Highlights from Super-Kamiokande

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**Super-K detector**

- Water Cherenkov imaging detector
- 1000 m underground in Kamioka mine
- 50 kton volume (fiducial 22.5 kton)
- 11129 20” PMTs in inner detector (ID) for Cherenkov ring imaging
- 1885 8” PMTs for outer detector (OD)

<table>
<thead>
<tr>
<th>Phase</th>
<th>Period</th>
<th># of PMTs</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK-I</td>
<td>1996.4 ~ 2001.7</td>
<td>11146 (40%)</td>
</tr>
<tr>
<td>SK-II</td>
<td>2002.10 ~ 2005.10</td>
<td>5182 (20%)</td>
</tr>
<tr>
<td>SK-III</td>
<td>2006.7 ~ 2008.8</td>
<td>11129 (40%)</td>
</tr>
<tr>
<td>SK-IV</td>
<td>2008.9 ~</td>
<td></td>
</tr>
</tbody>
</table>
Super-K physics
Multi-purpose detector with rich physics

- Solar neutrino
- Atmospheric ν
- Supernova (relic) ν
- Neutrino oscillation
- Proton decay
- Astrophysics
- Beyond SM
- Indirect WIMP search

Also used as far detector of T2K experiment (LBL)
Contents of this talk

• Neutrino oscillation physics
  ◆ Atmospheric neutrino
  ◆ Solar neutrino

• Dark matter
  ◆ indirect WIMP search from Sun

• News
  ◆ SuperK-Gd project
### Neutrino oscillation

#### Flavor State

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 1 & 0
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

#### Mass Hierarchy (MH):

- Atmospheric, LBL
  \[\Delta m_{32}^2 = (2.44 \pm 0.06) \times 10^{-3} \text{eV}^2\]
  \[\sin^2 \theta_{23} = 0.437^{+0.033}_{-0.023}\]

- Reactor, LBL
  \[\sin^2 \theta_{13} = 0.0234^{+0.0020}_{-0.0019}\]

- Solar, KamLAND
  \[\Delta m_{21}^2 = 7.54^{+0.26}_{-0.22} \times 10^{-5} \text{eV}^2\]
  \[\sin^2 \theta_{12} = 0.308 \pm 0.017\]

#### Octants and Mass Hierarchy:

- \(\theta_{23}\) octant (\(\theta_{23} > \pi/4\) or \(\theta_{23} < \pi/4\))

- CP violation phase (\(\delta_{\text{CP}}\))

- Mass hierarchy (Normal or Inverted)

- All mass splitting and mixing angles are measured by solar/atmos./reactor/LBL

- Still unknown:
Atmospheric neutrino

- Decay products from cosmic ray interaction with atmosphere
- Energy ranges from sub-GeV over TeV
- Atm. ν’s are suitable for oscillation study

\[
\begin{align*}
\pi^+ &\rightarrow \mu^+ + \nu_\mu \\
&\rightarrow e^+ + \nu_e + \overline{\nu}_\mu \\
\pi^- &\rightarrow \mu^- + \overline{\nu}_\mu \\
&\rightarrow e^- + \overline{\nu}_e + \nu_\mu
\end{align*}
\]

Downward-going: \( L \sim 10\sim 30 \text{ km} \)
Upward-going: \( L \sim 10000 \text{ km} \)

![Energy spectrum graph]

- \( \nu_e + \overline{\nu}_e \)
- \( \nu_\mu + \overline{\nu}_\mu \)
Super-K atmospheric sample

- $\nu_\mu \rightarrow \nu_\tau$ is dominant, but sensitive to other osc. parameters
- Interested in upward $\nu_\mu \rightarrow \nu_e$ containing sub-dominant effect
$\nu_\mu \rightarrow \nu_e$ effect in atmospheric $\nu$

- Multi-GeV: resonant-like peak due to matter effect in Earth
  - appear in ether $\nu$ or $\overline{\nu}$, and depends on mass hierarchy
  - $\theta_{23}$ octant changes size of resonance peak
- sub-GeV: flux normalization changes by CP phase $\delta_{CP}$
Oscillation fit result

- $\chi^2$ scan for $\delta_{CP}$, $\theta_{23}$, $\Delta m^2_{32}$, MH. ($\theta_{13}$ is fixed for reactor).
- SuperK data favored normal hierarchy, but not significant ($\chi^2_{NH}-\chi^2_{IH} = -3.0$)

<table>
<thead>
<tr>
<th>Fit (517 dof)</th>
<th>$\chi^2$</th>
<th>$\sin^2 \theta_{13}$ (fix)</th>
<th>$\delta_{CP}$</th>
<th>$\sin^2 \theta_{23}$</th>
<th>$\Delta m^2_{32}$</th>
</tr>
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<tbody>
<tr>
<td>Normal</td>
<td>582.4</td>
<td>0.0238</td>
<td>240</td>
<td>0.575</td>
<td>2.6x10^{-3}</td>
</tr>
<tr>
<td>Inverted</td>
<td>585.4</td>
<td>0.0238</td>
<td>220</td>
<td>0.575</td>
<td>2.3x10^{-3}</td>
</tr>
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</table>
Fit with T2K published data (NH)

- Introduce constraint from modeled T2K data for better sensitivity
- $\chi^2_{NH} - \chi^2_{IH} = -3.2$ (SK only: -3.0)
- SK and T2K favors $\delta_{CP} \sim -\pi/2$, but CP conservation ($\sin\delta_{CP} = 0$) allowed

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<tr>
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<td>0.0238</td>
<td>240</td>
<td>0.550</td>
<td>2.4x10^{-3}</td>
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Physics motivation of solar neutrino

1. Spectrum distortion
   - “Up-turn” by MSW oscillation is expected around 3MeV

2. Day / Night flux asymmetry
   - Regeneration of $\nu_e$ in Earth’s matter effect will enhance night flux
Observed $^8$B solar neutrino flux

- ~77 k solar events in SK I-IV
- Data/MC = 0.4459 ± 0.0084 (stat.+syst.)
- Measurement consistent within uncertainties among SuperK phases
- No correlation seen with sun spot number (p-value=0.786)

Yearly flux with sun spot number
Recoil electron spectrum

**SK-I** $E_{th}=4.5\text{MeV}$

**SK-II** $E_{th}=6.5\text{MeV}$

**SK-III** $E_{th}=4.0\text{MeV}$

**SK-IV 1669 days**

**SK-IV** $E_{th}=3.5\text{MeV}$
SK I-IV combined spectrum

- MSW is slightly disfavored (~1.7σ for solar+KL, ~1.0σ for solar global)
- Still spectral “up-turn” is not observable
SK I-IV combined spectrum

- MSW is slightly disfavored (~1.7σ for solar+KL, ~1.0σ for solar global)
- Still spectral “up-turn” is not observable
Day/Night flux asymmetry

- ~3% higher flux expected for night
- ~3σ difference seen between day and night
- Direct indication of matter effect in Earth
- Better agreement for solar $\Delta m^2$
Status of solar / KL oscillation fit

• fitted with reactor constraint:
  $\sin^2 \theta_{13} = 0.0242 \pm 0.0026$
• $\sim 2\sigma$ difference between solar and KL

Best fit:

$\sin^2 \theta_{12} = 0.312^{+0.033}_{-0.025}$
$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$

$\sin^2 \theta_{12} = 0.311^{+0.014}_{-0.014}$
$\Delta m^2_{21} = 4.85^{+1.4}_{-0.59}$

$\sin^2 \theta_{12} = 0.308^{+0.013}_{-0.013}$
$\Delta m^2_{21} = 7.50^{+0.19}_{-0.18}$

Solar + KamLAND
KamLAND
Solar Global
Solar WIMP search by SuperK

- DM, trapped in the center of Sun, could annihilate and produce neutrinos via $\chi\chi \rightarrow \tau^+\tau^-/b\bar{b}/W^+W^-$
- Tighter limits on spin-independent (SD) scattering due to hydrogen-rich composition of Sun
- Recent direct DM experiments report event excess / annual modulation below 30 GeV/c^2
Super-K WIMP analysis

- SuperK’s sensitivity to GeV energies are suitable for light WIMP search
- WIMP signal has angular correlations with Sun’s direction
Limit on neutrino flux from WIMP annihilation

Upper limit on muon neutrino flux

- Simulate $\chi\chi \rightarrow \tau^+\tau^-/b\bar{b}/W^+W^-$ for 4~200 GeV/c$^2$ and apply fit to data
- No significant excess are seen. upper limit (90% C.L.) was set on neutrino flux
- DarkSUSY 5.0.6 is utilized to convert to WIMP–proton cross sections

Assumptions:
- SI or SD interaction
- Standard DM halo
- Mono channel annihilation (bb, tt, WW)
- BS2005-OP model of solar composition
- Equilibrium between capture and annihilation
90% C.L. limit on SD/SI cross section

- SD interaction: current best limits were set below 200 GeV/c² even for the softest (bb) channel
- SI interaction: some fraction of allowed regions are ruled out

SD interaction

SI interaction
(Isospin conservation fp/fn=1)
SuperK-Gd project (was known as GADZOOKS!)

- Add 0.2% Gd$_2$(SO$_4$)$_3$ in water to enhance neutron capture
- Multiple gammas (~8 MeV in total) emitted from Gd by neutron capture
- Possible to identify anti-neutrino interaction with delayed coincidence

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

Capture efficiency:

- 0.2% Gd$_2$(SO$_4$)$_3$ (~100t for SK) gives 90% neutron capture

Gd capture eff.

Prompt signal

Delayed signal (~8 MeV in total)

Gadolinium sulfate concentration [%]
Supernova Relic Neutrino (SRN)

$10^{10}$ stellar/galaxy $\times 10^{10}$ galaxy $\times 0.3\%$ (become SNe) $\sim O(10^{17})$ SNe

Neutrinos from past SNe

Theoretical flux prediction: $0.3\sim1.5$ /cm$^2$/s (17.3MeV threshold)

Search for SRN at Super-K

Search window for SRN at SK: From $\sim 10\text{MeV}$ to $\sim 30\text{MeV}$

Now SRN search is limited by atmospheric neutrino BG
We need BG reduction by the neutron tagging!
**EGADS**
*(Evaluating Gadolinium’s Action on Detector System)*

Test tank was built with the same detector materials as Super-K, and study Gd water quality

Gd dissolving test has been performed from Oct 2014 to Apr 2015
Transparency of Gd water in EGAS

Light left at 15m in the 200m3 tank was ~70% for 0.2% Gd2(SO4)3, which corresponds to ~92% of SK-IV pure water average.
Rayleigh Scattering measurement

• Increase of scattering lights in Gd water may affect detector performance
• Measure fraction of scattering light by laser injector
• No significant increase of scattered light was observed
On June 27, 2015, the Super-Kamiokande collaboration approved the SuperK-Gd project which will enhance anti-neutrino detectability by dissolving gadolinium to the Super-K water. The actual schedule of the project including refurbishment of the tank and Gd-loading time will be determined soon taking into account the T2K schedule.
**Timeline of SuperK-Gd**

<table>
<thead>
<tr>
<th>201X</th>
<th>201X</th>
<th>201X</th>
<th>20XX</th>
<th>20XX</th>
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</table>

- **T₀ = Start leak stop work (~3.5)**
- **T₁ = Load first Gd₂(SO₄)₃ 1t=0.002% (~1)** and **2nd Gd₂(SO₄)₃ 10t=0.02% (~1)**
- **T₂ = Load full Gd₂(SO₄)₃ 100t=0.2% (~2)**

Numbers in parentheses are months to be taken for the work.

In order to set T₀, T₁, & T₂, T2K schedule will be also taken into account.
Summary

• **Atmospheric neutrino**
  * there is $\sim 1 \sigma$ preference in normal hierarchy
  * indicate $\delta_{\text{CP}} \sim -\pi/2$, but still CP conservation allowed

• **Solar neutrino**
  * energy spectrum slightly disfavor expected distortion
  * first indication of terrestrial matter effect at $\sim 3\sigma$

• **Indirect solar WIMP search**
  * Strongest limit for SD in 4-200 GeV/c$^2$
  * Partially reject SI allowed regions indicated by direct exp.

• **News on SuperK Gd project**
  * Aim to detect SNR using neutron capture by adding Gd
  * SuperK Gd project approved by collaboration