Solar Neutrinos in Super-Kamiokande

ICHEP2014 @Valencia
4 July 2014

Hiroyuki Sekiya
ICRR, University of Tokyo
for the Super-K Collaboration
Super-Kamiokande

- 50kton pure water Cherenkov detector
- 1km (2.7km w.e) underground in Kamioka
- 11129 50cm PMTs in Inner Detector
- 1885 20cm PMTs in Outer Detector

Physics targets of Super-Kamiokande

Solar $\nu$, Relic SN $\nu$, Proton decay, WIMPs, Atmospheric $\nu$

- $\sim$3.5 MeV
- $\sim$20
- $\sim$100
- $\sim$1 GeV
- TeV
Solar neutrinos observation
The results: Solar global fit

- This SK update and other latest results are combined.

Combined solar fit with KamLAND

\[ \sin^2 \theta_{13} = 0.0242 \pm 0.0026 \]

Without reactor \( \theta_{13} \) constraint

\[ \sin^2 \theta_{13} = 0.0221 \pm 0.0012 \]

\(~2\sigma\) tension in \( \Delta m^2_{21} \)
between solar and KamLAND

Non-zero \( \theta_{13} \) at 2\( \sigma \) from solar+KamLAND

Good agreement with \( \sin^2 \theta_{13} = 0.0221 \pm 0.0012 \)
Daya Bay, RENO & DC

(Neutrino2014)
**Motivation**

- Search for the direct signals of the MSW effect

**Solar matter effect**

**Energy spectrum distortion**

**Earth matter effect**

**Flux day-night asymmetry**

**Neutrino survival probability**

*JHEP 0311:004(2003)*

![Graph showing neutrino survival probability and mass squared differences](image)

- Vacuum oscillation dominant
- Solar + KamLAND
  \[
  \sin^2 \theta_{12} = 0.308, \quad \Delta m_{21}^2 = 7.50 \times 10^{-5} \text{eV}^2
  \]
- Solar
  \[
  \sin^2 \theta_{12} = 0.311, \quad \Delta m_{21}^2 = 4.85 \times 10^{-5} \text{eV}^2
  \]
- Matter oscillation dominant
- Regenerate $\nu_e$ by earth matter effect
Improvements in SK-IV

- Reduced $^{222}\text{Rn}$ BG
- New analysis in low energy bins
  Remaining BG-electrons from $^{214}\text{Bi}$ should have more multiple-scatterings than signal-electrons have: $\text{MSG}$

- Reduced systematic error
  1.7% for flux  cf. SK-I: 3.2%  SK-III: 2.1%

Achieved 3.5 MeV(kin.) energy threshold
8.6$\sigma$ signal is observed with MSG
$^8$B solar $\nu$ in SK-I+II+III+IV

- $^8$B $\nu$ signals

$\Phi_{SK}(^8B) = 2.344 \pm 0.034 \times 10^6$ cm$^{-1}$s$^{-1}$

$\Phi_{SK+SNO}(^8B) = 5.30 \pm 0.17 - 0.11 \times 10^6$ cm$^{-1}$s$^{-1}$

$^8$B $\nu$ could be the BG for DM search through NC coherent scattering.
Recoil electron spectra

SK-I Energy Spectrum

SK-II Energy Spectrum

SK-III Energy Spectrum

SK-IV Energy Spectrum

Data/MC (unoscillated)

Blue: Total uncertainty

Kinetic energy (MeV)

preliminary
N.B. All SK phase are combined without regard to energy resolution or systematics in this figure.

**SK-I+II+III+IV spectrum**

<table>
<thead>
<tr>
<th>(total # of bins of SKI - IV is 83)</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar+KamLAND</td>
<td>70.13</td>
</tr>
<tr>
<td>Solar</td>
<td>68.14</td>
</tr>
<tr>
<td>quadratic fit</td>
<td>67.67</td>
</tr>
<tr>
<td>exponential fit</td>
<td>66.54</td>
</tr>
</tbody>
</table>

Neutrino energy spectrum is convoluted in the electron recoil spectrum. For de-convolution, generic functions are used as a survival probability:

$$P_{ee}(E_\nu) = c_0 + c_1 \left( \frac{E_\nu}{\text{MeV}} - 10 \right) + c_2 \left( \frac{E_\nu}{\text{MeV}} - 10 \right)^2$$

$$P_{ee}(E_\nu) = e_0 + \frac{e_1}{e_2} \left( \exp \left( e_2 \left( \frac{E_\nu}{\text{MeV}} - 10 \right) \right) - 1 \right)$$

SK recoil electron spectrum constrain the fit parameters $(c_i, e_i)$ of the function and the allowed $P_{ee}(E\nu)$ is derived using the allowed $(c_i, e_i)$. 

$\phi^B_B = 5.25 \times 10^6/(\text{cm}^2\cdot\text{sec})$

$\phi_{\text{lep}} = 7.88 \times 10^3/(\text{cm}^2\cdot\text{sec})$
Allowed $P_{ee}(E_{\nu})$ for SK

$$P_{ee}(E_{\nu}) = c_0 + c_1 \left( \frac{E_{\nu}}{MeV} - 10 \right) + c_2 \left( \frac{E_{\nu}}{MeV} - 10 \right)^2$$

- MSW (solar+KamLAND) is consistent at ~1.6σ
- MSW (solar) fits better (at ~0.7σ)

$\sin^2 \theta_{12} = 0.308 \quad \Delta m^2_{21} = 7.50 \times 10^{-5} eV^2$

$\sin^2 \theta_{12} = 0.311 \quad \Delta m^2_{21} = 4.85 \times 10^{-5} eV^2$

$\sqrt{\text{MSW (solar+KamLAND) is consistent at } \sim 1.6\sigma}$
$\sqrt{\text{MSW (solar) fits better (at } \sim 0.7\sigma}$
Allowed $P_{ee}(E_\nu)$ for SK+SNO

\[ P_{ee}(E_\nu) = c_0 + c_1 \left( \frac{E_\nu}{MeV} - 10 \right) + c_2 \left( \frac{E_\nu}{MeV} - 10 \right)^2 \]

- $\text{Solar+KamLAND}$
  - $\sin^2 \theta_{12} = 0.308$
  - $\Delta m^2_{21} = 7.50 \times 10^{-5} eV^2$

- $\text{Solar}$
  - $\sin^2 \theta_{12} = 0.311$
  - $\Delta m^2_{21} = 4.85 \times 10^{-5} eV^2$

✓ SK and SNO are complementary for the shape constraint
✓ MSW is consistent at 1σ
Global view of $P_{ee}(E_{\nu})$

- Preliminary
- All solar (pp)
- Borexino (pep)
- Borexino ($^7$Be)
- Homestake + SK+SNO (CNO)
- SK+SNO

$P_{ee}(E_{\nu})$ vs. $\nu$ Energy in MeV
Flux zenith angle distribution

SK-I - IV combined (Eth=4.5 MeV for SK-I,III,IV  6.5 MeV for SK-II)

- Solar best fit
  - $\sin^2 \theta_{12} = 0.308$
  - $\Delta m^2_{21} = 7.50 \times 10^{-5} eV^2$

- Solar+KamLAND
  - $\sin^2 \theta_{12} = 0.308$
  - $\Delta m^2_{21} = 4.85 \times 10^{-5} eV^2$

preliminary
Day/Night asymmetry amplitude

- **Energy-dependence of the variation**

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Rate/Rate average</th>
<th>Cosine of the Day/Night Asymmetry</th>
<th>Fitted asymmetry amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>16-20 MeV</td>
<td>1.02</td>
<td>0.98</td>
<td>$\Delta m^2_{21}=4.84 \times 10^{-5} \text{eV}^2$</td>
</tr>
<tr>
<td>12.5-13 MeV</td>
<td>1.02</td>
<td>0.98</td>
<td>$\Delta m^2_{21}=7.50 \times 10^{-5} \text{eV}^2$</td>
</tr>
<tr>
<td>10-10.5 MeV</td>
<td>1.02</td>
<td>0.98</td>
<td>$\Delta m^2_{21}=4.84 \times 10^{-5} \text{eV}^2$</td>
</tr>
<tr>
<td>7.5-8 MeV</td>
<td>1.02</td>
<td>0.98</td>
<td>$\Delta m^2_{21}=7.50 \times 10^{-5} \text{eV}^2$</td>
</tr>
<tr>
<td>5-5.5 MeV</td>
<td>1.02</td>
<td>0.98</td>
<td>$\Delta m^2_{21}=4.84 \times 10^{-5} \text{eV}^2$</td>
</tr>
</tbody>
</table>

**Table:**

<table>
<thead>
<tr>
<th>Detector</th>
<th>Asymmetry Amplitude</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK-I</td>
<td>$-2.0 \pm 1.8 \pm 1.0%$</td>
<td>$-1.9 \pm 1.7 \pm 1.0%$</td>
</tr>
<tr>
<td>SK-II</td>
<td>$-4.4 \pm 3.8 \pm 1.0%$</td>
<td>$-4.4 \pm 3.6 \pm 1.0%$</td>
</tr>
<tr>
<td>SK-III</td>
<td>$-4.2 \pm 2.7 \pm 0.7%$</td>
<td>$-3.8 \pm 2.6 \pm 0.7%$</td>
</tr>
<tr>
<td>SK-IV</td>
<td>$-3.6 \pm 1.6 \pm 0.6%$</td>
<td>$-3.3 \pm 1.5 \pm 0.6%$</td>
</tr>
<tr>
<td>Combined</td>
<td>$-3.3 \pm 1.0 \pm 0.5%$</td>
<td>$-3.1 \pm 1.0 \pm 0.5%$</td>
</tr>
<tr>
<td>Non-zero</td>
<td>$3.0\sigma$</td>
<td>$2.8\sigma$</td>
</tr>
</tbody>
</table>

**First observation of day/night asymmetry at 3\(\sigma\) significance level**
$\Delta m^2_{21}$ dependence

$\sin^2 \theta_{12} = 0.311, \sin^2 \theta_{13} = 0.025$

1σ KamLAND 1σ Solar

SK-I,II,III,IV best fit

Solar region differ from zero by 2.9~3.0σ agree with expect by 1.0σ

KamLAND region differ from zero by more than 2.8σ agree with expect by 1.3σ
Summary

- SK has observed \( \sim 70000 \) solar \( \nu \) interactions, by far the largest sample of solar neutrino events in the world.
- SK data provide the first indication (at 2.8\( \sim \)3.0 \( \sigma \)) of terrestrial matter effects on \(^8\text{B}\) solar \( \nu \) oscillation.
- SK gives the world’s strongest constraints on the shape of the survival probability \( P_{ee}(E\nu) \) in the transition region between vacuum oscillations and MSW resonance.
  - SK spectrum results are consistent with MSW up-turn prediction within \( \sim 1\sigma \).
- SK measurements strongly constrain neutrino oscillation parameters:
  - SK gives world’s best constraint on \( \Delta m_{21}^2 \) using neutrinos.
  - There is a \( 2\sigma \) tension between SK’s neutrino and KamLAND’s anti-neutrino measurement of \( \Delta m_{21}^2 \).
- Last month SK started taking data at \( \sim 2.5 \) MeV at \( \sim 100\% \) trigger efficiency. Stay tuned for very low energy SK neutrino.
Extra slides
Full summary

- SK has observed ~70000 solar neutrino interactions in ~4500 days (1.5 solar cycles), by far the largest sample of solar neutrino events in the world.
- SK data provide the first indication (at 2.8~3.0 sigma) of terrestrial matter effects on 8B solar neutrino oscillation. This is the first observation using a single detector and identical neutrino beams that matter affects neutrino oscillations.
- SK has successfully lowered the analysis threshold to ~3.5 MeV kinetic recoil electron energy.
- SK gives the world’s strongest constraints on the shape of the survival probability $P_{ee}(E_{\nu})$ in the transition region between vacuum oscillations and MSW resonance.
- SK spectrum results slightly disfavor the MSW resonance curves, but are consistent with MSW prediction within 1-1.7 sigma.
- SK measurements strongly constrain neutrino oscillation parameters:
  - SK uniquely selects the Large Mixing Angle MSW region by >3sigma,
  - gives world’s best constraint on solar $\Delta m^2$ using neutrinos,
  - and significantly contributes to the measurement of the solar angle.
- There is a 2 sigma tension between SK’s neutrino and KamLAND’s anti-neutrino measurement of the solar $\Delta m^2$.
- Last month SK started taking data at ~2.5 MeV at ~100% trigger efficiency. Stay tuned for very low energy SK solar neutrino
Wide-band Intelligent Trigger

- Reconstruction and Reduction just after Front-end

```
100% trigger efficiency above 2.5MeV(kin.)
```

```
Just started
```
Oscillation parameter
SK and SNO

\[
\Delta m^2 \text{ in eV}^2 \\
\sin^2(\theta_{12}) = 0.317^{+0.017}_{-0.027} \\
m^{2}_{21} = (5.4^{+2.2}_{-1.1}) \times 10^{-5} \text{eV}^2
\]

\[
\sin^2(\theta_{12}) = 0.339^{+0.027}_{-0.024} \\
m^{2}_{21} = (4.74^{+1.6}_{-0.79}) \times 10^{-5} \text{eV}^2
\]

\[
\sin^2(\theta_{12}) = 0.313 \pm 0.014 \\
m^{2}_{21} = (4.86^{+1.4}_{-0.62}) \times 10^{-5} \text{eV}^2
\]
Probing the Unknown

Non-standard physics effects can alter the shape / position of the “MSW rise”

Non-standard interactions
(flavour changing NC)

Friedland, Lunardini, Peña-Garay,

Sterile Neutrinos

Holanda & Smirnov
PRD 83 (2011) 113011

Mass varying neutrinos (MaVaNs)

M.C. Gonzalez-Garcia, M. Maltoni
Improvements in SK-IV

- Reduced BG: Event rate becomes low and stable in SK-IV

- Reduced systematic error:
  1.7% for flux (cf. SK-I: 3.2% SK-III: 2.1%)

- Achieved 3.5 MeV(kin.) energy threshold
  7.5σ level signal is observed at 3.5 MeV bin
SK+SNO $^8$B total flux

- For each oscillation parameter set there is a minimum chi2 and a $^8$B error term describing the parabolic increase of the chi2 with deviations from the best chi2. The reduced chi2 vs. $^8$B flux is below. The jump is due to the relatively coarse grid in theta12.
- $5.30 \pm 0.17 - 0.11 \times 10^6/(\text{cm}^2 \text{ sec})$, which is a (+3\%, -2\%) error on the total $^8$B for SK+SNO compared to the 1.5\% error of SK's ES flux by itself.
## Systematic errors

<table>
<thead>
<tr>
<th>Source</th>
<th>SK-IV flux (3.5-19.5MeV)</th>
<th>SK-III flux (4.5-19.5MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy scale</td>
<td>+1.14, -1.16%</td>
<td>± 1.4%</td>
</tr>
<tr>
<td>energy resolution</td>
<td>+0.14, -0.08%</td>
<td>± 0.2%</td>
</tr>
<tr>
<td>B8 spectrum</td>
<td>+0.33, -0.37%</td>
<td>± 0.2%</td>
</tr>
<tr>
<td>trigger efficiency</td>
<td>± 0.1%</td>
<td>± 0.5%</td>
</tr>
<tr>
<td>angular resolution</td>
<td>+0.32, -0.25%</td>
<td>± 0.67%</td>
</tr>
<tr>
<td>vertex shift</td>
<td>± 0.18%</td>
<td>± 0.54%</td>
</tr>
<tr>
<td>BG event cut</td>
<td>± 0.36%</td>
<td>± 0.4%</td>
</tr>
<tr>
<td>hit pattern cut</td>
<td>± 0.27%</td>
<td>± 0.25%</td>
</tr>
<tr>
<td>another vertex cut</td>
<td>removed</td>
<td>± 0.45%</td>
</tr>
<tr>
<td>spallation cut</td>
<td>± 0.2%</td>
<td>± 0.2%</td>
</tr>
<tr>
<td>gamma cut</td>
<td>± 0.26%</td>
<td>± 0.25%</td>
</tr>
<tr>
<td>cluster hit cut</td>
<td>+0.45, -0.44%</td>
<td>± 0.5%</td>
</tr>
<tr>
<td>BG shape</td>
<td>± 0.1%</td>
<td>± 0.1%</td>
</tr>
<tr>
<td>signal extraction</td>
<td>± 0.7%</td>
<td>± 0.7%</td>
</tr>
<tr>
<td>cross section</td>
<td>± 0.5%</td>
<td>± 0.5%</td>
</tr>
</tbody>
</table>

- **Total 1.7 %**
Data set for global solar analysis
The most up-to-date data are used

- SK:
  - SK-I 1496 days, spectrum 4.5-19.5 MeV(kin.)+D/N: Ekin>4.5 MeV
  - SK-II 791 days, spectrum 6.5-19.5 MeV(kin.)+D/N: Ekin>7.0 MeV
  - SK-III 548 days, spectrum 4.0-19.5 MeV(kin.)+D/N: Ekin>4.5 MeV
  - SK-IV 1669 days, spectrum 3.5-19.5 MeV(kin.)+D/N: Ekin>4.5 MeV

- SNO:
  - Parameterized analysis (c0, c1, c2, a0, a1) of all SNO phased. (PRC88, 025501 (2013))
  - Same method is applied to both SK and SNO with a0 and a1 to LMA expectation

- Radiochemical: Cl, Ga

- 8B and hep flux $\phi_{8B}=5.25 \times 10^6/(cm^2\cdot sec)$
  $\phi_{hep}=7.88 \times 10^3/(cm^2\cdot sec)$