Supernova Explosion

- A Star which is more than ~8 times heavier than the Sun ends its life by an explosion.
  - kinetic energy: $\sim 10^{51}$ erg ($1 \text{ erg} = 1 \times 10^{-7} \text{ J} = 6.2 \times 10^{11} \text{ eV}$)
  - luminosity: ~galaxy
  - rate: 1–3/century/galaxy

- Classification by spectral characteristics
  - Ia, Ib, Ic, II

- Classification by explosion mechanism
  - thermonuclear (= Ia)
  - core-collapse (= Ib, Ic, II)
  -> neutrino emission

Supernovae

<table>
<thead>
<tr>
<th>No Hydrogen</th>
<th>Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>No Silicon</td>
</tr>
<tr>
<td>Helium</td>
<td>No Helium</td>
</tr>
</tbody>
</table>

Type-Ia: thermonuclear
Type-Ib: core-collapse
Type-Ic: core-collapse
Type-II: core-collapse

Crab Nebula by NASA
Neutrinos from Core-Collapse Supernovae

- **Experiment**  There is only one observation of neutrinos from a supernova (“SN1987A” in the Large Magellanic Cloud).

- **Theory**  There are many numerical simulations about CCSNe, but the explosion mechanism is not completely revealed.

![Graph showing neutrino energy and time](image)
Supernova Relic Neutrinos

- Neutrinos from all past CCSNe are accumulated to form an integrated flux.

  = **Supernova Relic Neutrinos (SRNs)**

- Various factors affect the SRN flux on Earth.
  - Neutrino oscillation (mass hierarchy)
  - Galactic evolution (star formation rate, initial mass function, etc)
  - Black hole formation rate (metallicity, equation-of-state, etc)
  - etc

\[
\frac{d\Phi(E_\nu)}{dE_\nu} = c \int_0^\infty \frac{dz}{H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_A}} \times \\
\left[ R_{CCSN}(z) \int_0^{Z_{\text{max}}} \Psi_{ZF}(z, Z) \right] \left\{ \int_{M_{\text{min}}}^{M_{\text{max}}} \frac{dN(M, Z, E'_\nu)}{dE'_\nu} dM \right\} dZ
\]
• There is nearly an order of magnitude difference in the flux depending on the model.
• Detecting SRNs would provide valuable information about the explosion mechanism as well as the star formation history.

![Graph showing supernova relic neutrino flux vs energy, with various models plotted.](image-url)
Status of SRN Searches

- **Signal in experimental search** = inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$)
- The most sensitive searches have been performed in Super-Kamiokande and KamLAND.

- **Search at SK**
  - SK-I/II/III (spectrum analysis): spectrum fitting to $E_\nu > 17.3$ MeV
  - SK-IV (neutron tagging analysis): tagging efficiency $\sim 20\%$

- **Search at KamLAND**
  - Delayed coincidence
    (tagging efficiency $\sim 100\%$)
Super-Kamiokande Detector

- A water Cherenkov detector located 1,000 m under the mountain.
- Fiducial volume: 22.5 kton
- Inner detector: 11,129 20-inch PMTs
- Outer detector: 1,885 8-inch PMTs, used for cosmic-ray muon veto
- Operated since 1996 in five periods.
Inverse beta decay of electron antineutrinos ($\bar{\nu}_e + p \rightarrow e^+ + n$) is searched.

- Larger than the other mode by $>2$ orders of magnitude.

- Signal: “$\beta+n$” events
  - Prompt signal = $\beta$
  - Delayed signal = 2.2 MeV $\gamma$ from neutron capture
## Background (1): Muon Spallation

### Backgrounds

- **Not direct backgrounds in SK**
  - stable (no decay)
  - long lifetime
  - invisible decay
  - very low energy

### Table: Muon Spallation Isotopes

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life [sec.]</th>
<th>Decay mode</th>
<th>Yield ( \times 10^{-7} \text{muon}^{-1}\text{g}^{-1}\text{cm}^2 )</th>
<th>Primary process</th>
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<tbody>
<tr>
<td>( n )</td>
<td>0.624</td>
<td>( \beta^- )</td>
<td>0.02</td>
<td>( ^{18}\text{O}(n, p) )</td>
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<tr>
<td>( ^{17}\text{N} )</td>
<td>4.173</td>
<td>( \beta^- ), ( \beta^-n ) (66%), ( \beta^- ) (28%)</td>
<td>0.59</td>
<td>( ^{18}\text{O}(n, n + p) )</td>
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<tr>
<td>( ^{16}\text{N} )</td>
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<tr>
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<tr>
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<td>0.10</td>
<td>( (\pi^-, \alpha + p + n) )</td>
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<td>13.8</td>
<td>( \beta^- ) (55%), ( \beta^- ) (31%)</td>
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<td>( ^{11}\text{Li} )</td>
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<tr>
<td>( ^{8}\text{B} )</td>
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<td>( ^{7}\text{Li} )</td>
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<td>351</td>
<td>( \beta^- )</td>
<td>351</td>
<td>( (\gamma, n) )</td>
</tr>
<tr>
<td>( ^{15}\text{N} )</td>
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<td>( \beta^- )</td>
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<tr>
<td>( ^{14}\text{O} )</td>
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<td>( \gamma )</td>
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<td>( \gamma )</td>
<td>64</td>
<td>( (n, n + 2p) )</td>
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<td>( \gamma )</td>
<td>19</td>
<td>( (\gamma, ^3\text{H}) )</td>
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<tr>
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<td>( \gamma )</td>
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<td>( \gamma )</td>
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<td>105</td>
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<tr>
<td>( ^{11}\text{B} )</td>
<td>174</td>
<td>( \gamma )</td>
<td>174</td>
<td>( (n, \alpha + p + n) )</td>
</tr>
<tr>
<td>( ^{10}\text{C} )</td>
<td>7.6</td>
<td>( \gamma )</td>
<td>7.6</td>
<td>( (n, \alpha + 3n) )</td>
</tr>
<tr>
<td>( ^{10}\text{B} )</td>
<td>77</td>
<td>( \gamma )</td>
<td>77</td>
<td>( (n, \alpha + 2p + n) )</td>
</tr>
<tr>
<td>( ^{10}\text{Be} )</td>
<td>24</td>
<td>( \gamma )</td>
<td>24</td>
<td>( (n, \alpha + 2p + n) )</td>
</tr>
<tr>
<td>( ^{9}\text{Be} )</td>
<td>38</td>
<td>( \gamma )</td>
<td>38</td>
<td>( (n, 2\alpha) )</td>
</tr>
</tbody>
</table>

**Sum:** 3015
Background (2): Atmospheric Neutrinos

- **NCQE Interactions**
  - “γ+n” mimics “β+n”.
  - Constrained by the recent T2K results.
    
    K. Abe et al. (T2K Collaboration), PRD 100, 112009

- **Other Interactions**
  - CC-induced muons, pion production, etc
  - These form a Michel spectrum then are estimated using the sideband region (>30 MeV).

**Atmospheric Neutrino Flux (HKKM2011)**

- NCQE Interactions
  - "γ+n" mimics “β+n”.
  - Constrained by the recent T2K results.

  K. Abe et al. (T2K Collaboration), PRD 100, 112009

- Other Interactions
  - CC-induced muons, pion production, etc
  - These form a Michel spectrum then are estimated using the sideband region (>30 MeV).

**Supernova relic neutrino (IBD)**

**Atmospheric neutrino (NCQE)**

- **ν_e γ** or **H Gd γ** (2.2 MeV) (~8 MeV)

  - Thermalized

  - Constrained by the recent T2K results.

- Other interactions
  - CC-induced muons, pion production, etc
  - These form a Michel spectrum then are estimated using the sideband region (>30 MeV).
Background (2): Atmospheric Neutrinos

- **NCQE Interactions**
  - “\(\gamma + n\)” mimics “\(\beta + n\)”.  
  - Constrained by the recent T2K results.
    
    K. Abe et al. (T2K Collaboration), PRD 100, 112009

- **Other Interactions**
  - CC-induced muons, pion production, etc  
  - These form a Michel spectrum then are estimated.

Atmospheric Neutrino Flux (HKKM2011)
Background (2): Atmospheric Neutrinos

Atmospheric Neutrino Flux

\[ E^2 \Phi \left[ \text{GeV}^2 \text{cm}^{-4} \text{sec}^{-1} \text{sr}^{-1} \right] \]

\[ \sim 600 \text{ MeV} \]

T2K Run 1-9 Flux at SK (FHC)

T2K Run 1-9 Flux at SK (RHC)
Background (3): Reactor & Accidental Events

• Reactor neutrinos
  • Electron antineutrinos from reactor plants.
  • IBD reaction is an irreducible background.

• Accidental background events
  • “True”: $\beta$-like + neutron (due to muon spallation)
  • “Fake”: $\beta$-like + neutron-like (due to PMT noise, radioactive $\gamma$, etc)

![Reactor-$\nu$ Flux obtained from the IAEA database](image-url)
3σ Sensitivities

  - ~90% neutron tagging efficiency with the Gd.
  - ~8 MeV γ-rays are emitted, then the search does not suffer from accidental backgrounds.

- **Hyper-Kamiokande**  K. Abe et al. (HK Proto-Collaboration), arXiv:1109.3262
  - ~8.4 times larger fiducial mass.
  - Better photosensors and more coverage lead to doubled neutron tagging efficiency.
Let’s work forward to discovery!!
BACKUP SLIDES
Neutrinos from Core-Collapse Supernovae

(1) H

(2) H He

(3) H He C,O Si Fe O,Ne,Mg

(4) Fe core

νelectron neutrino trapping

νelectron neutrino trapping

“accretion phase”

νneutronization burst

νbounce & shock wave

νneutrino trapping

νshock stall & revival

νsuccess

νfailure

black hole

neutron star or black hole

“explosion”
Table 1.1: Best-fit values of the neutrino oscillation parameters from PDG2018 [22]. NH and IH represent the normal and inverted neutrino mass hierarchy, respectively.

<table>
<thead>
<tr>
<th>Oscillation parameter</th>
<th>Best-fit value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>$0.307 \pm 0.013$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$ (NH, Octant I)</td>
<td>$0.417^{+0.025}_{-0.028}$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$ (NH, Octant II)</td>
<td>$0.597^{+0.024}_{-0.030}$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$ (IH, Octant I)</td>
<td>$0.421^{+0.033}_{-0.025}$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$ (IH, Octant II)</td>
<td>$0.592^{+0.023}_{-0.030}$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>$(2.12 \pm 0.08) \times 10^{-2}$</td>
</tr>
<tr>
<td>$\Delta m_{12}^2$</td>
<td>$(7.53 \pm 0.18) \times 10^{-5}$ eV$^2$</td>
</tr>
<tr>
<td>$\Delta m_{32}^2$ (NH)</td>
<td>$(2.51 \pm 0.05) \times 10^{-3}$ eV$^2$</td>
</tr>
<tr>
<td>$\Delta m_{32}^2$ (IH)</td>
<td>$(-2.56 \pm 0.04) \times 10^{-3}$ eV$^2$</td>
</tr>
</tbody>
</table>
Figure 2. CSFRD as a function of redshift. Dashed, solid and dotted lines correspond to the models in HB06, DA08 and K13, respectively. Plots are calculated from the data in Tables 1 and 2 in DA08.
BH Formation Criteria


The diagram illustrates the criteria for black hole (BH) formation as a function of initial mass ($M_{\text{init}}$) and metallicity ($Z$). The plot shows different scenarios for BH formation based on the mass of the initial star ($M_{\text{init}}$) and the initial metallicity ($Z$), with $M_{\text{init}}$ ranging from 0 to $100M_{\odot}$ and $Z$ ranging from $Z=0.02$ to $Z=0.004$. The shaded areas indicate the conditions under which a BH forms.

- For $Z=0.02$ and $Z=0.004$, different masses are critical for BH formation:
  - $13M_{\odot}$: SN at $Z=0.02$, SN at $Z=0.004$,
  - $20M_{\odot}$: SN at $Z=0.02$, SN at $Z=0.004$,
  - $30M_{\odot}$: BH at $Z=0.004$,
  - $50M_{\odot}$: SN at $Z=0.02$, SN at $Z=0.004$.

The critical metallicity ($Z_{\text{crit}}$) is marked on the y-axis, and the minimum mass ($M_{\text{min}}$) required for BH formation is indicated on the x-axis.
\[ \frac{dN_{\nu_e}}{dE_\nu} = |U_{e1}|^2 \frac{dN_{\bar{\nu}_1}}{dE_\nu} + |U_{e2}|^2 \frac{dN_{\bar{\nu}_2}}{dE_\nu} + |U_{e3}|^2 \frac{dN_{\bar{\nu}_3}}{dE_\nu} \]

\[ = \cos^2 \theta_{12} \cos^2 \theta_{13} \frac{dN_{\bar{\nu}_1}}{dE_\nu} + \sin^2 \theta_{12} \cos^2 \theta_{13} \frac{dN_{\bar{\nu}_2}}{dE_\nu} + \sin^2 \theta_{13} \frac{dN_{\bar{\nu}_3}}{dE_\nu} \]

\[ \sim 0.68 \cdot \frac{dN_{\bar{\nu}_1}}{dE_\nu} + 0.30 \cdot \frac{dN_{\bar{\nu}_2}}{dE_\nu} + 0.02 \cdot \frac{dN_{\bar{\nu}_3}}{dE_\nu}, \]

\[ \frac{dN_{\bar{\nu}_e}}{dE_\nu} \sim 0.68 \cdot \frac{dN_{\nu_e}}{dE_\nu} + 0.32 \cdot \frac{dN_{\bar{\nu}_x}}{dE_\nu}. \quad \text{Normal Hierarchy} \]

\[ \frac{dN_{\bar{\nu}_e}}{dE_\nu} \sim \frac{dN_{\bar{\nu}_x}}{dE_\nu}. \quad \text{Inverted Hierarchy} \]
Figure 4. Neutrino number spectra of supernova with $30M_\odot$, $Z = 0.02$ and shock revival times of $t_{\text{revive}} = 100$ ms (dotted), 200 ms (solid), and 300 ms (dashed). The left, central, and right panels correspond to $\nu_e$, $\bar{\nu}_e$, and $\nu_x$ ($=\nu_\mu = \bar{\nu}_\mu = \nu_\tau = \bar{\nu}_\tau$), respectively.
Equation-Of-State Effect

$M_{\text{init}} = 30M_\odot$
$Z = 0.004$

Figure 6. Neutrino number spectra for black hole formation with $30M_\odot$, $Z = 0.004$ and Shen EOS (solid) and LS EOS (dotted). The left, central, and right panels correspond to $\nu_e$, $\bar{\nu}_e$, and $\nu_x$ ($=\nu_\mu = \bar{\nu}_\mu = \nu_\tau = \bar{\nu}_\tau$), respectively.
Figure 10. Total fluxes of SRNs (solid) and contributions from various redshift ranges for the reference model. The lines except for the solid line correspond, from top to bottom, to the redshift ranges $0 < z < 1$, $1 < z < 2$, $2 < z < 3$, $3 < z < 4$, and $4 < z < 5$, for $E_\gamma > 10$ MeV. The left and right panels show the cases for normal and inverted mass hierarchies, respectively.
Redshift

1 pc $\sim 3.26$ light-year
### Table 3

SRN Event Rates in Various Ranges of Positron Energy in Super-Kamiokande Over 1 yr (i.e., per 22.5 kton yr) for Models With Metallicity Evolution of DA08+M08

<table>
<thead>
<tr>
<th>Model</th>
<th>$t_{reviv}$</th>
<th>EOS for BH</th>
<th>Normal Mass Hierarchy</th>
<th>Inverted Mass Hierarchy</th>
<th>Figure 12</th>
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<tbody>
<tr>
<td></td>
<td></td>
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<td>18–26</td>
<td>10–18</td>
<td>10–26 MeV</td>
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<td><strong>HB06</strong></td>
<td>100 ms</td>
<td>Shen</td>
<td>0.286</td>
<td>0.704</td>
<td>0.990</td>
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<td>LS</td>
<td>0.227</td>
<td>0.635</td>
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<td></td>
<td>200 ms</td>
<td>Shen</td>
<td>0.361</td>
<td>0.833</td>
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<td>0.432</td>
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<td>0.642</td>
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<tr>
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<td><strong>K13</strong></td>
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<td>0.443</td>
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<td>0.266</td>
<td>0.537</td>
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</table>
NCQE Background

- At $E_\nu > \sim 200$ MeV, neutrinos are likely to knock-out a nucleon in the NC interaction.
  - = NC quasielastic nucleon knock-out ("NCQE")
- This mimics the SRN signal (IBD) and becomes a background (mainly $E_\nu = 12$–20 MeV).
  So far the background was estimated by the simulation based on theories.
- A 100% uncertainty was assigned to this channel because of little experimental data.
- Previous measurements about this channel
  - SK: large uncertainty, mixture of neutrinos and antineutrinos
  - T2K: large uncertainty, only for neutrinos

L. Wan et al. (SK Collaboration), PRD 99, 032005 (2019)
K. Abe et al. (T2K Collaboration), PRD 90, 072012 (2014)
T2K Experiment

- Bunched proton beams (8 bunch per spill) are injected on the graphite target to produce hadrons (pions and kaons).
- Hadrons are focused by magnetic fields and decay to produce neutrino beams.
- Beam polarity (neutrino or antineutrino) is changed by the magnetic field direction.
- Neutrinos are detected at 295 km away Super-Kamiokande.
Bunched proton beams (8 bunch per spill) are injected on the graphite target to produce hadrons (pions and kaons).

Hadrons are focused by magnetic fields and decay to produce neutrino beams.

Beam polarity (neutrino or antineutrino) is changed by the magnetic field direction.

Neutrinos are detected at 295 km away Super-Kamiokande.

**FHC (neutrino mode):** $14.94 \times 10^{20}$ protons-on-target (Previous: $3.01 \times 10^{20}$ POT)

**RHC (antineutrino mode):** $16.35 \times 10^{20}$ protons-on-target
\[ \langle \sigma_{\nu-\text{NCQE}} \rangle = 1.70 \pm 0.17 \text{(stat.)}^{+0.51}_{-0.38} \text{(syst.)} \times 10^{-38} \text{ cm}^2/\text{oxygen}, \]

\[ \langle \sigma_{\bar{\nu}-\text{NCQE}} \rangle = 0.98 \pm 0.16 \text{(stat.)}^{+0.26}_{-0.19} \text{(syst.)} \times 10^{-38} \text{ cm}^2/\text{oxygen}, \]
# SK Operation Periods

<table>
<thead>
<tr>
<th>Phase</th>
<th>SK-I</th>
<th>SK-II</th>
<th>SK-III</th>
<th>SK-IV</th>
<th>SK-V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live time [days]</td>
<td>1496</td>
<td>791</td>
<td>548</td>
<td>2970</td>
<td>-</td>
</tr>
<tr>
<td>Number of ID PMTs</td>
<td>11,146</td>
<td>5,182</td>
<td>11,129</td>
<td>11,129</td>
<td>11,129</td>
</tr>
<tr>
<td>ID PMT coverage</td>
<td>40%</td>
<td>19%</td>
<td>40%</td>
<td>40%</td>
<td>40%</td>
</tr>
<tr>
<td>Number of OD PMTs</td>
<td>1,885</td>
<td>1,885</td>
<td>1,885</td>
<td>1,885</td>
<td>1,885</td>
</tr>
<tr>
<td>PMT protection</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Neutron tagging</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Threshold [MeV]</td>
<td>4.5</td>
<td>6.5</td>
<td>4.0</td>
<td>3.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>
## SK Triggers

<table>
<thead>
<tr>
<th>Trigger Type</th>
<th>Threshold</th>
<th>Time Window [μs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLE</td>
<td>$34 \rightarrow 31$ (after May of 2015)</td>
<td>$[-1.5, +1.0]$</td>
</tr>
<tr>
<td>LE</td>
<td>47</td>
<td>$[-5, +35]$</td>
</tr>
<tr>
<td>HE</td>
<td>50</td>
<td>$[-5, +35]$</td>
</tr>
<tr>
<td>SHE</td>
<td>$70 \rightarrow 58$ (after September of 2011)</td>
<td>$[-5, +35]$</td>
</tr>
<tr>
<td>OD</td>
<td>22 (in OD)</td>
<td>$[-5, +35]$</td>
</tr>
<tr>
<td>AFT</td>
<td>SHE + no OD</td>
<td>$[+35, +535]$</td>
</tr>
<tr>
<td>T2K</td>
<td>Beam on</td>
<td>$[-500, +535]$</td>
</tr>
</tbody>
</table>
Event Reconstruction in SK

• SK low energy fitter is used to reconstruct events.
  • **Vertex** ← PMT hit timing information
  • **Direction** ← Cherenkov ring pattern of hit PMTs
  • **Energy** ← Number of hit PMTs
  • **Cherenkov angle** ← Pattern of hit PMTs

• Fitter performance is checked by various calibrations.
• Important variables = \{ \( E_{\text{rec}} \), \( d\text{wall} \), \( \text{effwall} \), \( ovaQ \), \( \theta_C \) \}.

\[
ovaQ = g_{\text{vtx}}^2 - g_{\text{dir}}^2
\]

\( g_{\text{vtx}} \): Quality of reconstructed vertex
\( g_{\text{dir}} \): Quality of reconstructed direction
Cross Sections Results

**Neutrino**

\[ \langle \sigma_{\nu-NCQE} \rangle = 1.70 \pm 0.17 \text{(stat.)}^{+0.51}_{-0.38} \text{(syst.)} \times 10^{-38} \text{ cm}^2/\text{oxygen}, \]

\[ \langle \sigma_{\bar{\nu}-NCQE} \rangle = 0.98 \pm 0.16 \text{(stat.)}^{+0.26}_{-0.19} \text{(syst.)} \times 10^{-38} \text{ cm}^2/\text{oxygen}, \]
• The measured cross sections are the most precise results to date.
• The antineutrino result is the first measurement of this channel.
• Currently the dominant error source is the primary-/secondary-\(\gamma\) emission model.

**Secondary-\(\gamma\) emission model**
• Neutron experiment to measure \(\gamma\)-rays from the neutron-oxygen reactions.
• The first beam test using an 80 MeV neutron beam was performed to \(\sim\)20% precision.
• Measurements with the similar sized precision over neutron energies would improve the current 13% uncertainty to <5%.

**Neutron information**
• Relation between neutrons and secondary-\(\gamma\)’s
• Event counting in the 2D \(E_{\text{rec}}-\theta_c\) phase space with the neutron tagging → direct estimation of the SRN background
• These are more plausible with higher statistics in SK-Gd and Hyper-Kamiokande.
  • >1000 events are expected in the SRN signal region with the neutron tagging.
The measured cross sections are the most precise results to date.

The antineutrino result is the first measurement of this channel.

Currently, the dominant error source is the primary-/secondary-$\gamma$ emission model.

Secondary-$\gamma$ emission model
- Neutron experiment to measure $\gamma$-rays from the neutron-oxygen reactions.
- The first beam test using an 80 MeV neutron beam was performed to ~20% precision.
- Measurements with similar precision over neutron energies would improve the current 13% uncertainty to <5%.

Neutron information
- Relation between neutrons and secondary-$\gamma$'s
- Event counting in the 2D $E_{\text{rec}}$–$\theta_C$ phase space with the neutron tagging → direct estimation of the SRN background
- These are more plausible with higher statistics in SK-Gd and Hyper-Kamiokande.
  - >1000 events are expected in the SRN signal region with the neutron tagging.
Search Overview

- **Data set**
  - Run 61525 – 77958 (2790.1 live days)
  - SHE+AFT events for relic candidates: >8(10) MeV before(after) Run 68670
  - HE+OD muons for spallation cut tuning

- **Software**
  - nuebar MC: new package made by Sonia (to be released)
  - atmospheric-ν MC: ATMPD production apr16 (no reduction)
  - reconstruction: lowfit_sk4 (w/o PMT gain correction), mufit_sk4
  - neutron tagging: new BDT package

<table>
<thead>
<tr>
<th>Start Date</th>
<th>End Date</th>
<th>Live time</th>
<th>SHE threshold</th>
<th>AFT window length</th>
</tr>
</thead>
<tbody>
<tr>
<td>6th, Oct., 2008</td>
<td>22nd, Nov., 2008</td>
<td>25.0 days</td>
<td>70 hits</td>
<td>350 µs</td>
</tr>
<tr>
<td>22nd, Nov., 2008</td>
<td>9th, Sep., 2011</td>
<td>869.8 days</td>
<td>70 hits</td>
<td>500 µs</td>
</tr>
<tr>
<td>9th, Sep., 2011</td>
<td>31st, May., 2018</td>
<td>2075.3 days</td>
<td>58 hits</td>
<td>500 µs</td>
</tr>
</tbody>
</table>
Atmospheric Neutrino Flux (HKKM2011)

\[ \nu(E) \propto 10^{10 \log_{10}(E - 0.002)} \text{ GeV/cm}^2\text{sec./sr} \]

\( E^2 \phi_{\nu} [\text{GeV/cm}^2\text{sec./sr}] \)

- \( \nu_\mu \)
- \( \bar{\nu}_\mu \)
- \( \nu_e \)
- \( \bar{\nu}_e \)

\[ \log_{10}(E_{\nu} \text{ [GeV]}) \]

\[ \log_{10}(E_{\nu} \text{ [GeV]}) \]
Lithium-9

\[ ^9\text{Li} \rightarrow ^8\text{Be} + \text{n} \]

\[ \beta^- \]

\[ ^9\text{Li} \]

\[ ^{13.6065} 3/2^+; 3/2 \]

\[ 0.03 \]

\[ 0.01 \]

\[ 11.81 5/2^- \]

\[ 11.283 (7/2^-) \]

\[ 7.94 (5/2^-) \]

\[ 0.16 \]

\[ 2.78 \]

\[ 2.4294 1/2^- \]

\[ ^{16.654} 0^+; 0 \]

\[ ^{3/2^+; 1/2} \]

\[ ^8\text{Be} + \text{n} \]

\[ ^{11.11} \text{MeV} \]

\[ ^{0.76} \text{MeV} \]

\[ ^{8.25} \text{MeV} \]

\[ ^{8.78} \text{MeV} \]

\[ ^9\text{Li} \beta \text{ spectrum (with n emission)} \]

\[ \text{Normalized Events} \]

\[ \beta \text{ Energy [MeV]} \]

\[ \text{Events} \]

\[ K_n = 1.11 \text{ MeV} \]

\[ K_n = 0.76 \text{ MeV} \]

\[ K_n = 8.25 \text{ MeV} \]

\[ K_n = 8.78 \text{ MeV} \]
Reactor Neutrino Flux

Reactor Flux \([/0.01\text{-MeV/SK-IV-Period}]\)

Neutrino Energy [MeV]
SK-Gd

0.1% Gd: ~90% capture efficiency =Gd₂(SO₄)₃ 100t

0.01% Gd: ~50% capture efficiency =Gd₂(SO₄)₃ 10t

Capture efficiency on Gd [%]

Gd rate in water [%]
Hyper-Kamiokande