2 + \sigma_{\text{sys}}^2} \]
Fitting the Final Data

\[ \chi^2 = \sum_{l=1}^{16} \frac{[\alpha \cdot A_l + (\beta \cdot B_l) + (\gamma \cdot C_l) - N_l]^2}{\sigma_{\text{stat}}^2 + \sigma_{\text{sys}}^2} \]

Total B.G. + 90\% C.L.
SRN limit

Atmospheric \( \nu_e \)

Total background (Atm. + decay e)

Decay electrons
Efficiency-Corrected Data

\[ N_i' = \frac{N_i}{\varepsilon(E_i)} \times \frac{365\text{ days}}{\tau} \]

- Total B.G. + 90% C.L.
- SRN limit
- Atmospheric $\nu_e$
- Total background (Atm. + decay e)
- Decay electrons
Background Event Rates

**Michel Electrons**
- Best fit to data: \(174 \pm 16\) events
- Expected from MC: \(145 \pm 43\) events

**Atmospheric \((\nu_e)\)**
- Best fit to data: \(88 \pm 12\) events
- Expected from MC: \(75 \pm 23\) events

Expected backgrounds fit data well!
Best fit to \(\alpha\) (# SRN events) is ZERO for all six models.
Flux Calculation

Use 90% C.L. limit on $\alpha$ to get full spectrum flux limits:

$$F = \frac{\alpha_{90}}{N_p \times \tau \times \int f(E_\nu) \sigma(E_\nu) \varepsilon(E_\nu) \, dE_\nu}$$

Where:

- $N_p$ = # of free protons in SK = $1.5 \times 10^{33}$
- $\tau$ = detector livetime = 1496 days = $1.29 \times 10^8$ seconds
- $f(E_\nu)$ = normalized SRN spectrum shape function
- $\sigma(E_\nu)$ = cross section = $9.52 \times 10^{-44}$ $E_e$ $p_e$
- Integral runs from $E_\nu = 19.3$ MeV to $83.3$ MeV

Use 90% C.L. limit on $\alpha$ to get full spectrum flux limits:
<table>
<thead>
<tr>
<th>Theoretical Model</th>
<th>SK SRN Rate Limit</th>
<th>SK SRN Flux Limit</th>
<th>Predicted SRN Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Population Synthesis</strong></td>
<td>$&lt; 3.2$ Evt$^s$ / 22.5 kton yr</td>
<td>$&lt; 130$ $\overline{\nu_e}$ / cm$^2$ sec</td>
<td>44 $\overline{\nu_e}$ / cm$^2$ sec</td>
</tr>
<tr>
<td><strong>Cosmic Gas Infall</strong></td>
<td>$&lt; 2.8$ Evt$^s$ / 22.5 kton yr</td>
<td>$&lt; 32$ $\overline{\nu_e}$ / cm$^2$ sec</td>
<td>5.4 $\overline{\nu_e}$ / cm$^2$ sec</td>
</tr>
<tr>
<td><strong>Cosmic Chemical Evolution</strong></td>
<td>$&lt; 3.3$ Evt$^s$ / 22.5 kton yr</td>
<td>$&lt; 25$ $\overline{\nu_e}$ / cm$^2$ sec</td>
<td>8.3 $\overline{\nu_e}$ / cm$^2$ sec</td>
</tr>
<tr>
<td><strong>Heavy Metal Abundance</strong></td>
<td>$&lt; 3.0$ Evt$^s$ / 22.5 kton yr</td>
<td>$&lt; 29$ $\overline{\nu_e}$ / cm$^2$ sec</td>
<td>$&lt; 54$ $\overline{\nu_e}$ / cm$^2$ sec</td>
</tr>
<tr>
<td><strong>Constant SN Rate</strong></td>
<td>$&lt; 3.4$ Evt$^s$ / 22.5 kton yr</td>
<td>$&lt; 20$ $\overline{\nu_e}$ / cm$^2$ sec</td>
<td>52 $\overline{\nu_e}$ / cm$^2$ sec</td>
</tr>
<tr>
<td><strong>LMA Neutrino Oscillation</strong></td>
<td>$&lt; 3.5$ Evt$^s$ / 22.5 kton yr</td>
<td>$&lt; 31$ $\overline{\nu_e}$ / cm$^2$ sec</td>
<td>11 $\overline{\nu_e}$ / cm$^2$ sec</td>
</tr>
</tbody>
</table>
SK Flux Limits vs. Theoretical Predictions

<table>
<thead>
<tr>
<th>Category</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population Synthesis</td>
<td>Totani et al., 1996</td>
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<tr>
<td>Cosmic Gas Infall</td>
<td>Malaney, 1997</td>
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<tr>
<td>Cosmic Chemical Evolution</td>
<td>Hartmann et al., 1997</td>
</tr>
<tr>
<td>Heavy Metal Abundance</td>
<td>Kaplinghat et al., 2000</td>
</tr>
<tr>
<td>Constant SN Rate</td>
<td>Totani et al., 1996</td>
</tr>
<tr>
<td>LMA MSW Oscillation</td>
<td>Ando et al., 2002</td>
</tr>
</tbody>
</table>

**SK SRN Limit (90% C.L.)**

**Predicted SRN Flux**
Constant SN Model

- SRN flux scales with SN rate
- 90% C.L. limit on flux $\rightarrow$ 90% C.L. limit on SN rate
- Prediction of $52 \ \bar{\nu}_e \text{ cm}^{-2} \text{ sec}^{-1}$ corresponds to SN rate of $1.6 \times 10^3 \text{ SN year}^{-1} \text{ Mpc}^{-3}$ (based on $^{16}\text{O}$ abundance)
- SK limit of $20 \ \bar{\nu}_e \text{ cm}^{-2} \text{ sec}^{-1}$ corresponds to SN rate limit of $6.2 \times 10^2 \text{ SN year}^{-1} \text{ Mpc}^{-3}$ $\leftarrow$ TOO LOW!
- Previous best limit (Kam-II) was $780 \ \bar{\nu}_e \text{ cm}^{-2} \text{ sec}^{-1}$
- SK limit is better by factor of 39!
Model-Insensitive Limit

- Full spectrum flux limits have strong model dependence, based on spectrum in low energy regions.
- Remove model dependence and get flux in directly observable region ($E_\nu > 19.3$ MeV):

$$F_{\text{insen.}} = F \times \frac{\int_{19.3 \text{ MeV}}^{\infty} f(E_\nu) \, dE_\nu}{\int_{0}^{\infty} f(E_\nu) \, dE_\nu}$$

- For all models, this limit is same: $< 1.2 \, \overline{\nu}_e \, \text{cm}^{-2} \, \text{sec}^{-1}$
- Compare with previous limit: $< 226 \, \overline{\nu}_e \, \text{cm}^{-2} \, \text{sec}^{-1}$

[From Kamiokande-II, see W. Zhang et al. Phys. Rev. Lett. 61, 385]
## Model-Insensitive Results

<table>
<thead>
<tr>
<th>Theoretical Model</th>
<th>SRN Flux Limit (E(_{\nu} &gt; 19.3) MeV)</th>
<th>Predicted SRN Flux (E(_{\nu} &gt; 19.3) MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population Synthesis</td>
<td>(&lt;1.2 \overline{\nu_e} / \text{cm}^2 \text{ sec})</td>
<td>(0.41 \overline{\nu_e} / \text{cm}^2 \text{ sec})</td>
</tr>
<tr>
<td>Cosmic Gas Infall</td>
<td>(&lt;1.2 \overline{\nu_e} / \text{cm}^2 \text{ sec})</td>
<td>(0.2 \overline{\nu_e} / \text{cm}^2 \text{ sec})</td>
</tr>
<tr>
<td>Cosmic Chemical Evolution</td>
<td>(&lt;1.2 \overline{\nu_e} / \text{cm}^2 \text{ sec})</td>
<td>(0.39 \overline{\nu_e} / \text{cm}^2 \text{ sec})</td>
</tr>
<tr>
<td>Heavy Metal Abundance</td>
<td>(&lt;1.2 \overline{\nu_e} / \text{cm}^2 \text{ sec})</td>
<td>(&lt;2.2 \overline{\nu_e} / \text{cm}^2 \text{ sec})</td>
</tr>
<tr>
<td>Constant SN Rate</td>
<td>(&lt;1.2 \overline{\nu_e} / \text{cm}^2 \text{ sec})</td>
<td>(3.1 \overline{\nu_e} / \text{cm}^2 \text{ sec})</td>
</tr>
<tr>
<td>LMA Neutrino Oscillation</td>
<td>(&lt;1.2 \overline{\nu_e} / \text{cm}^2 \text{ sec})</td>
<td>(0.43 \overline{\nu_e} / \text{cm}^2 \text{ sec})</td>
</tr>
</tbody>
</table>
Model-Insensitive Results vs. Flux Predictions

- **Population Synthesis** (Totani et al., 1996)
- **Cosmic Gas Infall** (Malaney, 1997)
- **Cosmic Chemical Evolution** (Hartmann et al., 1997)
- **Heavy Metal Abundance** (Kaplinghat et al., 2000)
- **Constant SN Rate** (Totani et al., 1996)
- **LMA MSW Oscillation** (Ando et al., 2002)

The graph shows the predicted SRN flux and the SK SRN limit (90% C.L.) for energies greater than 19.3 MeV.
Other Experiments

**KamLAND**
- Lq. Scintillator (408 t fid) detector
- 1.8 MeV threshold
- After inverse $\beta$: $n + p \rightarrow d + \gamma$ ($E\gamma = 2.2$ MeV)
- By searching for the delayed $\gamma$, virtually all BG can be removed
- Threshold can be set at $\sim 10$ MeV (below which reactor $\nu$ dominate)
- Expected event rate is 0.1 ev/year due to small fiducial volume

**SNO**
- 1 kt heavy water w/ salt added
- With D$_2$O: $n + d \rightarrow ^3H + \gamma$ ($E\gamma = 6.3$ MeV)
- With NaCl: $n + ^{35}\text{Cl} \rightarrow ^{36}\text{Cl} + \gamma$ ($E\gamma = 8.6$ MeV)
- Search for delayed $\gamma$ after an $e^+$
- Event rate 0.03 ev/yr for thresh. of $E > 10$ MeV
Possible Upgrade for SK?

- Neutron detection in Si via Gadolinium?
- Gd has large x-section
- 100 t (0.2%) in SK to catch > 90% n
- Capture $\rightarrow$ 8 MeV $\gamma$ cascade
- Above 12 MeV thresh. ~2 SRN/year expected
- First SRN discovery??
# Water Cherenkov: The Next Generation

<table>
<thead>
<tr>
<th><strong>DUSEL</strong></th>
<th><strong>Hyper-Kamiokande</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• 650 kton total volume</td>
<td>• 1,000 kton total volume</td>
</tr>
<tr>
<td>• 440 kton fiducial volume ( = 20 × SK)</td>
<td>• 540 kton fiducial volume ( = 24 × SK)</td>
</tr>
<tr>
<td>• sensitivity $\propto$ (exposure)$^{1/2}$</td>
<td>• Current plans call for depth of 1400 – 1900 m.w.e</td>
</tr>
<tr>
<td>• First approximation: Detection within 3 yrs</td>
<td>• Too shallow for SRN search!</td>
</tr>
<tr>
<td>• If Gd works in SK, scale it to larger detectors</td>
<td>• Depth might not pose a problem with Gd-enriched Hyper-K</td>
</tr>
<tr>
<td>• May see $\sim$40 SRN/yr measure E spectrum?</td>
<td>• HK may see $\sim$50 SRN / yr → Neutrino cosmology??</td>
</tr>
</tbody>
</table>
Supernova Relic Neutrinos: A Summary

- SRN signal would manifest as distortion of Michel spectrum
- Above $E_e = 18$ MeV, no distortion seen $\rightarrow$ flux limits can be set
- The Super-Kamiokande flux limits on the SRN are 1-2 orders of magnitude better than previous limits
- Some SRN models can be constrained or rejected
- An increase in sensitivity of factor 3-6 is needed to probe all models
- Future experiments (DUSEL, Hyper-Kamiokande) may be able to observe SRN due to higher statistics
- New methods, such as enhancing Super-Kamiokande with Gd, have been proposed to detect the SRN