Supernova Neutrino Observations: What Could We Learn?

Georg Raffelt, Max-Planck-Institut für Physik, München
Supernova Neutrino Observations: What Could We Learn?

- Neutrino observations of SN 1987A
- Opportunities to observe the next galactic supernova in neutrinos
- Some particle-physics lessons from SN 1987A and possible improvements
- Oscillations of supernova neutrinos
Selected Anniversaries at Neutrino 2006 (± 1 year)

- **50 years Neutrino Discovery**
- **10 years Super-Kamiokande data taking (1 April 1996)**
- **1000 years Supernova 1006 (30 April)**
- **20 years Leptogenesis proposed**
  - M. Fukugita & T. Yanagida
  - "Baryogenesis without Grand Unification"
- **20 years Supernova 1987A**
  - 23 February 1987
Sanduleak –69 202

Tarantula Nebula

Large Magellanic Cloud
Distance 50 kpc
(160,000 light years)
Sanduleak −69 202

Large Magellanic Cloud
Distance 50 kpc
(160,000 light years)

Tarantula Nebula

Supernova 1987A
23 February 1987
Neutrino Signal of Supernova 1987A

Kamiokande-II (Japan) Water Cherenkov detector 2140 tons Clock uncertainty $\pm 1$ min

Irvine-Michigan-Brookhaven (US) Water Cherenkov detector 6800 tons Clock uncertainty $\pm 50$ ms

Baksan Scintillator Telescope (Soviet Union), 200 tons Random event cluster $\sim 0.7$ day Clock uncertainty $+2/-54$ s

Within clock uncertainties, signals are contemporaneous.
Energy Distribution of SN 1987A Neutrinos

Kamiokande II

IMB
Interpreting SN 1987A Neutrinos

Assume thermal spectra and equipartition of energy between the six degrees of freedom $\nu_e, \nu_\mu, \nu_\tau$ and their antiparticles.

Theory

95 % CL Contours

Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

Neutrino 2006, 13-19 June 2006, Santa Fe, New Mexico
Angular Distribution of SN 1987A Neutrinos

Main detection reaction

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

is essentially isotropic for the relevant energies.

Expect only a fraction of an event from forward-peaked reaction

\[ \nu + e^- \rightarrow e^- + \nu \]
SN 1987A Signal in LSD (Mont Blanc)?

- Observed a 5-event cluster 4.72 hours before IMB/Kam-II
- Triggered automatic SN alert
- Statistical fluctuation very unlikely
- No significant signal in IMB/Kam-II at LSD time
- No significant LSD signal at IMB time

LSD (Liquid Scintillator Detector) in the Mont Blanc Tunnel (Oct. 1984 - March 1999)  
Supernova monitor for our galaxy  
90 tons scintillator  
200 tons iron (support structure)

- Interpretation as “double bang”: Huge $\nu_e$ flux (~ 40 MeV) at LSD time  
- LSD signal caused by interactions in iron of support structure  
- Second bang ordinary multi-flavor signal

### Supernova Neutrino Observations: What Could We Learn?

1. **Neutrino observations of SN 1987A**
2. **Opportunities to observe next the galactic supernova in neutrinos**
3. **Some particle-physics lessons from SN 1987A and possible improvements**
4. **Oscillations of supernova neutrinos**
Large Detectors for Supernova Neutrinos

- SNO (800)
- MiniBooNE (190)
- LVD (400)
- Borexino (80)
- Super-Kamiokande ($10^4$)
- KamLAND (330)

In brackets events for a "fiducial SN" at distance 10 kpc

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

Neutrino 2006, 13-19 June 2006, Santa Fe, New Mexico
Large Detectors for Supernova Neutrinos

See Posters:
- Supernova detection with KamLAND (Kazumi Ishii, #111)
- Search for SN burst neutrinos (Atsushi Takeda, #113)
- Galactic SN Monitoring at LVD (LVD Collaboratino, #107)

In brackets events for a “fiducial SN” at distance 10 kpc.
Supernova Distance Distribution

Average distance 10.7 kpc, rms dispersion 4.9 kpc
(11.9 kpc and 6.0 kpc for SN Ia distribution)

Neutrino observation can alert astronomers several hours in advance to a supernova. To avoid false alarms, require alarm from at least two experiments.

Super-K
SNO
LVD
IceCube

Coincidence Server @ BNL

Alert

http://snews.bnl.gov
astro-ph/0406214
Neutrino observation can alert astronomers several hours in advance to a supernova. To avoid false alarms, require alarm from at least two experiments.

See Poster:
- SNEWS - The SN Early Warning System (Clarence J. Virtue, #115)
**Supernova Pointing with Neutrinos**

- Beacom & Vogel: Can a supernova be located by its neutrinos? [astro-ph/9811350]

### Neutron tagging efficiency

<table>
<thead>
<tr>
<th>Detector</th>
<th>Neutron tagging efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>90%</td>
</tr>
<tr>
<td>SK</td>
<td>7.8°</td>
</tr>
<tr>
<td>SK × 30</td>
<td>1.4°</td>
</tr>
</tbody>
</table>

**Neutron tagging in a large water Cherenkov detector by gadolinium loading**

- Investigated within Super-K Collaboration, R&D apparently going well
- (GADZOOKS!, for original idea see Beacom and Vagins, hep-ph/0309300)
Simulated Supernova Signal at Super-Kamiokande

Simulation for Super-Kamiokande SN signal at 10 kpc, based on a numerical Livermore model
Each optical module (OM) picks up Cherenkov light from its neighborhood. SN appears as “correlated noise”.

- About 300 Cherenkov photons per OM from a SN at 10 kpc
- Noise per OM < 500 Hz
- Total of 4800 OMs in IceCube

**IceCube SN signal at 10 kpc, based on a numerical Livermore model**

[Dighe, Keil & Raffelt, hep-ph/0303210]

**Method first proposed by Halzen, Jacobsen & Zas**

[astro-ph/9512080]
### Core-Collapse SN Rate in the Milky Way

<table>
<thead>
<tr>
<th>SN statistics in external galaxies</th>
<th>0 1 2 3 4 5 6 7 8 9 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>van den Bergh &amp; McClure (1994)</td>
<td></td>
</tr>
<tr>
<td>Cappellaro &amp; Turatto (2000)</td>
<td></td>
</tr>
<tr>
<td>Gamma rays from $^{26}$Al (Milky Way)</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>Diehl et al. (2006)</td>
<td></td>
</tr>
<tr>
<td>Historical galactic SNe (all types)</td>
<td>0 1 2 3</td>
</tr>
<tr>
<td>Strom (1994)</td>
<td></td>
</tr>
<tr>
<td>Tammann et al. (1994)</td>
<td></td>
</tr>
<tr>
<td>No galactic neutrino burst</td>
<td>90 % CL (25 y observation)</td>
</tr>
<tr>
<td>Alekseev et al. (1993)</td>
<td></td>
</tr>
</tbody>
</table>

**References:**
Core-Collapse SN Rate in the Milky Way

<table>
<thead>
<tr>
<th>Core-collapse SNe per century</th>
<th>SN statistics in external galaxies</th>
<th>Gamma rays from $^{26}$Al (Milky Way)</th>
<th>Historical galactic SNe (all types)</th>
<th>No galactic neutrino burst</th>
</tr>
</thead>
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<tr>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Alekseev et al. (1993)</td>
</tr>
</tbody>
</table>

Neutrinos from about 1000 galactic supernovas on their way!

Local Group of Galaxies

Events in a detector with 30 x Super-K fiducial volume, (Hyper-K, MEMPHYS, UNO, ...)

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Neutrino 2006, 13-19 June 2006, Santa Fe, New Mexico
Nearby Galaxies with Many Observed Supernovae

M83 (NGC 5236, Southern Pinwheel)  
D = 4.5 Mpc

Observed Supernovae:  

NGC 6946  
D = (5.5 ± 1) Mpc

Observed Supernovae:  
Supernova Rate in Nearby Galaxies

Expected rates and their uncertainties based on galaxy types and sizes, scaled with SN statistics derived from external galaxies.

However, observed SNe in this volume in recent years about 3 times the expected rate (9 within 10 Mpc with 2.8 expected, 4 within 4 Mpc with 1.0 expected).

Cosmic Diffuse Supernova Neutrino Background (DSNB)

- About 1 SN per sec in the visible universe
- Diffuse SN neutrino background (DSNB) from all past SNe few $\bar{\nu}_e$ cm$^{-2}$s$^{-1}$
- Can be measured even in Super-K sized detector (few events/year)
- Need neutron tagging
  - Gadolinium loading of SK
  - Large scintillator detector (LENA project, 50 kt)


Pushing the boundaries of neutrino astronomy to cosmological distances

FIG. 1: Spectra of low-energy $\bar{\nu}_e + p \rightarrow e^+ + n$ coincidence events and the sub-Čerenkov muon background. We assume full efficiencies, and include energy resolution and neutrino oscillations. Singles rates (not shown) are efficiently suppressed.
The Red Supergiant Betelgeuse (Alpha Orionis)

First resolved image of a star other than Sun

Distance
(Hipparcos)
130 pc (425 lyr)

If Betelgeuse goes Supernova:
- $6 \times 10^7$ neutrino events in Super-Kamiokande
- $2.4 \times 10^3$ neutron events per day from Silicon-burning phase (few days warning!), need neutron tagging

[Odrzywolek, Misiaszek & Kutschera, astro-ph/0311012]
The Red Supergiant Betelgeuse (Alpha Orionis)

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  [Odrzywolek, Misiaszek & Kutajarvi, astro-ph/0311012]

See Poster:
• Thermal neutrinos from pre-SN (Andrzej Odrzywolek, #117)
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Dispersion between Neutrinos and Photons

Transit time for photons and neutrinos are equal to within ~ 3h

\[ \text{Total transit time} \sim 5 \times 10^{12} \text{ sec} \]
\[ \rightarrow \text{Equal for photons and neutrinos within} \sim 2 \times 10^{-9} \]

(Longo 1987, Stodolsky 1988)

\[ \left| \frac{c_v - c_\gamma}{c_v + c_\gamma} \right| < 10^{-9} \]

Shapiro time delay for particles moving through a gravitational potential
\[ \Delta t_{\text{Shapiro}} = -2 \int_A^B \left[ r(t) \right] dt \approx 2 - 6 \times 10^6 \text{ sec} \]

(Krauss & Tremaine 1988)

Equal within \sim 1 - 4 \times 10^{-3}

- Proves directly that neutrinos respond to gravity in the standard way
- Provides limits on parameters of certain non-GR theories of gravitation
- Could be extended to neutrinos vs. anti-neutrinos or different flavors from signal of a future galactic SN
**Neutrino Limits by Intrinsic Signal Dispersion**

<table>
<thead>
<tr>
<th>Time of flight delay by neutrino mass</th>
<th>For “milli charged” neutrinos, path bent by galactic magnetic field, inducing a time delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ \Delta t = 2.57s \left( \frac{D}{50 \text{kpc}} \right) \left( \frac{10 \text{MeV}}{E_\nu} \right)^2 \left( \frac{m_\nu}{10 \text{eV}} \right)^2 ]</td>
<td>[ \frac{\Delta t}{t} = \frac{e_\nu^2 (B_\perp d_B)^2}{6E_\nu^2} &lt; 3 \times 10^{-12} ]</td>
</tr>
<tr>
<td>[ m_{\nu e} \lesssim 20 \text{ eV} ]</td>
<td>[ \frac{e_\nu}{e} &lt; 3 \times 10^{-17} \left( \frac{1 \mu \text{G}}{B_\perp} \right) \left( \frac{1 \text{kpc}}{d_B} \right) ]</td>
</tr>
<tr>
<td><strong>Details:</strong></td>
<td>Assuming charge conservation in neutron decay yields a more restrictive limit of about ( 3 \times 10^{-21} ) e</td>
</tr>
<tr>
<td>- Detailed maximum-likelihood analysis yields similar limit</td>
<td></td>
</tr>
<tr>
<td>- At the time of SN 1987A competitive with tritium end-point limits, today ( m_{\nu e} &lt; 2.2 \text{ eV} )</td>
<td></td>
</tr>
<tr>
<td>- Cosmological limit today ( m_\nu \lesssim 0.2 \text{ eV} )</td>
<td></td>
</tr>
</tbody>
</table>

**Next galactic SN observation:**
Time-of-flight dispersion not important for signal interpretation

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*Georg Raffelt, Max-Planck-Institut für Physik, München, Germany*

*Neutrino 2006, 13-19 June 2006, Santa Fe, New Mexico*
The Energy-Loss Argument

Emission of very weakly interacting particles would “steal” energy from the neutrino burst and shorten it. (Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable
Sterile Neutrinos

Active-sterile mixing

\[ e \quad \rightarrow \quad x \quad \rightarrow \quad \nu_s \]

\[ p \quad \rightarrow \quad W \quad \rightarrow \quad n \]

Electron neutrino appears as sterile neutrino in \( \frac{1}{2} \sin^2(2\Theta_{es}) \) of all cases

\[ \Gamma_s \approx \frac{1}{2} \sin^2(2\Theta_{es}) \Gamma_L \]

Average scattering rate in SN core involving ordinary left-handed neutrinos

\[ \Gamma_L \approx 10^{10}\text{ s}^{-1} \]

To avoid complete energy loss in \( \sim 1 \) s

\[ \frac{1}{2} \sin^2(2\Theta_{es}) 10^{10}\text{ s}^{-1} < 1\text{ s}^{-1} \]

\[ \sin^2(2\Theta_{es}) \lesssim 3 \times 10^{-10} \]

(for \( m_s \geq 100 \text{ keV} \))
Axion Emission Processes in Stars

Nucleons
\[ \frac{C_N}{2\pi f_a} \bar{\Psi}_N \gamma_\mu \gamma_5 \Psi_N \partial^\mu a \]

Nucleon Bremsstrahlung

Photons
\[ \frac{C e}{2\pi f_a} \bar{\Psi}_e \gamma_\mu \gamma_5 \Psi_e \partial^\mu a \]

Primakoff

Electrons
\[ C_\gamma \frac{\alpha}{2\pi f_a} \frac{1}{4} F_{\mu\nu} F^{\mu\nu} a \]
\[ = -C_\gamma \frac{\alpha}{2\pi f_a} \bar{E} \cdot \bar{B} a \]

Compton

Pair Annihilation

Electromagnetic Bremsstrahlung
Astrophysical Axion Bounds

- **Experiments**
  - Globular clusters (a-γ-coupling)
  - Hot dark matter limits (a-π-coupling)
  - SN 1987A (a-N-coupling)

- **Telescopes**
  - Direct search

- **Axion dark matter possible**
  - (Late inflation scenario)
  - (String scenario)

- **DM o.k.**
  - Too much DM

- **Indicators**
  - Too many events
  - Too much energy loss

- **Energy Scale**
  - 10^3 keV
  - 10^6 eV
  - 10^9 meV
  - 10^12 μeV

- **Mass Scale**
  - m_a
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Flavor Oscillations of Supernova Neutrinos

Shortly after collapse

- L-resonance (~10^5 km)
- H-resonance (~10^4 km)
- Shock Wave (~150 km)
- SN Core (~15 km)

Late time (few sec after bounce)

- H-resonance (100-10^3 km)

• Flavor conversion suppressed in core and near shockwave by large matter effects
• Flavor oscillations only important for freely streaming neutrinos at large r

Collective effects from nu-nu interaction important in hot bubble region


Flavor conversion can be important for r-process nucleosynthesis in hot bubble region

[Qian, Fuller & Woosley, PRL 71 (1993) 1965]
Level-Crossing Diagram in a SN Envelope

**Normal mass hierarchy**

\[
\begin{align*}
\bar{\nu}_\tau' & \quad \bar{\nu}_\mu' \\
\nu_3m & \quad L \\
\nu_{1m} & \quad \nu_\tau' \\
\bar{\nu}_e & \quad \bar{\nu}_e \\
\end{align*}
\]

**Inverted mass hierarchy**

\[
\begin{align*}
\bar{\nu}_\mu' & \quad \bar{\nu}_{2m} \\
\bar{\nu}_{1m} & \quad L \\
\nu_\tau' & \quad \nu_{3m} \\
\bar{\nu}_e & \quad \bar{\nu}_e \\
\end{align*}
\]

Dighe & Smirnov, Identifying the neutrino mass spectrum from a supernova neutrino burst, hep-ph/9907423
## Spectra Emerging from Supernovae

### Primary fluxes

<table>
<thead>
<tr>
<th>Flux</th>
<th>Flavor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F^0_e$</td>
<td>$\nu_e$</td>
</tr>
<tr>
<td>$F^0_{\bar{e}}$</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>$F^0_\chi$</td>
<td>$\nu_\mu, \bar{\nu}<em>\mu, \nu</em>\tau, \bar{\nu}_\tau$</td>
</tr>
</tbody>
</table>

### After leaving the supernova envelope, the fluxes are partially swapped

\[
F^0_e = pF^0_e + (1-p)F^0_\chi \\
F^0_{\bar{e}} = \bar{p}F^0_e + (1-\bar{p})F^0_\chi \\
\frac{1}{4} \sum F_\chi = \frac{2+p+\bar{p}}{4} F^0_\chi + \frac{1-p}{4} F^0_e + \frac{1-\bar{p}}{4} F^0_e
\]

### Survival probability

<table>
<thead>
<tr>
<th>Case</th>
<th>Mass ordering</th>
<th>$\sin^2(2\Theta_{13})$</th>
<th>$p$ (for $\nu_e$)</th>
<th>$\bar{p}$ (for $\bar{\nu}_e$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Normal</td>
<td>$\geq 10^{-3}$</td>
<td>0</td>
<td>$\cos^2(\Theta_{12}) \approx 0.7$</td>
</tr>
<tr>
<td>B</td>
<td>Inverted</td>
<td></td>
<td>$\sin^2(\Theta_{12}) \approx 0.3$</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>Any</td>
<td>$\leq 10^{-5}$</td>
<td>$\sin^2(\Theta_{12}) \approx 0.3$</td>
<td>$\cos^2(\Theta_{12}) \approx 0.7$</td>
</tr>
</tbody>
</table>
Kitaura, Janka & Hillebrandt, “Explosions of O-Ne-Mg cores, the Crab supernova, and subluminous Type II-P supernovae”, astro-ph/0512065
Neutronization Burst in a Mt Detector w/ Neutron Tagging

After angular cuts, almost background-free neutronization burst from $\nu$-e-scattering

Neutrino oscillations cause a significantly different time profile (absolute flux depends on distance)

If mixing scenario is known, perhaps best method to determine SN distance, especially if obscured (better than 5-10%)

**Supernova Neutrino Spectra Formation**

**Electron flavor** \((\nu_e, \bar{\nu}_e)\)

- Free streaming

- Neutrino sphere \((T_{NS})\)

- Thermal Equilibrium

\[
\bar{\nu}_e + p \leftrightarrow n + e^+
\]

\[
\nu_e + n \leftrightarrow p + e^-
\]

**Other flavors** \((\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau)\)

- Scattering Atmosphere

- Diffusion

- Free streaming

- Energy sphere \((T_{ES})\)

- Transport sphere

- Thermal Equilibrium

\[
\nu + N \leftrightarrow \bar{\nu} + N
\]

\[
\nu_e + e^- \leftrightarrow \bar{\nu} + \bar{\nu}
\]

\[
\nu_e + \bar{\nu}_e \leftrightarrow \nu_\mu + \nu_\mu
\]

Supernova Neutrino Spectra Formation

**Electron flavor** \( (\nu_e, \bar{\nu}_e) \)

- Thermal Equilibrium
  - \( \bar{\nu}_e \) + \( p \) ± \( e^+ \)
  - \( \nu_e \) + \( n \) ± \( e^- \)
- Neutrino sphere (\( T_{\text{NS}} \))
- Flux \( T_{\text{flux}} \approx T_{\text{NS}} \)

**Other flavors** \( (\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau) \)

- Scattering Atmosphere
  - \( \nu_N \leftrightarrow \bar{N}_N \)
  - \( \nu_e \leftrightarrow \bar{\nu}_e \)
  - \( N_N \leftrightarrow \bar{N}_N N_{\nu} \bar{\nu} \)
  - \( e^+ e^- \leftrightarrow \nu_N \bar{\nu} \)
  - \( \nu_e \bar{\nu}_e \leftrightarrow \nu_\mu \bar{\nu}_\mu \)
- Thermal Equilibrium
- Energy sphere (\( T_{\text{ES}} \))
- Transport sphere
- Flux \( T_{\text{flux}} \approx 0.6 T_{\text{ES}} \)

Oscillation of Supernova Anti-Neutrinos

Measured $\bar{\nu}_e$ spectrum at a detector like Super-Kamiokande

Assumed flux parameters
- Flux ratio $\bar{\nu}_e : \bar{\nu}_\mu = 0.8 : 1$
- $\langle E(\bar{\nu}_e) \rangle = 15\text{ MeV}$
- $\langle E(\bar{\nu}_x) \rangle = 18\text{ MeV}$

Mixing parameters
- $\Delta m_{\text{sol}}^2 = 60\text{ meV}^2$
- $\sin^2(2\theta) = 0.9$

No oscillations

Oscillations in SN envelope

Earth effects included

Model-Independent Strategies for Observing Earth Effects

One detector observes SN shadowed by Earth

Case 1:
- Another detector observes SN directly
- Identify Earth effects by comparing signals

Case 2: Identify “wiggles” in signal of single detector
Problem: Smearing by limited energy resolution

If 13-mixing angle is known to be “large”, e.g. from Double Chooz, observed “wiggles” in energy spectrum signify normal mass hierarchy

- Scintillator detector: ~ 2000 events may be enough
- Water Cherenkov: Need megaton detector with ~ 10^5 events

Dighe, Keil & Raffelt, “Identifying Earth matter effects on supernova neutrinos at a single detector” [hep-ph/0304150]
Galactic Distribution of Core-Collapse Supernovae

“Surface density” depleted near center (from pulsar distribution and other indicators)

\[
\sigma \propto r^\xi \exp\left(-\frac{r}{u}\right)
\]

Assumed vertical distribution in the galactic disk

\[
R(z) \propto 0.79 \exp\left[-\left(\frac{z}{212 \text{ pc}}\right)^2\right] + 0.21 \exp\left[-\left(\frac{z}{636 \text{ pc}}\right)^2\right]
\]

Dependence on geographic latitude quite robust relative to details of assumed galactic distribution

Dependence on geographic latitude quite robust relative to details of assumed galactic distribution

Probability of Earth and core shadowing as a function of geographic latitude

SUPERNOVA NEUTRINOS
EARTH SHADOWING PROBABILITY

(one detector)

Latitude: 54°
Longitude: 25°

Earth crossing, L (km): 0.0
Core crossing, L (km): 10665.35
Minimal path length L (km): 

SHADOWING PROBABILITY:
0.581

(two detectors)

Latitude 1 (deg): 64°
Latitude 2 (deg): 16°
Longitude 1 (deg): 35°
Longitude 2 (deg): 156°
Earth crossing, L (km): 0.0
Core crossing, L (km): 10665.35
Minimal path length L (km): 

SHADOWING PROBABILITY:
P(1, not 2): 0.270
P(not 1, 2): 0.214
P(1 and 2): 0.311
P(1 or 2, or both): 0.785
P(1 or 2, not both): 0.484
P(not 1, not 2): 0.206
Supernova Shock Propagation and Neutrino Oscillations

Schirato & Fuller: Connection between supernova shocks, flavor transformation, and the neutrino signal [astro-ph/0205390]

See Poster:
• Looking at the SN shock in neutrinos (Amol Dighe, #116)
Megatonne Cherenkov Detector (Inverted Hierarchy)

\[
\frac{\text{Flux}(\bar{\nu}_e)}{\text{Flux}(\bar{\nu}_x)} = 0.8
\]
\[
E_0(\bar{\nu}_e) = 15 \text{ MeV}
E_0(\bar{\nu}_x) = 18 \text{ MeV}
\]

\[
\frac{\text{Flux}(\bar{\nu}_e)}{\text{Flux}(\bar{\nu}_x)} = 0.5
\]
\[
E_0(\bar{\nu}_e) = 15 \text{ MeV}
E_0(\bar{\nu}_x) = 15 \text{ MeV}
\]
Shock-Wave Propagation in IceCube

\[
\frac{\text{Flux}(\bar{\nu}_e)}{\text{Flux}(\bar{\nu}_x)} = 0.8, \quad \langle E_{\bar{\nu}_e} \rangle = 15\,\text{MeV}, \quad \langle E_{\bar{\nu}_x} \rangle = 18\,\text{MeV}
\]

Choubey, Harries & Ross, “Probing neutrino oscillations from supernovae shock waves via the IceCube detector”, astro-ph/0604300
Stochastic Density Fluctuations

Schematic time-dependent shock-wave profile

Events in a 0.4 Mt water Cherenkov detector

Assume $\delta$-correlated noise, length-scale of order the oscillation length (10 km), amplitude 4% (line-width on plot)

**So what could we learn?**

<table>
<thead>
<tr>
<th>Depends on which detectors will be running, what they will see, and what else will be known at that time, e.g. about neutrino mixing parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Even small-statistics signal (e.g. SN at Andromeda distance with a Mt detector) useful to determine spectra and duration better than SN 1987A (especially useful for particle-physics limits and for prediction of diffuse SN neutrino background)</td>
</tr>
</tbody>
</table>
| High-statistics observation from galactic SN:  
  - Early warning, direction and distance  
  - Follow in detail stellar collapse, test SN theory  
  - May observe new features (e.g. collapse to black hole) |
| Neutrino oscillations:  
  - May observe evidence for flavor oscillations and determine mass hierarchy and/or magnitude of Theta-13  
  - May observe shock-wave propagation effects |
| Probably requires new detectors, e.g. Mton water Cherenkov (Hyper-K, MEMPHYS, UNO), neutron tagging (GADZOOKS!), large scintillator detectors (LENA), large nu-e detector (liquid argon TPC). In Europe: LAGUNA R&D initiative forming |
Supernova 1054 Petrograph

Possible SN 1054 Petrograph by the Anasazi people (Chaco Canyon, New Mexico)

3 concentric circles, diameter ~ 1 foot, with huge red flames trailing to the right. (Halley’s Comet?)

Hand signifies sacred place

Crescent Moon

SN 1054