# Recent milestones in $\nu$ physics

- 1988 Kamiokande (K.S. Hirata et al., Phys. Lett. B205 (1988) 416) and IMB (R.M. Bionta et al., Phys. Rev. D38 (1988) 768) water Cherenkov detectors found evidence of muon neutrino disappereance (about 1/2) in the atmospheric neutrino beam, contrary to 2 iron tracking detectors (Frejus and Nusex) Puzzle: experimental effect or new physics? Atmospheric neutrino problem
- 1994 Kamiokande Multi-GeV flavor ratio angular dependence
- 1996 LSND claims evidence of $\nu_\mu \rightarrow \nu_e$ oscillations
- 1997 first negative results from CHOOZ
- 1998 Super-Kamiokande (Y. Fukuda et al., PRL 81 (1998) 1562, hep-ex/9807003)

  $\sin^2 2\theta > 0.82$ and $5\times10^{-4} < \Delta m^2 < 6\times10^{-3}$ eV$^2$ at 90% confidence level.

  and MACRO (M. Ambrosio, PLB434 (1998) 451, hep-ex/9807005)
  Model independent evidence!
- 2002 the year of neutrino physics: Apr 19 SNO direct evidence for $\nu$ flavor conversion from NC, after results on CC in 2001. Oct 8 Nobel prize to Davis and Koshiba. Dec 4 K2K LBL observes deficit of $\nu_\mu$ and distorsion of the E spectrum, Dec 6 KamLAND reactor LBL: only viable solution to the solar n problem is LMA

# Solar νs

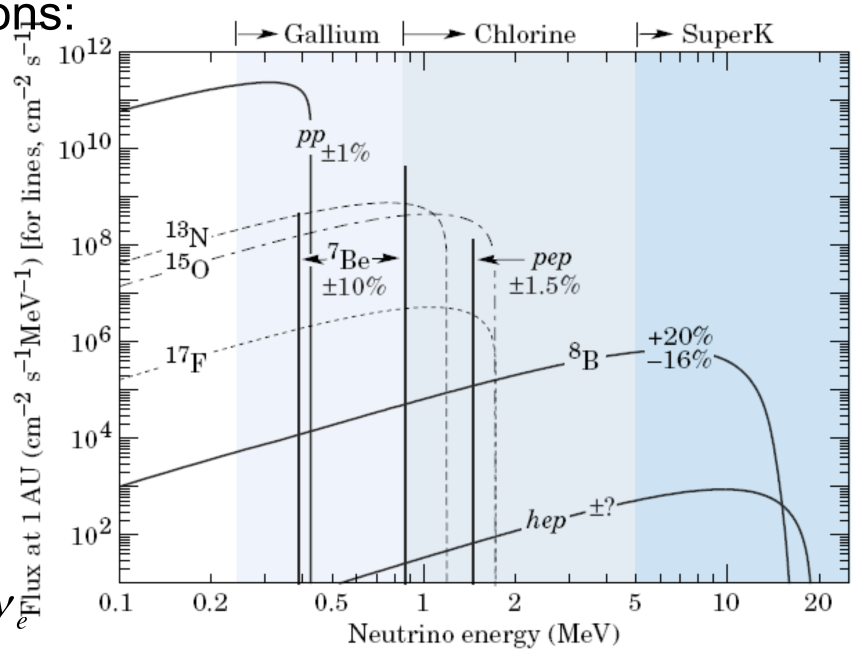
The Sun is a main sequence star at a stage of stable hydrogen burning.
Combined effect of nuclear fusion reactions:

$$4p \rightarrow {}^4\text{He} + 2e^+ + 2\nu_e$$

Positrons annihilate with electrons and thermal energy is generated

$$4p + 2e^- \rightarrow {}^4\text{He} + 2\nu_e + 26.73\ \text{MeV} - E_\nu$$

$$\langle E_\nu \rangle \sim 0.6\ \text{MeV}$$




Predicted fluxes from Standard Solar Model
Uncertainty ~ 0.1%

| ν type | Energy | Φ cm$^{-2}$s$^{-1}$ |
|---|---|---|
| pp | < 420 keV | 5.95 $10^{10}$ |
| $^7$Be | = 891 keV (90%)<br>= 380 keV (10%) | 4.77 $10^9$ |
| $^8$B | < 14 MeV | 5.05 $10^6$ |
| | … and … | |
| pep | = 1.44 MeV | 4.77 $10^8$ |
| CNO | < 1.7 MeV | 1.02 $10^9$ |
| hep | = 18.8 MeV | 9.3 $10^3$ |

$$p + p \rightarrow {}^2H + e^+ + \nu_e$$

$${}^7Be + e^- \rightarrow {}^7Li + \nu_e$$

$${}^8B \rightarrow {}^8Be + e^+ + \nu_e$$

$$p + e^- + p \rightarrow {}^2H + \nu_e$$

$${}^3\text{He}\ p \rightarrow {}^4\text{He}\ e^+ \nu$$

$${}^{12}C + p \rightarrow {}^{13}N + \gamma$$

$${}^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$$

$${}^{13}C + p \rightarrow {}^{14}N + \gamma$$

$${}^{14}N + p \rightarrow {}^{15}O + \gamma$$

$${}^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$$

# The solar neutrino problem

Pioneer experiment: 1966 R. Davis in Homestake Mine
Radiochemical experiment: exploit $\nu_e$ absorption on nuclei followed by their decay through electron capture. Produced Auger electrons are counted.
615 tons of liquid perchloroethylene ($C_2Cl_4$) in a mine at 4500 mwe depth in South Dakota
The main limit of these experiments are the low event rates (~1 ev/day), they do not provide information on the energy and time of detection
Reaction $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$, $E_{th}$=0.814 MeV, $^{37}Ar$ is extracted with a He gas stream radioactive with half-life 34.8 days, decay products are chemically extracted and introduced in proportional counters where the Auger electrons from their decay are counted
Observed event rate since 1970: 2.56±0.23 SNU
(1 SNU =$10^{-36}$ interactions per target atom per second)
Standard Solar Model prediction: 8.1+1.3 SNU

$R(exp/SSM) = 0.32 \pm 0.03_{exp} \pm 0.05_{th}$

http://www.bnl.gov/bnlweb/raydavis/PRL_1964.pdf

# The solar neutrino problem

Table 2: Results from the seven solar-neutrino experiments. Recent solar model calculations are also presented. The first and the second errors in the experimental results are the statistical and systematic errors, respectively. SNU (Solar Neutrino Unit) is defined as $10^{-36}$ neutrino captures per atom per second.

| | $^{37}$Cl→$^{37}$Ar (SNU) | $^{71}$Ga→$^{71}$Ge (SNU) | $^{8}$B $\nu$ flux ($10^6$cm$^{-2}$s$^{-1}$) |
|---|---|---|---|
| Homestake | | | |
| (CLEVELAND 98)[18] | $2.56 \pm 0.16 \pm 0.16$ | — | — |
| GALLEX | | | |
| (HAMPEL 99)[19] | — | $77.5 \pm 6.2^{+4.3}_{-4.7}$ | — |
| GNO | | | |
| (ALTMANN 05)[20] | — | $62.9^{+5.5}_{-5.3} \pm 2.5$ | — |
| GNO+GALLEX | | | |
| (ALTMANN 05)[20] | — | $69.3 \pm 4.1 \pm 3.6$ | — |
| SAGE | | | |
| (ABDURASHI...02)[21] | — | $70.8^{+5.3+3.7}_{-5.2-3.2}$ | — |
| Kamiokande | | | |
| (FUKUDA 96)[22] | — | — | $2.80 \pm 0.19 \pm 0.33^{\dagger}$ |
| Super-Kamiokande | | | |
| (HOSAKA 05)[23] | — | — | $2.35 \pm 0.02 \pm 0.08^{\dagger}$ |
| SNO (pure $D_2O$) | | | |
| (AHMAD 02)[4] | — | — | $1.76^{+0.06}_{-0.05} \pm 0.09^{\ddagger}$ |
| | — | — | $2.39^{+0.24}_{-0.23} \pm 0.12^{\dagger}$ |
| | — | — | $5.09^{+0.44+0.46}_{-0.43-0.43}{}^{*}$ |
| SNO (NaCl in $D_2O$) | | | |
| (AHARMIM 05)[11] | — | — | $1.68 \pm 0.06^{+0.08}_{-0.09}{}^{\ddagger}$ |
| | — | — | $2.35 \pm 0.22 \pm 0.15^{\dagger}$ |
| | — | — | $4.94 \pm 0.21^{+0.38}_{-0.34}{}^{*}$ |
| BS05(OP) SSM [12] | $8.1 \pm 1.3$ | $126 \pm 10$ | $5.69(1.00 \pm 0.16)$ |
| Seismic model [16] | $7.64 \pm 1.1$ | $123.4 \pm 8.2$ | $5.31 \pm 0.6$ |

* Flux measured via the neutral-current reaction.
† Flux measured via $\nu e$ elastic scattering.
‡ Flux measured via the charged-current reaction.

Gallex & GNO (LNGS, 3300 mwe) SAGE (Baksan, 4700 mwe)
Sensitive also to pp neutrinos
pp (54.5%) $^{7}$Be (26.8%) $^{8}$B (9.5%)

$$^{71}\text{Ga} + \nu_e \rightarrow {}^{71}\text{Ge} + e^- \quad (\text{threshold } 233 \text{ keV}).$$

Gallex: 101 ton $GaCl_3$ acidic solution (from 1991), 30 ton of Ga ⇒GNO
SAGE 55 ton of metallic Ga
Result (May 91-Apr 03) Gallex-GNO (Jan 1990-Jan 2003) SAGE
$R(\text{GNO+GALLEX}) = 0.55 \pm 0.04_{exp} \pm 0.04_{th}$
$R(\text{SAGE}) = 0.56 \pm 0.04_{exp} \pm 0.04_{th}$

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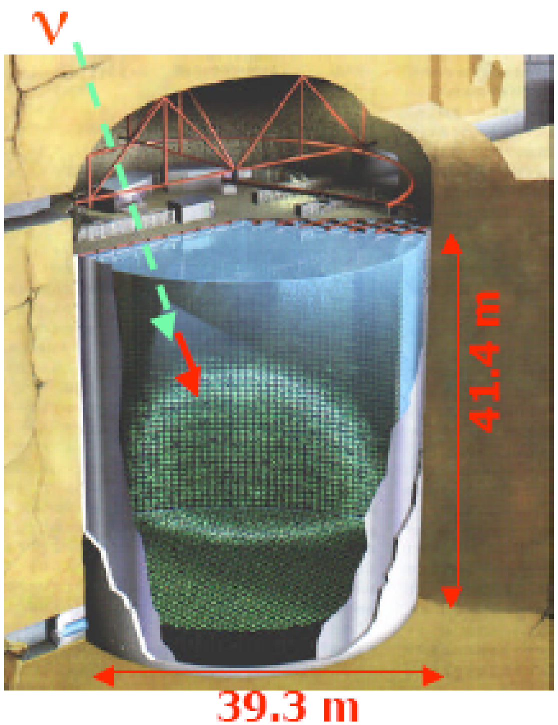
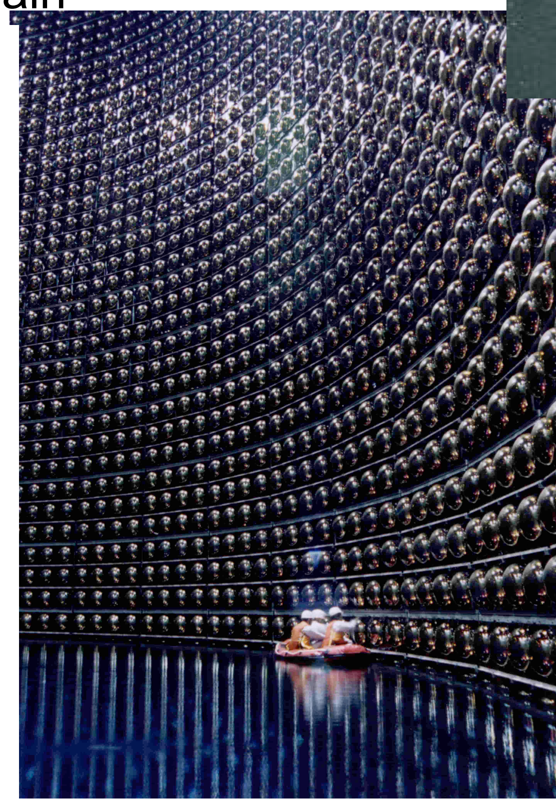
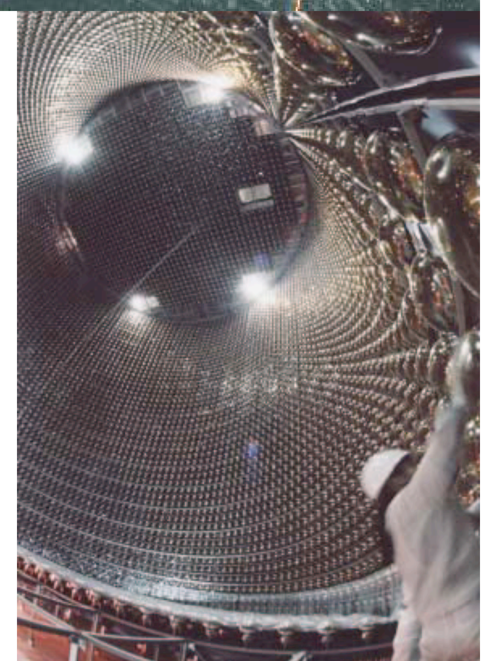
R(SAGE) = $0.56 \pm 0.04_{exp} \pm 0.04_{th}$

# Super-Kamiokande

Water Cherenkov detector following the previous Kamiokande 3 kton (1 kton fiducial) of utra-pure water
SK: 50 kton (22.5 kton fiducial)
Run time: 1996-2001, Jan 2003: K2K beam
Nov 2001: 50% of PMT destruction. Dec 2002 SK-II starts data taking again

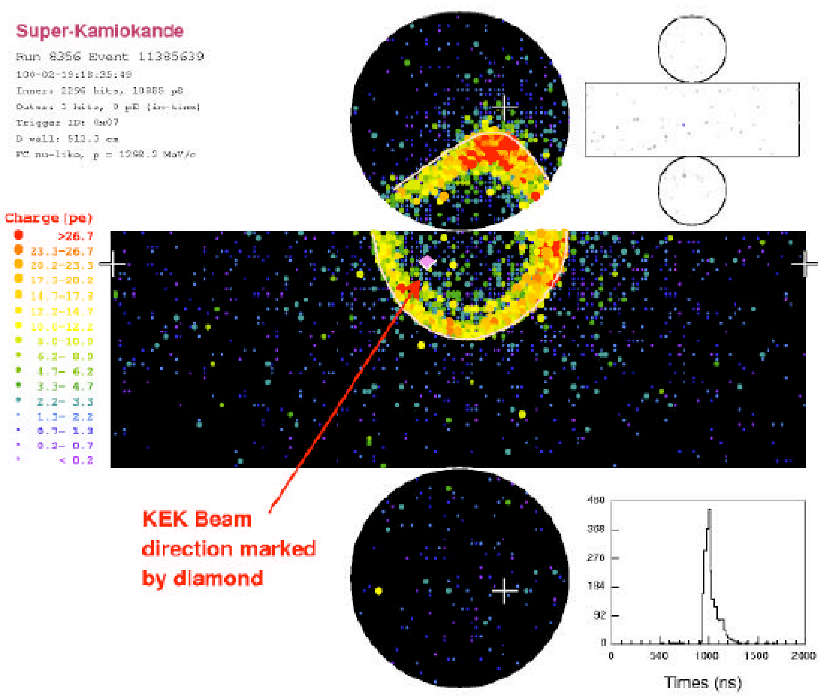


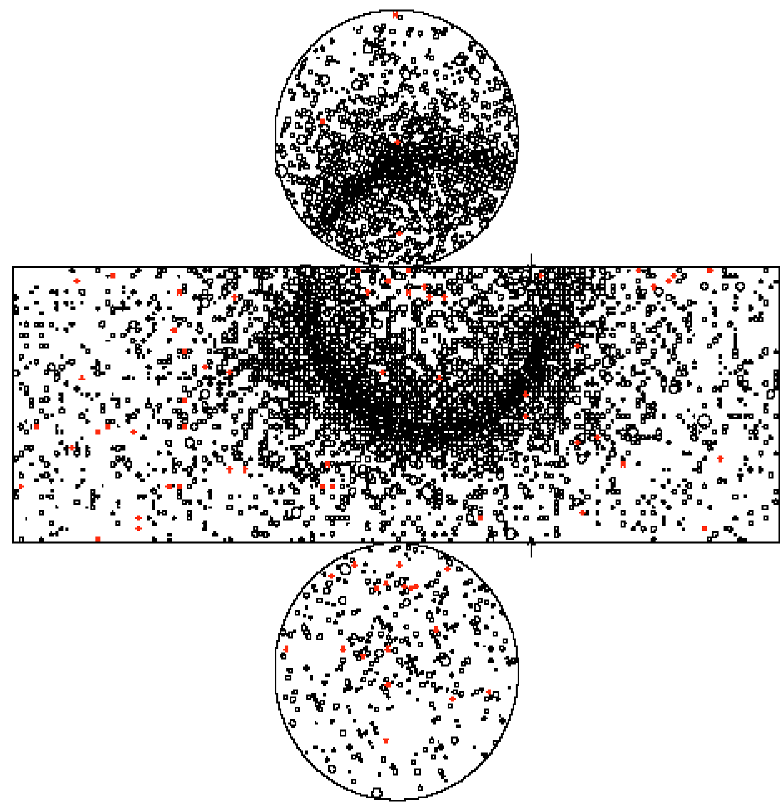

(Oct. 1995)

# PID in SK

Typical mu-like




Typical e-like



# Super-Kamiokande

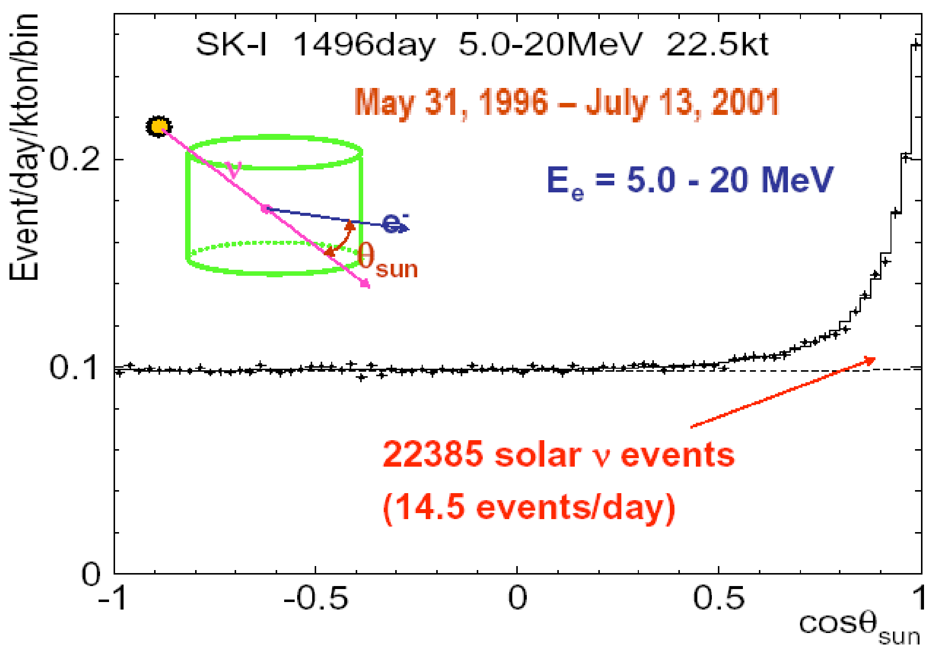
SK-I: inner detector 40% photocatode coverage 11,146 51 cm PMTs
OD (1885 20 cm PMTs): external veto
Rock coverage: 2700 mwe ($\mu$ surface flux reduction $10^5 \Rightarrow$ 2 Hz rate)
Resolutions: angular = 26° vertex = 87 cm energy = 14% @ 10 MeV
Real time solar neutrino detectors (elastic scattering): $\nu_x + e^- \rightarrow \nu_x + e^-$

direction and energy spectrum of recoil electron (correlated to $\nu$)

Time variations as expected from eccentricity

$E_{th}$ = 4.75 MeV sensitive to $^8B$, hep
Sensitive to all flavors but
$\sigma(\nu_e) \sim 6\sigma(\nu_{\mu,\tau})$

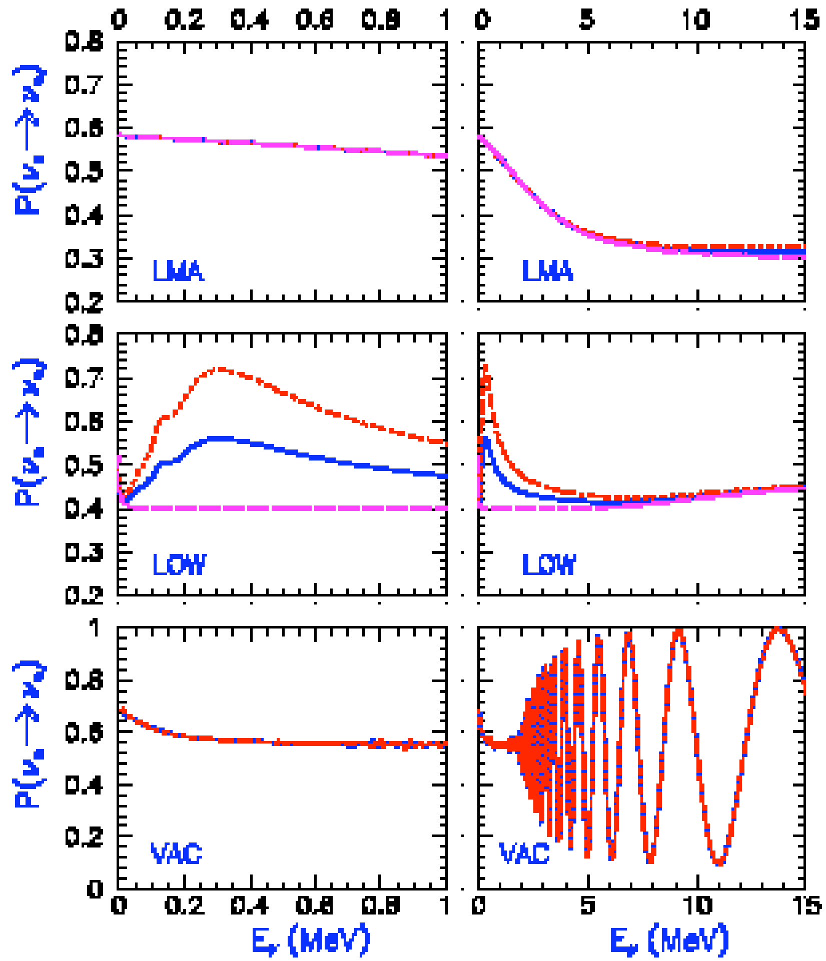
$$\frac{\text{Data}}{\text{SSM(BP2000)}} = 0.465 \pm 0.005^{+0.016}_{-0.015}$$



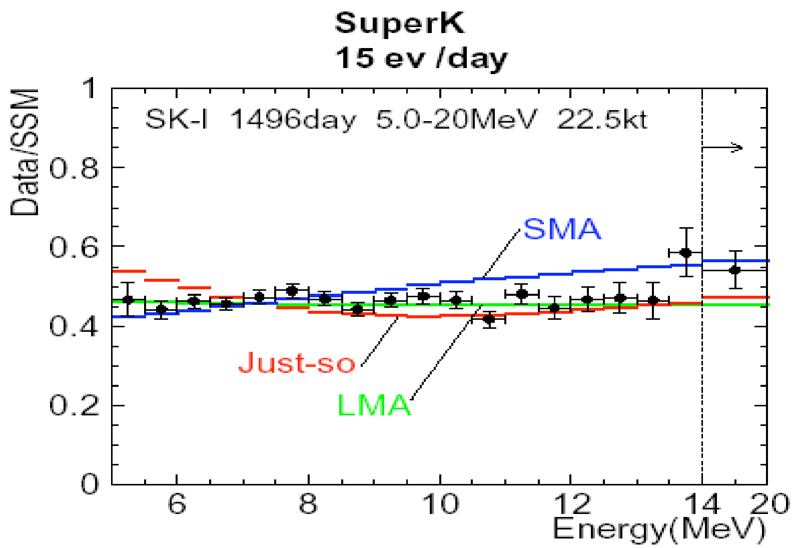
# Different ν oscillation solutions

## Typical values

| | | |
|---|---|---|
| LMA (Large Mixing Angle): | $\Delta m^2 \sim 5 \times 10^{-5}\,\mathrm{eV}^2$, | $\tan^2\vartheta \sim 0.8$ |
| LOW (LOW $\Delta m^2$): | $\Delta m^2 \sim 7 \times 10^{-8}\,\mathrm{eV}^2$, | $\tan^2\vartheta \sim 0.6$ |
| SMA (Small Mixing Angle): | $\Delta m^2 \sim 5 \times 10^{-6}\,\mathrm{eV}^2$, | $\tan^2\vartheta \sim 10^{-3}$ |
| Quasi-Vacuum Oscillations): | $\Delta m^2 \sim 10^{-9}\,\mathrm{eV}^2$, | $\tan^2\vartheta \sim 1$ |
| VAC (VACuum oscillations): | $\Delta m^2 \lesssim 5 \times 10^{-10}\,\mathrm{eV}^2$, | $\tan^2\vartheta \sim 1$ |



# Energy spectrum



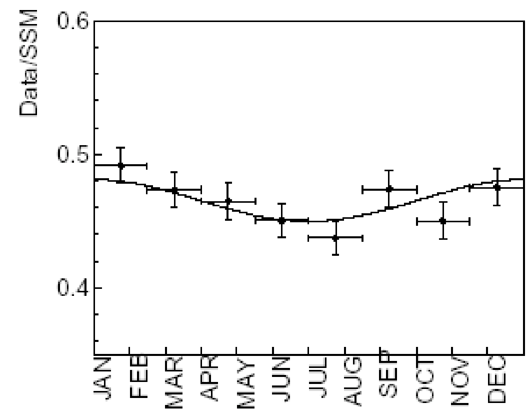
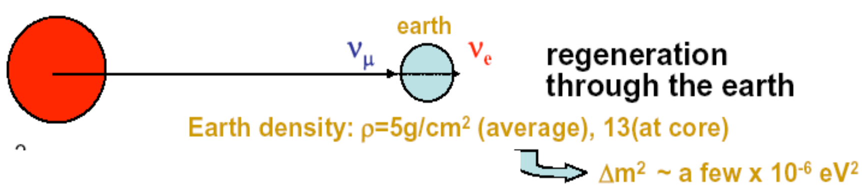




FIG. 6: Seasonal variation of the solar neutrino flux. The curve shows the expected seasonal variation of the flux introduced by the eccentricity of the Earth's orbit.

$$A_{\mathrm{DN}} = \frac{\mathrm{Day} - \mathrm{Night}}{0.5(\mathrm{Day} + \mathrm{Night})} = -0.021 \pm 0.020^{+0.013}_{-0.012}.$$

No evidence for distortion of the energy spectrum
Day night asymmetry: during the night the Sun is below the horizon



# Sudbury Neutrino Observatory

19 Apr 02: direct evidence for $\nu_e$ transitions, independently of solar models

**1000 tonnes $D_2O$ (heavy water)**

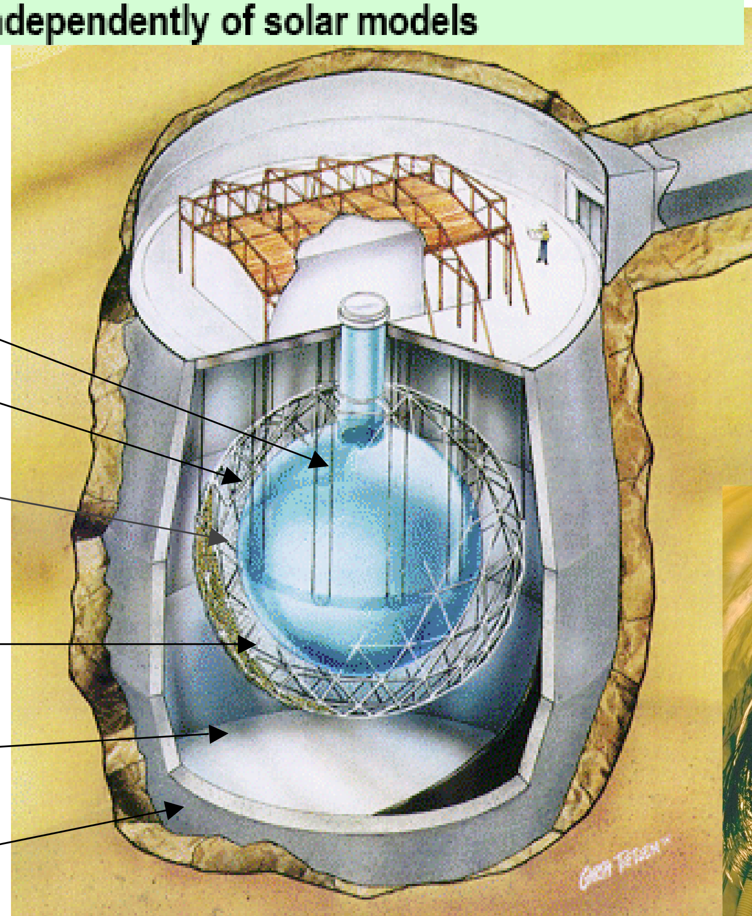
12 m Diameter Acrylic Vessel

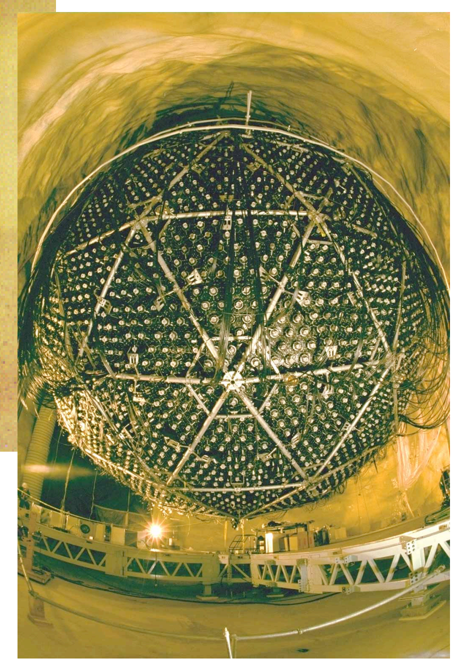
Support Structure for 9500 20 cm PMTs, 60% coverage

1700 tonnes Inner Shielding $H_2O$

5300 tonnes Outer Shield $H_2O$

Urylon Liner and Radon Seal





Creighton (Ontario) mine 6010 mwe

**Results from 1st phase:** **CC:** PRL 87 (2001) **Day-Night:** PRL 89 (2002) **NC:** PRL 89 (2002)

# A model independent measurement

3 phases: NC detection

- Nov. 1999- May 2001

Pure $D_2O$:
good CC sensitivity
neutron capture on deuterium

$$n + d \rightarrow t + \gamma \ldots \rightarrow e^-$$
$$(E_\gamma = 6.3 \text{ MeV})$$

- Jun. 2001- Mar. 2002

2 tons of Salt in $D_2O$ to enhance (>3) NC sensitivity n capture on Cl

$$n + {}^{35}Cl \rightarrow {}^{36}Cl + \Sigma\gamma \ldots \rightarrow e^-$$
$$(E_{\Sigma\gamma} = 8.6 \text{ MeV})$$

- Neutral Current Detectors

$^3$He proportional counters in $D_2O$, salt removed
Capture on $^3$He

$$n + {}^3He \rightarrow p + t$$

Now!

**ES** $\nu_x + e^- \Rightarrow \nu_x + e^-$

- Both SK, SNO
- Mainly sensitive to $\nu_e$, less to $\nu_\mu$ and $\nu_\tau$
- Strong directional sensitivity

**CC** $\nu_e + d \Rightarrow p + p + e^-$

- Good measurement of $\nu_e$ energy spectrum
- Weak directional sensitivity ∝ 1-1/3cos(θ)
- $\nu_e$ ONLY

**NC** $\nu_x + d \Rightarrow p + n + \nu_x$

Measure total $^8$B ν flux from the Sun.
- equal cross section for all ν types

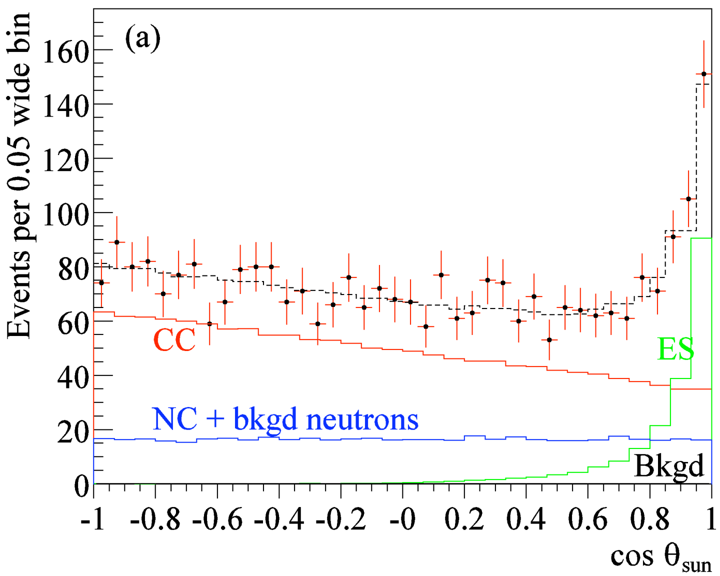
# Results

$$\phi_{CC} = \phi_e$$

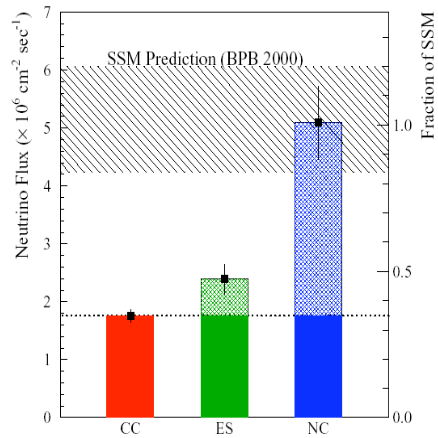
$$\phi_{NC} = \phi_{tot} = \phi_e + \phi_{\mu,\tau}$$

$$\phi_{ES} = \phi_e + \phi_{\mu,\tau} / 6.48$$

$P_{ee}$ = CC/NC




Assuming $^8$B energy spectrum ...




Fluxes ($\times 10^6$ cm$^{-2}$ sec$^{-1}$)

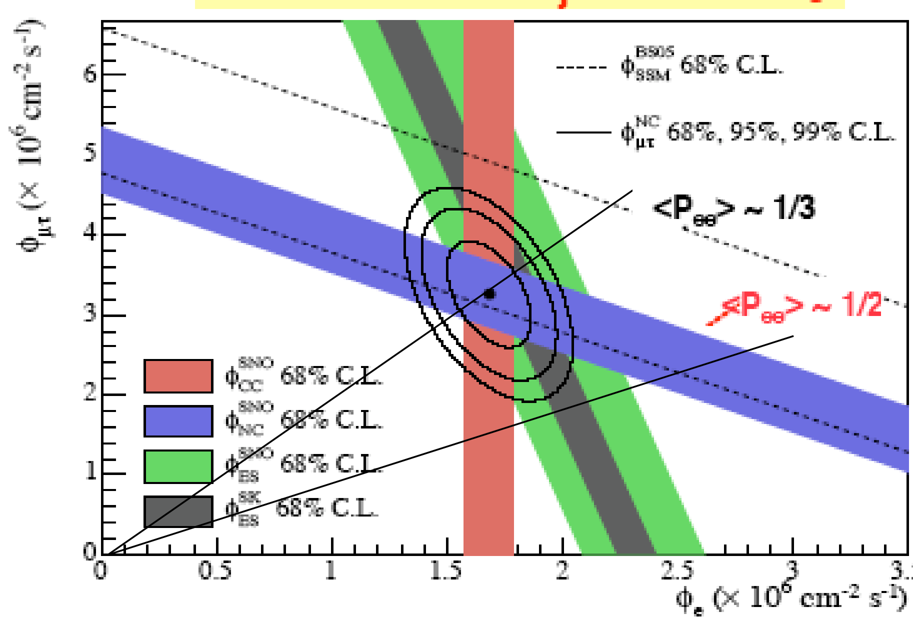
$$\phi_{CC} = 1.76^{+0.06}_{-0.05}\,(\text{stat.}) \pm 0.09\,(\text{sys.})$$

$$\phi_{ES} = 2.39^{+0.24}_{-0.23}\,(\text{stat.}) \pm 0.12\,(\text{sys.})$$

$$\phi_{NC} = 5.09^{+0.44}_{-0.43}\,(\text{stat.})^{+0.46}_{-0.43}\,(\text{sys.})$$

$$\Phi_{ssm} = 5.05^{+1.01}_{-0.81} \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$$

**Null hypothesis of no flavor transformation rejected at 5.3σ**




**By comparing ES, CC and NC fluxes measured by SNO:**

- extremely good confirmation of SSM
- clear evidence of active oscillations

$\Phi_{CC} < \Phi_{ES} < \Phi_{NC}$

~2/3 of $\nu_e$ oscillate into active flavors

- preferred $\langle P_{ee}\rangle \sim 1/3$ (matter effects)
- $2^{nd}$ phase data fundamental to rule out $\langle P_{ee}\rangle \sim 1/2$

<E> ~ 3 MeV <base line> ~ 180 km

(79% from 26 reactors 138-214 km)

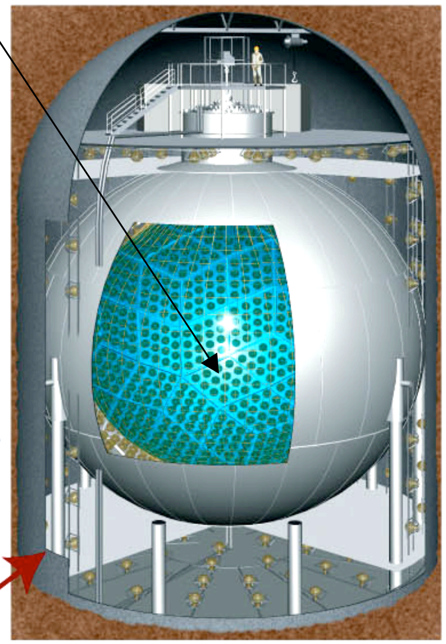
$\Delta m^2 \sim 10^{-5}\ eV^2$

# KamLAND

**1,000 ton liquid scintillator neutrino detector located at the former site of Kamiokande**

in $\Phi$=13m plastic balloon
seen by 1879 PMTs
VETO: 3.2 kt water

2700 mwe



## 1st phase experiment

**$E_{th}$ (trigger) 0.7 MeV**

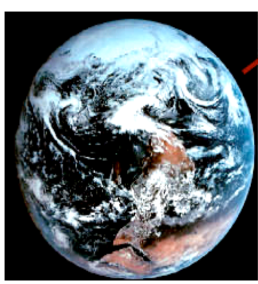
$\bar{\nu}_e + p \rightarrow e^+ + n$

○ **Neutrino Oscillation Search by Reactor Anti-neutrinos**

175 km

$\bar{\nu}_e$

**Terrestrial Anti-neutrino Detection**



$\bar{\nu}_e$

## 2nd phase experiment

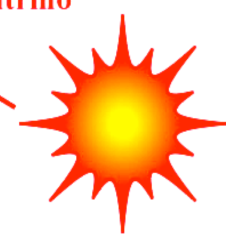
( $E_{th}$ = 200 keV)

$\nu_e + e^- \rightarrow \nu_e + e^-$

○ **Solar neutrino Detection**

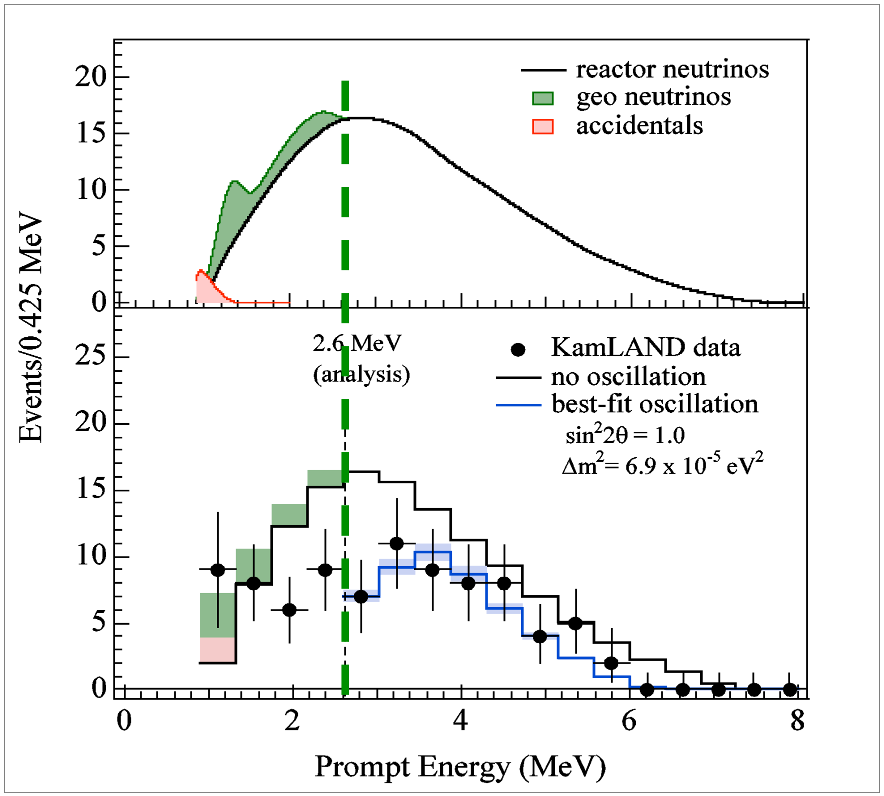
$^7$Be Neutrino

$\nu_e$

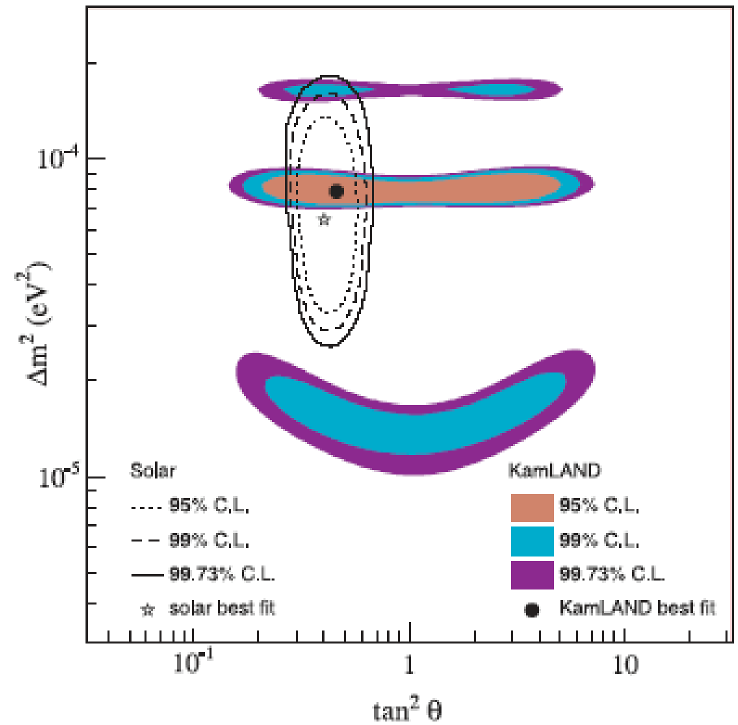


**supernova-burst ν, relic supernova ν, atmospheric ν, Proton Decays, ・・・**

# Results




Jun 2004
766 ton yr

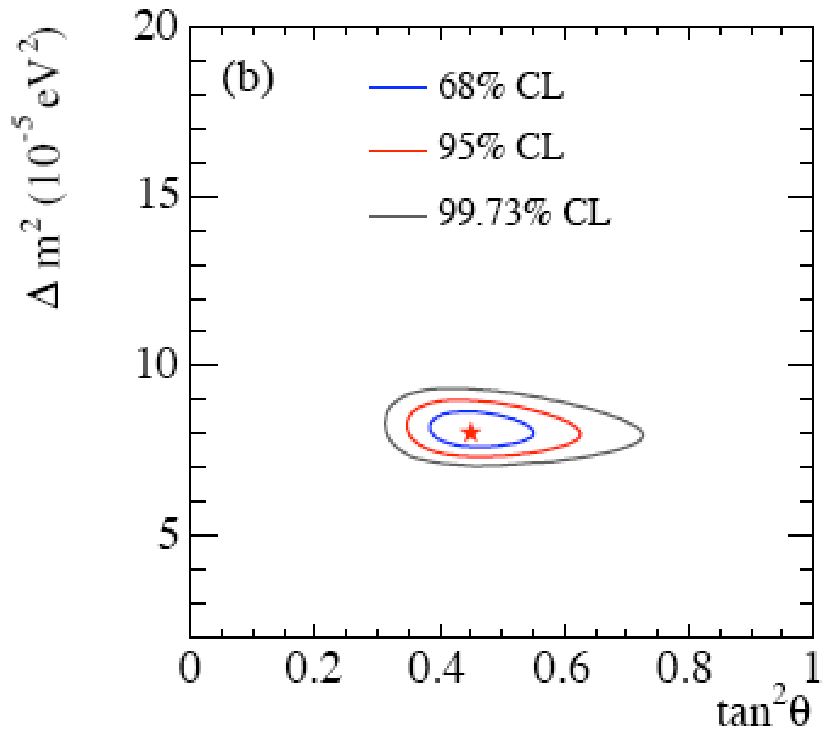



Deficit of events and distortion of positron E spectrum

$$\frac{N_{\mathrm{obs}} - N_{\mathrm{BG}}}{N_{\mathrm{NoOsc}}} = 0.611 \pm 0.085 \pm 0.041.$$

# Solar+KamLAND

B. Aharmim *et al.*, nucl-ex/0502021.




$(\theta = 33.9^{+2.4}_{-2.2})$.

$\Delta m^2 = 8.0^{+0.6}_{-0.4} \times 10^{-5}$ eV$^2$ and $\tan^2\theta = 0.45^{+0.09}_{-0.07}$