Search for neutrinos in Super-Kamiokande associated with gravitational wave events

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@Kolymbari, Crete Greece

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(Kamioka Observatory, ICRR, The University of Tokyo)
Contents

■ Brief Introduction
  - Gravitational wave events
  - Motivation of this study

■ Super-Kamiokande
  - Detector and brief history
  - Its performance

■ Analysis strategies and Results

■ Future prospect and summary
Observation of gravitational wave events

Masses in the Stellar Graveyard

*in Solar Masses*

BH-BH

NS-NS

https://twitter.com/LIGO/status/930993834195955712
Motivation of this study

■ Era of multi-messenger
- LIGO-Vergo detected the gravitational wave events in 2015. → GW150914, GW151226....
- Many efforts of astronomical counterparts.

■ Experimental search for neutrinos
- No significant neutrino signal has been observed yet.
- Test astrophysical mechanisms of neutrino emission.
- **New physics** if the coincidence of neutrino signal is observed.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>keV</th>
<th>MeV</th>
<th>GeV</th>
<th>TeV</th>
<th>PeV</th>
<th>EeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borexino</td>
<td></td>
<td></td>
<td>250 keV~15 MeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KamLAND</td>
<td></td>
<td></td>
<td>1.8 MeV~111 MeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Super-Kamiokande</td>
<td></td>
<td></td>
<td>3.5 MeV~100 PeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANTARES</td>
<td></td>
<td></td>
<td>100 GeV~100 PeV</td>
<td></td>
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<tr>
<td>IceCube</td>
<td></td>
<td></td>
<td>100 GeV~100 PeV</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Pierre Auger</td>
<td></td>
<td></td>
<td>100 PeV~25 PeV</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
Super-Kamiokande
Super-Kamiokande (SK)

- **Detector**
  - Located at Kamioka Japan.
  - 50 kton of ultra pure water tank.
  - 20-inch PMTs, 11,129 for ID.
  - 22.5 kton for analysis fiducial volume.
  - Water Cherenkov light technique.
  - Long term operation since 1996 (~22 yrs).

- **Physics target**
  - Atmospheric neutrino
  - Astrophysical neutrino (solar, supernova)
  - Proton decay
  - Long base line neutrino (T2K)
  - Dark matter search etc...

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Solar $\nu$
3.5-20 MeV

Supernova $\nu$
20-100 MeV

Atmospheric $\nu$ and proton decay
~100 MeV, GeV, TeV, PeV
History of Super-Kamiokande

Brief history and current status
- SK-I started on 1996 April and SK-IV ended on 2018 May.
- Total live time is more than 5,500 days.
- Refurbishment works toward SK-Gd have started since May 31st.

<table>
<thead>
<tr>
<th>Year</th>
<th>PMT</th>
<th>PMT coverage (%)</th>
<th>Recoil electron kinetic energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>96</td>
<td>11,146 (40%*)</td>
<td>SK-I</td>
<td>4.5 MeV**</td>
</tr>
<tr>
<td>97</td>
<td>5,182 (19%*)</td>
<td>SK-II</td>
<td>6.5 MeV**</td>
</tr>
<tr>
<td>98</td>
<td>11,129 (40%*)</td>
<td>SK-III</td>
<td>4.0 MeV**</td>
</tr>
<tr>
<td>99</td>
<td>11,129 (40%*)</td>
<td>SK-IV</td>
<td>3.5 MeV**</td>
</tr>
<tr>
<td>00</td>
<td>11,129 (40%*)</td>
<td>SK-Gd</td>
<td></td>
</tr>
<tr>
<td>01</td>
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<tr>
<td>02</td>
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<td>16</td>
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<td>18</td>
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<tr>
<td>19</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

* Photo coverage [%], ** Recoil electron kinetic energy [MeV].

- SK-Gd

[Images of Super-Kamiokande detectors SK-I to SK-Gd]

[Diagram of neutrino decay process with symbols: \(\bar{\nu}_e\), p, n, Gd, e^+, γ, Delayed coincidence (2.2MeV) ~8MeV]
Inside of the detector
Neutrino analysis in SK

- Analysis targets in SK
  - SK has sensitivity to a **wide** neutrino energy range:
    → From multi-MeV region to 100 PeV.
  - Interactions occurring in SK depends on its energy.

- **Sample name** | **Energy range** | **Specific category**
---|---|---
Low energy | 3.5-15.5 MeV | Solar neutrino
| 15.5-100 MeV | Relic neutrino
High energy | 100 MeV – 100 PeV | Fully Contained (FC)
| | | Partially Contained (PC)
| | | Up-going muon (UPMU)

- 3 analysis samples are available according to its energy.
  → Difference of topology of event in SK.
Typical event in SK

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

Angular resolution \( \sim 23^\circ @ 10 \, \text{MeV} \)

\( \sim 15^\circ @ 1 \, \text{GeV} \)

Solar \( v \)
\( 3.5-15.5 \, \text{MeV} \)

Supernova relic \( v \)
\( 15.5-100 \, \text{MeV} \)

Atmospheric \( v \) and so on
\( 100 \, \text{MeV} \) \quad GeV \quad TeV \quad PeV

FC
PC
UPMU
BH-BH merger
(GW150914 & GW151226)
Search for $\nu$ from BH-BH merger

- **Observation of BH-BH merger**
  - No counterpart except for Fermi-LAT.

<table>
<thead>
<tr>
<th>GW event</th>
<th>Time [UTC]</th>
<th>Astronomical counterpart</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW150914</td>
<td>9:50:45</td>
<td>Fermi-LAT ~0.4 second later</td>
</tr>
<tr>
<td>GW151226</td>
<td>3:38:53</td>
<td>---</td>
</tr>
</tbody>
</table>

- **Theoretical models**
  - No theory of neutrino generation associated with BH-BH merger.
  - Possibility of high energy $\nu$ emission from relativistic jet when accretion disk is formed around source.

- **Data acquisition status in SK**
  - Physics data-taking was operated at the time when both mergers.
  - Searching for neutrino-like event within $\pm 500$ seconds.

Neutrino signal in SK (BH-BH)

GW150914
- 4 events remain below 15.5 MeV (in solar sample).
  No.1 & 2: Spallation event (Next page)
  No.3: Radon daughter event
  No.4: Solar neutrino event
- 4 or more events passing the reduction cuts → 33.0%.

GW151226
- No event is found around GW151226 in SK.
- 0 events passing the reduction cuts → 5.5%.
Event No.1 & 2 (spallation BG)

Time difference between the event and preceding muon
No.1 $\rightarrow$ 10.77 sec, No.2 $\rightarrow$ 17.38 sec. ($^{16}$N BG since it has long decay constant)
Fluence limits for BH-BH (MeV region)

Assumption of energy spectrum
- No reason for power spectrum
  \( \rightarrow \) **index 0 (flat)** is used.

Fluence calculation
- Energy range: Solar + Relic sample.
  \( \rightarrow 3.5 \text{ MeV} - 100 \text{ MeV} \).
- Considering:
  1. Target \((N_T)\)
  2. Cross section \((\sigma)\)
  3. Detector response \((R)\)
  4. Reduction efficiency \((\varepsilon)\)

\[
\Phi_{\text{lowe}} = \frac{N_{90}}{N_T \int dE_{\nu} \lambda(E_{\nu}) \sigma(E_{\nu}) R(E_e, E_{\text{vis}}) \varepsilon(E_{\text{vis}})}
\]

- Best limit above \( \sim 5 \text{ MeV} \).
Fluence limits for BH-BH (Above 100 MeV)

- Fluence limit for high energy sample
  - Assumption of energy spectrum: power spectrum with index -2.
  - FC+PC sample: basically same as low energy sample
  - UPMU sample: Zenith angle dependence $A_{\text{eff}}(z)$

Shadow effect of the earth $S(z,E)$

<table>
<thead>
<tr>
<th>Sample</th>
<th>Energy range</th>
<th>Fluence calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC+PC</td>
<td>100 MeV- 10 GeV</td>
<td>$\Phi_{\text{FC+PC}} = \frac{N_{90}}{N_T \int dE_\nu \sigma(E_\nu) \epsilon(E_\nu) \lambda(E_\nu^{-2})}$</td>
</tr>
<tr>
<td>UPMU</td>
<td>1.6 GeV-100 PeV</td>
<td>$\Phi_{\text{UPMU}} = \frac{N_{90}}{A_{\text{eff}}(z) \int dE_\nu P(E_\nu) S(z, E_\nu) \lambda(E_\nu^{-2})}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>GW150914 $\Phi_\nu$ (cm$^{-2}$)</th>
<th>GW151226 $\Phi_\nu$ (cm$^{-2}$)</th>
<th>Combined $\Phi_\nu$ (cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>From FC+PC only</td>
<td>$\nu_\mu$ $5.6 \times 10^4$</td>
<td>$5.6 \times 10^4$</td>
<td>$2.8 \times 10^4$</td>
</tr>
<tr>
<td></td>
<td>$\bar{\nu}_\mu$ $1.3 \times 10^5$</td>
<td>$1.3 \times 10^5$</td>
<td>$6.5 \times 10^4$</td>
</tr>
<tr>
<td></td>
<td>$\nu_\tau$ $4.8 \times 10^4$</td>
<td>$4.8 \times 10^4$</td>
<td>$2.4 \times 10^4$</td>
</tr>
<tr>
<td></td>
<td>$\bar{\nu}_\tau$ $1.2 \times 10^5$</td>
<td>$1.2 \times 10^5$</td>
<td>$6.0 \times 10^4$</td>
</tr>
<tr>
<td>From UPMU only</td>
<td>$\nu_\mu$ 14–37</td>
<td>14–37</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>$\bar{\nu}_\mu$ 19–50</td>
<td>19–50</td>
<td>...</td>
</tr>
</tbody>
</table>
Fluence limits for BH-BH (Above 100 MeV)

- Fluence limit for high energy sample

- Assumption of energy spectrum: power spectrum with index $-2$

- FC+PC sample: basically same as low energy sample
- UPMU sample: Zenith angle dependence

Neutrino

Anti-neutrino

GW150914

GW151226

UPMU sample

Strong constraint
Weak constraint

Fluence Limit [cm$^{-2}$]
NS-NS merger
Search for $\nu$ from NS-NS merger

GW170817 (GRB170817A)
- Binary neutron star merger
- Radiation energy $\rightarrow 4.5 \times 10^{52}$ erg.
- Multi-messenger detection $\rightarrow$ Short gamma-ray burst kilonova/micronova


Search for ν from NS-NS merger

- Models of neutrino emission
  - Many models of neutrino emission are proposed.
    → High energy ν (10^{14} eV) in relativistic ejecta.
    → Similar mechanism as for core-collapse SN (simulation base).

- Data acquisition status in SK
  - Searching for neutrino-like event within ±500 seconds.
    → Fortunately, data-taking was operated at the time of merger.
    → However, we had taken LINAC calibrations from Aug 3rd to 22nd.
  - 14-day time window relevant for longer-lived emission process.

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- Models of neutrino emission

  Many models of neutrino emission are proposed.

  - High energy ν (10^{14} eV) in relativistic ejecta.
  - Similar mechanism as for core-collapse SN (simulation base).

- Data acquisition status in SK

  - Searching for neutrino-like event within ±500 seconds.
    - Fortunately, data-taking was operated at the time of merger.
    - However, we had taken LINAC calibrations from Aug 3rd to 22nd.
  - 14-day time window relevant for longer-lived emission process.
Neutrino signal (NS-NS) in ±500s

GW170817 (±500 seconds)
- No event is found in all samples in ±500 seconds.
  → 7 events are found on the surface of the LINAC beam pipe. Just after extending the beam pipe (No beam).
  → They are removed by the calibration source cut (2m).

Below 5 MeV
Radioactive impurities
β decay of $^{214}\text{Bi}$ (3.27 MeV)

Observed event within ±500 seconds window
Fluence limits in ±500s

Fluence of GW170817 (±500 seconds)
- Same method used in BH-BH merger.
- Expected neutrino energy spectrum is simulated in case of BNS merger.
→ Newly analyze Fermi-Dirac spectrum in low energy sample.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Energy range</th>
<th>Energy spectrum</th>
<th>Fluence calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOWE</td>
<td>3.5 MeV 100 MeV</td>
<td>Flat (index 0)</td>
<td>$\Phi_{\text{lowe}} = \frac{N_{90}}{N_T \int dE_{\nu} \lambda(E_{\nu}) \sigma(E_{\nu}) \epsilon(E_{\nu}) R(E_{\nu}, E_{\text{vis}}) \epsilon(E_{\text{vis}})}$</td>
</tr>
<tr>
<td>FC+PC</td>
<td>100 MeV 10 GeV</td>
<td>Index -2</td>
<td>$\Phi_{\text{FC,PC}} = \frac{N_{90}}{N_T \int dE_{\nu} \sigma(E_{\nu}) \epsilon(E_{\nu}) \lambda(E^{-2}_{\nu})}$</td>
</tr>
<tr>
<td>UPMU</td>
<td>1.6 GeV 100 PeV</td>
<td>Index -2</td>
<td>$\Phi_{\text{UPMU}} = \frac{N_{90}}{A_{\text{eff}}(z) \int dE_{\nu} P(E_{\nu}) S(z, E_{\nu}) \lambda(E_{\nu}^{-2})}$</td>
</tr>
</tbody>
</table>
Fluence limits in ±500s

<table>
<thead>
<tr>
<th>GW170817 $\Phi_\nu$ (cm$^{-2}$)</th>
<th>From FC+PC only</th>
<th>From UPMU only</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$</td>
<td>$5.6 \times 10^4$</td>
<td>$16.0^{+0.7}_{-0.6}$</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>$1.3 \times 10^5$</td>
<td>$21.3^{+1.1}_{-0.8}$</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>$4.8 \times 10^4$</td>
<td>...</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>$1.2 \times 10^5$</td>
<td>...</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>From low-energy only</th>
<th>Fermi–Dirac with $E_{\text{ave}} = 20$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_e$</td>
<td>$1.2 \times 10^7$</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>$1.0 \times 10^9$</td>
</tr>
<tr>
<td>$\bar{\nu}_x$</td>
<td>$7.5 \times 10^9$</td>
</tr>
<tr>
<td>$\nu_x$</td>
<td>$6.3 \times 10^9$</td>
</tr>
</tbody>
</table>

Fluence limit (below 100 MeV)
(Monochromatic neutrino energy)

Strong constraint
Weak constraint

UPMU sample

GW170817
Observed events in following 14 days

- Due to the calibration, solar sample has large background.
  → Many radioactive impurities in SK pure water.
- Other samples are checked.
  → No significant neutrino signal over the background is observed.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Livetime</th>
<th>Observed [event/livetime]</th>
<th>Expected [event/livetime]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>After LINAC calibration</td>
<td>Many radioactive impurities</td>
<td>--</td>
</tr>
<tr>
<td>Relic</td>
<td>9.15</td>
<td>2±1.41</td>
<td>(1.93±0.08)×10^{-3}</td>
</tr>
<tr>
<td>FC</td>
<td>11.30</td>
<td>76±8.72</td>
<td>91.44±0.57</td>
</tr>
<tr>
<td>PC</td>
<td>11.30</td>
<td>8±2.83</td>
<td>7.35±0.23</td>
</tr>
<tr>
<td>UPMU</td>
<td>11.30</td>
<td>13±3.61</td>
<td>16.05±0.23</td>
</tr>
<tr>
<td>UPMU (&lt;5°)*</td>
<td>11.30</td>
<td>0</td>
<td>(6.11±0.04)×10^{-2}</td>
</tr>
</tbody>
</table>

(*)The UPMU events are higher in energy than the other topologies and therefore the detected lepton points back to the incoming neutrino with more accuracy, allowing for a smaller search cone. See detail: Astrophys. J. Lett. 850 (2017) 116.
Following 14 days for all sky

Relic sample (2)

PC sample (8)

FC sample (76)

UPMU sample (13, 0(<5°))

No significant neutrino signal over background
Future prospects and summary
Future prospects

**SK-Gd project**
- Current SK observation is not enough to distinguish $\nu_e/\bar{\nu}_e$.
- Adding Gd enhances the detection efficiency of $\bar{\nu}_e + p \rightarrow e^+ + n$.
  → Delayed coincidence technique by neutron tagging.
- More precise measurement of neutrino flux is expected.

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

Time difference: ~30 μsec, Vertex : ~50 cm.
Summary

■ Era of Multi-messenger
- The observation of the gravitational wave events opens new window for understanding our universe.
- Multi-messenger astrophysics has been started.

■ Super-Kamiokande
- Multi-purpose detector.
- Chance to search for neutrino from Multi-MeV to PeV region.

■ GW150814 & GW151226
- 4 events remain within ±500 seconds (consistent with BG).
- Set the 90% neutrino fluence limits for both merge events.

■ GW170817
- No events remain within ±500 seconds.
- No significant signal over BG is observed in following 14 days.
- Set the 90% neutrino fluence limits for GW170817.
Back up slides
Topologies of atmospheric $\nu$ events

- **Fully contained (FC)**
- **Partially contained (PC)**
- **Up-going $\mu$ (UPMU)**

**Event/0.1Log$_{10}$($E_\nu$)/500years (MC)**

- **FC (e-like)**
- **FC ($\mu$-like)**
- **PC**
- **UPMU**

Neutrino Energy [GeV]

- 1 GeV
- 1 TeV

- Stop
- Through
### Spallation products in SK

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$\tau_{1/2}$ [sec]</th>
<th>decay mode</th>
<th>Kinetic Energy [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^8_2$He</td>
<td>0.119</td>
<td>$\beta^-$</td>
<td>9.67 + 0.98($\gamma$) 16%</td>
</tr>
<tr>
<td>$^8_3$Li</td>
<td>0.838</td>
<td>$\beta^-$</td>
<td>$\sim$ 13</td>
</tr>
<tr>
<td>$^8_3$B</td>
<td>0.77</td>
<td>$\beta^+$</td>
<td>13.9</td>
</tr>
<tr>
<td>$^9_3$Li</td>
<td>0.178</td>
<td>$\beta^-$</td>
<td>13.6(50.5%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\beta^-n$</td>
<td>($\sim$ 50%)</td>
</tr>
<tr>
<td>$^9_6$C</td>
<td>0.127</td>
<td>$\beta^+n$</td>
<td>3 $\sim$ 15</td>
</tr>
<tr>
<td>$^{11}_3$Li</td>
<td>0.0085</td>
<td>$\beta^-$</td>
<td>16 $\sim$ 20(50%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\beta^-n$</td>
<td>$\sim$ 16(50%)</td>
</tr>
<tr>
<td>$^{11}_4$Be</td>
<td>13.8</td>
<td>$\beta^-$</td>
<td>11.51(54.7%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>9.41 + 2.1($\gamma$) (31.4%)</td>
</tr>
<tr>
<td>$^{11}_4$Be</td>
<td>13.8</td>
<td>$\beta^-$</td>
<td>11.71</td>
</tr>
<tr>
<td>$^{12}_5$B</td>
<td>0.0236</td>
<td>$\beta^-$</td>
<td>13.37</td>
</tr>
<tr>
<td>$^{12}_7$N</td>
<td>0.0110</td>
<td>$\beta^+$</td>
<td>16.32</td>
</tr>
<tr>
<td>$^{13}_5$B</td>
<td>0.0174</td>
<td>$\beta^-$</td>
<td>13.44</td>
</tr>
<tr>
<td>$^{13}_8$O</td>
<td>0.086</td>
<td>$\beta^+$</td>
<td>13.2 or 16.7</td>
</tr>
<tr>
<td>$^{14}_5$B</td>
<td>0.0138</td>
<td>$\beta^-$</td>
<td>14.55 + 6.09($\gamma$)</td>
</tr>
<tr>
<td>$^{15}_6$C</td>
<td>2.449</td>
<td>$\beta^-$</td>
<td>9.77(36.8%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.47 + 5.30($\gamma$)</td>
</tr>
<tr>
<td>$^{16}_6$C</td>
<td>0.747</td>
<td>$\beta^-n$</td>
<td>$\sim$ 4</td>
</tr>
<tr>
<td>$^{16}_7$N</td>
<td>7.13</td>
<td>$\beta^-$</td>
<td>10.42(28.0%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.29 + 6.13($\gamma$)(66.2%)</td>
</tr>
</tbody>
</table>
LINAC calibration