Overview and Searches at Super-Kamiokande

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Novel Searches for Dark Matter 17/11/2008
CCAPP, Ohio State University
Introduction
- Super-Kamiokande detector
- Atmospheric neutrino analysis

Indirect WIMP searches at Super-K
- Published results
- Recent analysis
  - Recently started by T.Tanaka for his PhD work

Summary
Super-Kamiokande detector

Operation since Apr 1996

- 50kt water Cherenkov
- 1000m underground
- ID viewed by 11K PMT
- 2m thick OD for veto
- Fiducial mass 22.5kt
- Effective area 1200m²
- E_th > 4.5MeV
- E_th > 1.7GeV for upµ
  (7m pass length cut)
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10 years of Super-Kamiokande

1996.4 Start data taking
1998 Atmospheric $\nu$ oscillation (SK)

1999.6 K2K started

2001 Solar $\nu$ oscillation (SNO+SK)

2001.11 Accident
  partial reconstruction

2002.10 SK-II started

2005 Accelerator $\nu$ oscillation (K2K)

2005.10 SK-II finish
  full reconstruction

2006.7 SK-III started
  DAQ upgrade

2008.9 SK-IV started

2009.4 T2K will start
Atmospheric $\nu$ categories at SK

Energy $\text{Atm}_\nu$ for each category

$E_\nu (\text{GeV})$
Usual $\mu$, radiative $\mu$

Usual downgoing $\mu$

“Showering” downgoing $\mu$
Up-showering $\mu$

- Upgoing through muon sample is separated into “showering” or “non-showering”


Example of Showering muon in Super-K-II
Zenith Angle Distributions (SK-I + SK-II)

Livetime
- SK-I
  - 1489d (FCPC)
  - 1646d (Upmu)
- SK-II
  - 804d (FCPC)
  - 828d (Upmu)

Sub-GeV e-like $P < 400$ MeV/c vs $\nu_\mu - \nu_\tau$ oscillation (best fit)
- SK-I
  - 1489d (FCPC)
  - 1646d (Upmu)
- SK-II
  - 804d (FCPC)
  - 828d (Upmu)

Sub-GeV $\mu$-like $P > 400$ MeV/c vs null oscillation
- SK-I
  - 1489d (FCPC)
  - 1646d (Upmu)
- SK-II
  - 804d (FCPC)
  - 828d (Upmu)

Multi-GeV e-like vs null oscillation
- SK-I
  - 1489d (FCPC)
  - 1646d (Upmu)
- SK-II
  - 804d (FCPC)
  - 828d (Upmu)

Multi-GeV $\mu$-like vs null oscillation
- SK-I
  - 1489d (FCPC)
  - 1646d (Upmu)
- SK-II
  - 804d (FCPC)
  - 828d (Upmu)

PC stop vs null oscillation
- SK-I
  - 1489d (FCPC)
  - 1646d (Upmu)
- SK-II
  - 804d (FCPC)
  - 828d (Upmu)

PC through vs null oscillation
- SK-I
  - 1489d (FCPC)
  - 1646d (Upmu)
- SK-II
  - 804d (FCPC)
  - 828d (Upmu)

Upward stopping $\mu$ vs null oscillation
- SK-I
  - 1489d (FCPC)
  - 1646d (Upmu)
- SK-II
  - 804d (FCPC)
  - 828d (Upmu)

Upward through-going non-showering $\mu$ vs null oscillation
- SK-I
  - 1489d (FCPC)
  - 1646d (Upmu)
- SK-II
  - 804d (FCPC)
  - 828d (Upmu)

Upward through-going showering $\mu$ vs null oscillation
- SK-I
  - 1489d (FCPC)
  - 1646d (Upmu)
- SK-II
  - 804d (FCPC)
  - 828d (Upmu)

All distributions agree with oscillated expectations
Published Indirect WIMP Search at Super-K


- Based on upward through going \( \mu \) sample
  - Energetic \( \nu \) from the sun
  - Energetic \( \nu \) from the earth center
  - (Energetic \( \nu \) from the Galactic center)
Advantage of using upgoing $\mu$

<table>
<thead>
<tr>
<th>Vtx contained</th>
<th>$\sigma \cdot E_{\nu}$</th>
<th>$V=\text{const}$</th>
<th>$N_{SK} \cdot E_{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upgoing $\mu$</td>
<td>$\sigma \cdot E_{\nu}$</td>
<td>$V \cdot E_{\nu}$</td>
<td>$N_{SK} \cdot E_{\nu}^2$</td>
</tr>
</tbody>
</table>

- 1 TeV $\nu$ produces up-going through $\mu$ at SK
- Assuming $E_{\mu} \sim 1\text{TeV}$, $R_{\mu} \sim 1000\text{m}$

Effective area $S=1200\text{m}^2$

Effective target volume $S \cdot R_{\mu} \cdot \rho_{\text{rock}} \sim 3 \times 10^{12}\text{g}$

High $E_{\nu}$s from vector boson decays dominate in a event rate
Neutrino flux at Earth as BG

Solar $\nu_e$

SN $\nu$ @G.C.

B$^8$

reactor $\nu_e$

Atmospheric $\nu_\mu$

Galactic neutrinos

Relic supernova neutrinos $\nu_e$ (200 cm$^{-2}$sec$^{-1}$)

$\nu_e$ from the earth

Cyg X-3 ($\propto E^{-2.5}$)

SK
Angular correlation between $\nu$ and $\mu$

Contain 90% of events

Neutralino mass (GeV)

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Upmu’s from the sun

$\cos \theta_{\text{sun}}$

The number of upward thru-muons towards the sun

WIMP signal expected in this region

Upmu’s from the earth center

Zenith angle

#ev in each cone angle

WIMP signal expected in this region

BOX : MC w/o osc / Hist : MC w. osc

Upper limits for upward muon flux

**SK-I up thr-\(\mu\) 1679.6 days**

**10^{-14}\mu/cm^2s**

\(\sim 3000\mu/km^2yr\)

Limit on WIMP-induced upward muons (cm^{-2} sec^{-1})

From the Sun

From the earth center
Comparison to direct detection exp.

From the earth ($SI$) $10^4$-$10^6$ m$^2$ $\nu$ detector $\rightarrow$ 1kg Ge detector
From the sun ($SD$) 10-500 m$^2$ $\nu$ detector $\rightarrow$ 50g H detector

Max ratio ($M$) = \[
\frac{\text{Direct Detection Rate} (M,\sigma)}{\text{Super-K flux limit} (M)}
\]

M.Kamionkowski et al.
PRL 74(1995)5174
Comparison to direct detection

SI cross section

SD cross section

SK limit
Recent progress of analysis
(By T. Tanaka)

- Lowering $\nu$ energy window
  - Add up stop $\mu$
  - Sensitivity for light WIMP ($>18\text{GeV} \rightarrow >10\text{ GeV}$)

- Energy dependent analysis
  - Divided into up-stop $\mu$, non-showering $\mu$ and showering $\mu$
  - Consider typical $E_\nu$ of 3 up $\mu$ categories

- Increasing statistics
  - Add SKII+SKIII
  - 1679.6 days $\rightarrow$ 2828.3 days
Motivation to include lower energy samples

WIMP-proton $\sigma_{SD}$

Low mass range (> a few 10 GeV) is ruled out by usual SUSY parameter. But recent DAMA result considering channeling effect is not rejected at low mass region (afew ~ 10 GeV) by indirect search.

New limit from COUPP excludes the region?

*Science, 319: 933-936 (2008).*
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Ratio of each category of event

- Black: FC mu-like (multi-GeV)
- Red: PC
- Green: stopping upmu
- Yellow: non-showering upmu
- Blue: showering upmu

Given $E_\nu$, fraction of each categories shown
Cos $\theta_{\text{sun}}$ in 3 categories of upmu

SKI+II+III data (2828.344 day)
MC (with oscillation)

Stopping
Non-showering
Showering
Updating muon flux limit

Expected flux region
(E > 1 GeV)

<table>
<thead>
<tr>
<th>mass (GeV)</th>
<th>flux (10^{-15} cm^{-2}sec^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>4.96</td>
</tr>
<tr>
<td>100</td>
<td>6.11</td>
</tr>
<tr>
<td>$10^3$</td>
<td>4.16</td>
</tr>
<tr>
<td>$10^4$</td>
<td>3.43</td>
</tr>
</tbody>
</table>

SK I+II+III (2828.3 days)
Using 3-up $\mu$ samples

Now working for converting to $\sigma_{SD}$ limit
Summary

- **Super-Kamiokande**
  - 22.5kt FV, 1200m$^2$ area
  - For $u_\mu$, $E_{u_\mu} > 1.7$ GeV, angular resolution $\sim 1$deg,

- **Indirect search (Super-K 2004)**
  - From the sun, the earth center (and the galactic center)
  - Muon flux limit $10^{-14}$ $\mu$/cm$^2$s
  - Indirect search from the sun is still the best limit for $\sigma_{SD}$

- **Updating at neutrino08**
  - Including lower E samples (up stop-$\mu$)
  - Energy dependent analysis
  - Push down by 1.4 times for $M_\chi > 10$GeV

- **On-going activity**
  - Use FC/PC? Need new simulations to translate to $\sigma$ limit
  - Search for diffuse $\nu$ from halo based on FC