Solar Neutrino Experiments

Alain Bellerive

Canada Research Chair

Carleton University

Thanks to:

E. Bellotti, M. Boulay, J. Formaggio, V. Gavrin, K. Graham, K. Heeger, R. Hemingway, A. Ianni, A. Marino, M. Nakahata, A. Poon, Y. Takeuchi, J. Wilkerson

Outline

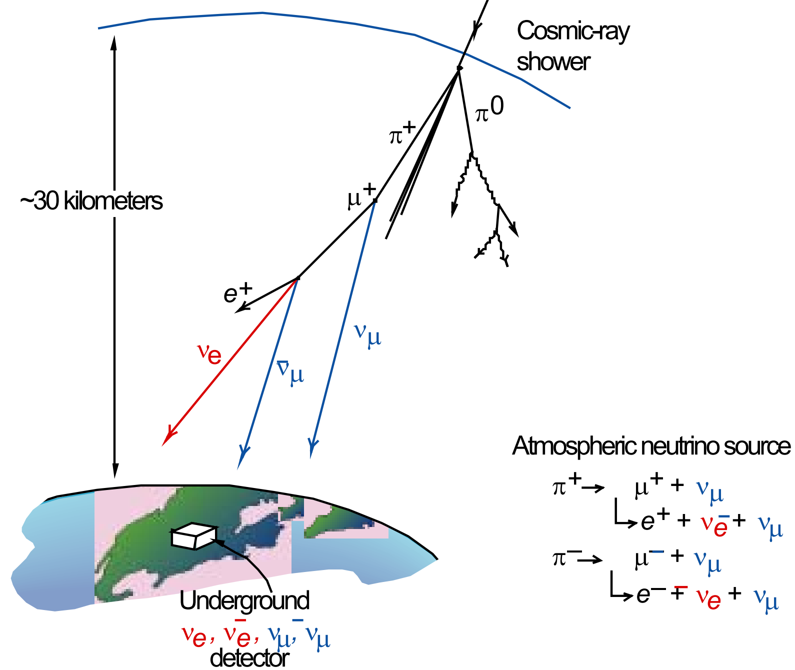
- Introduction
- First Generation of Solar Neutrino Experiments
    - ❖ Chlorine – Gallium – Kamiokande
- Standard Solar Model (SSM)
- Solar Neutrino Problem
- Neutrino Oscillation and Matter Effects
- Second Generation of Solar Neutrino Experiments
    - ❖ SuperK – SNO
- Constraints on Oscillation Parameters
- Future Prospects
- Summary and Conclusion

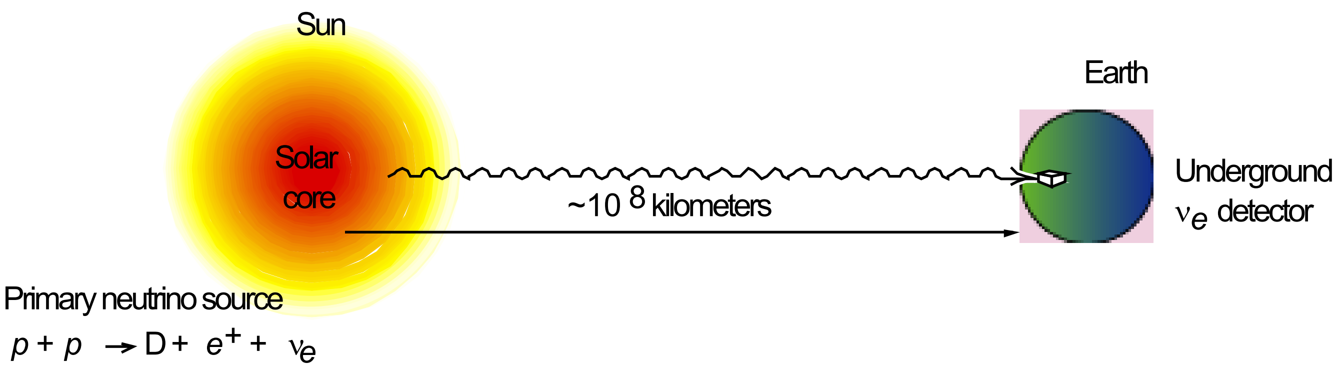
Evidence for Neutrino Oscillations

First evidence of neutrino oscillation

$$\frac{\nu_\mu}{\nu_e} \neq 2$$

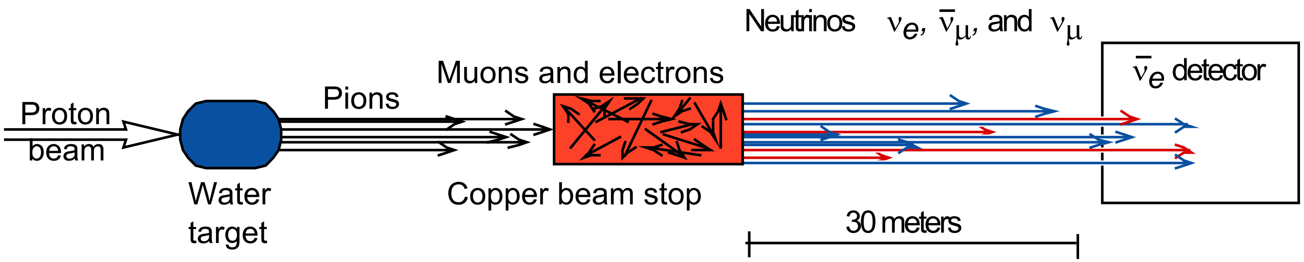
Atmospheric Neutrinos high energies





Solar Neutrinos low energies

Today's talk !!!



Neutrino Beams and Reactors

Tunable energies and distances!

Macroscopic Properties of the Sun

Mean Distance from the Earth: 1.5×10^{11}m

Mass: 2×10^{30} kg

Radius: 6.96×10^{8} m

Luminosity: 3.8×10^{26} W

Neutrino flux: 6.5×10^{10} cm^{-2} s^{-1}

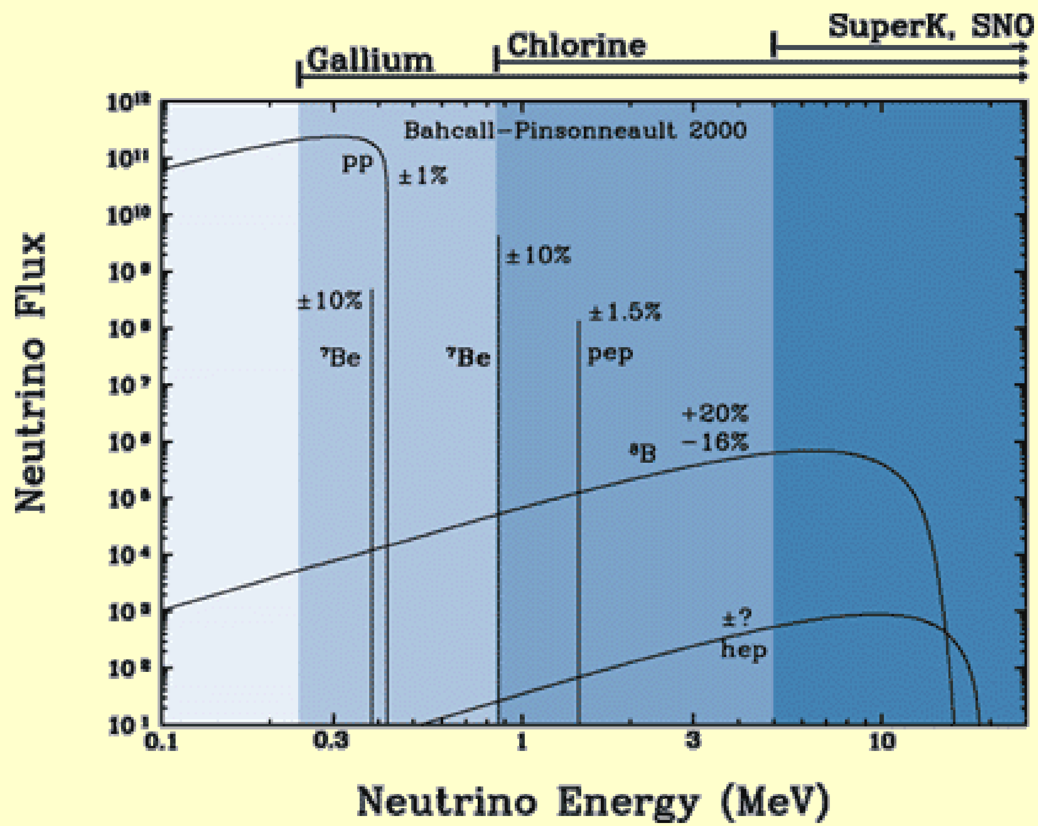
SNU: Product of solar neutrino fluxes (measured or calculated) and calculated cross-sections

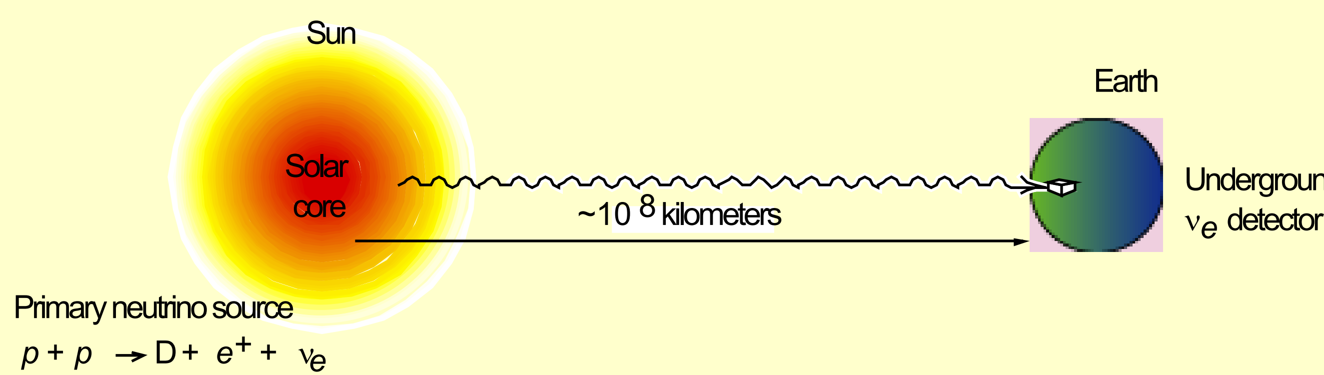
1 SNU $\equiv$ 1 capture per s & per 10^{36} target atoms

Neutrino Production in the Sun

Light Element Fusion Reactions

$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$	99.75 %
$p + e^{-} + p \rightarrow {}^{2}H + \nu_e$	0.25 %
${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$	~10^{-5} %
${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$	15 %
${}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e$	0.02 %



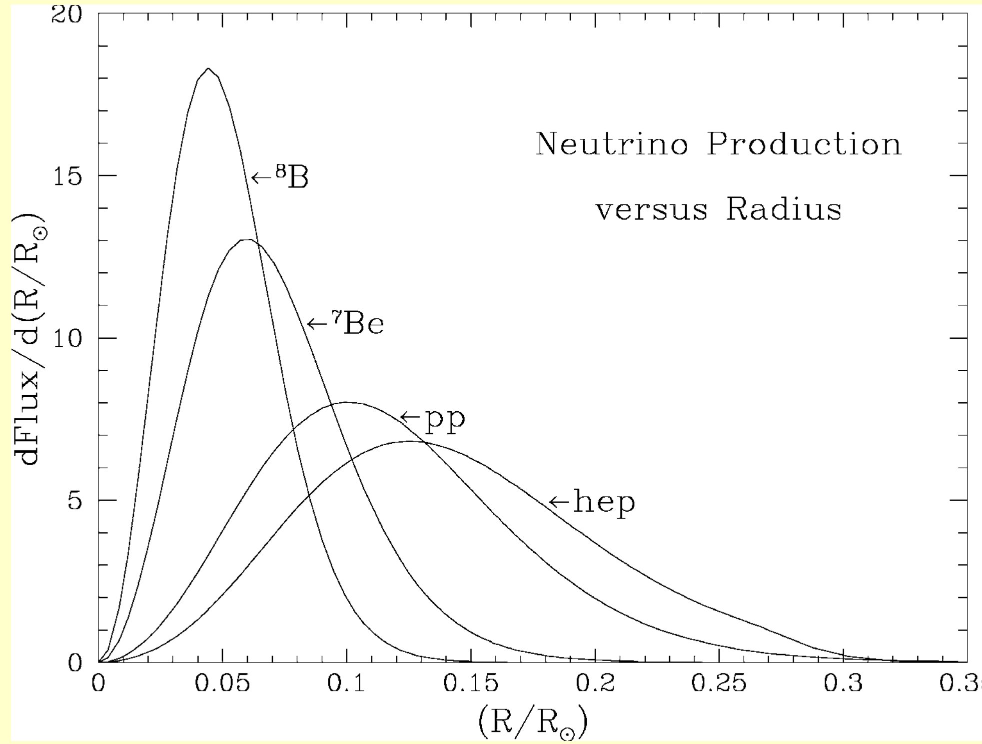


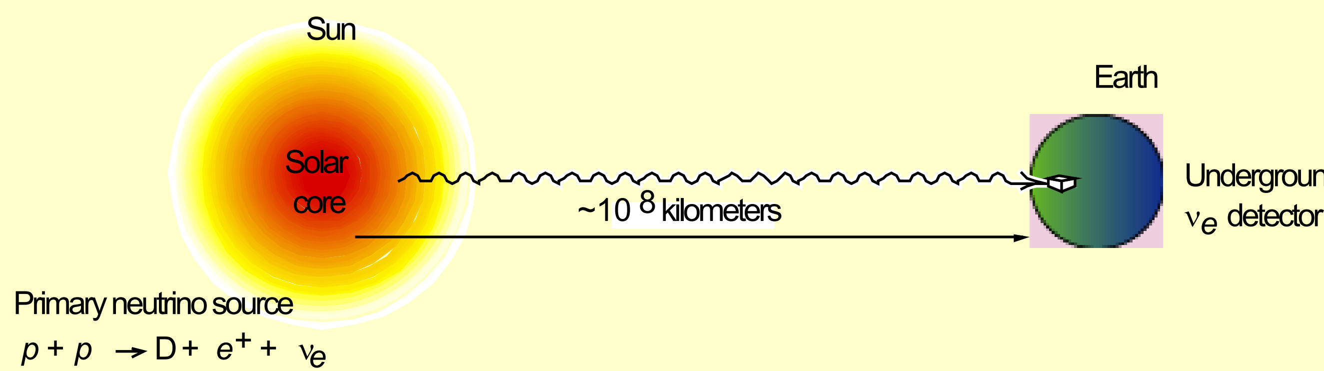
Neutrino Production in the Sun

Light Element Fusion Reactions

$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$	99.75 %
$p + e^{-} + p \rightarrow {}^{2}H + \nu_e$	0.25 %
${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$	~10^{-5} %
${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$	15 %
${}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e$	0.02 %

Neutrino Production Radius





Chlorine Measurements: Homestake

- 1960's: $^{37}\mathbf{Cl} + \nu_e \rightarrow$ $^{37}\mathbf{Ar} + \mathbf{e}^-$
  Construction of the Chlorine detector by Ray Davis
- Depth: 4850 ft
- Detector fluid: 3.8 x 10^5 l of C_2Cl_4
- Energy Thresold: 0.814 MeV
- 1970 – 1995
  Measurements of solar ν flux
  Sensitive to ^{8}B & ^{7}Be ν's
- **Observed rate (SNU)**
  2.56 ± 0.16(stat) ± 0.16(syst)
- **Expected rate (SNU)**
  $\mathbf{7.6}\ ^{+1.3}_{-1.1}$ **[1σ from BP2000]**

Cleveland et al.,Ap. J. 496, 505(1998)

Gallium Experiments

$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$

Radiochemical Target

Small proportional counters are used to count the Germanium

Energy Threshold: 0.233 MeV

Sensitive to pp, ^{7}Be, ^{8}B, CNO, and pep ν's

SAGE: Russian-American Gallium solar neutrino Experiment (INR RAS)

- A liquid metal target which contains 50 tons of gallium.

- **GALLEX/GNO**: Gallium Neutrino Observatory in Gran Sasso

- 30 tons of natural gallium in an aqueous acid solution.

Gallium Experiments

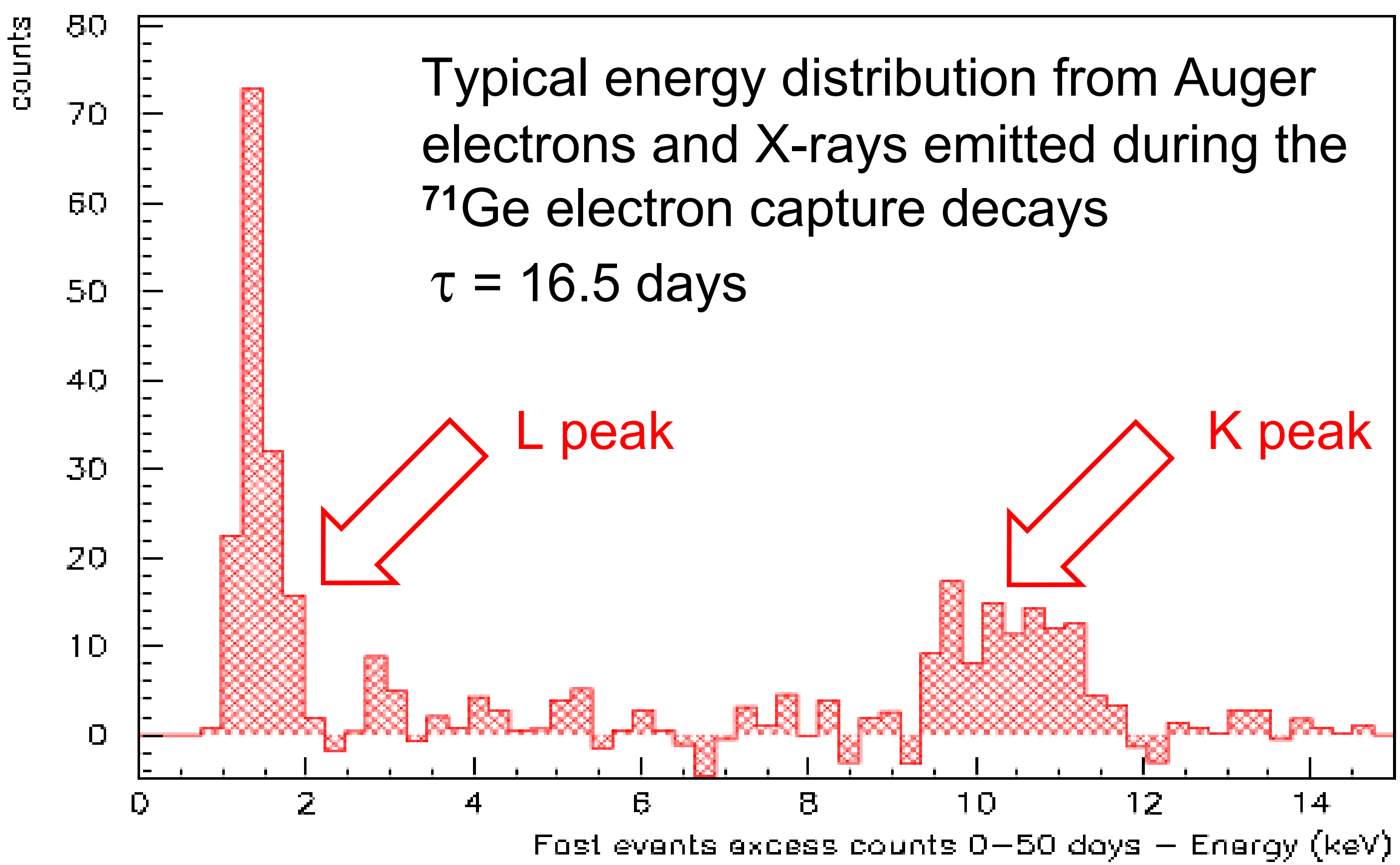
$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$

Radiochemical Target

Energy Threshold: 0.233 MeV

Small proportional counters are used to count the Germanium

Sensitive to pp, ^{7}Be, ^{8}B, CNO, and pep ν's



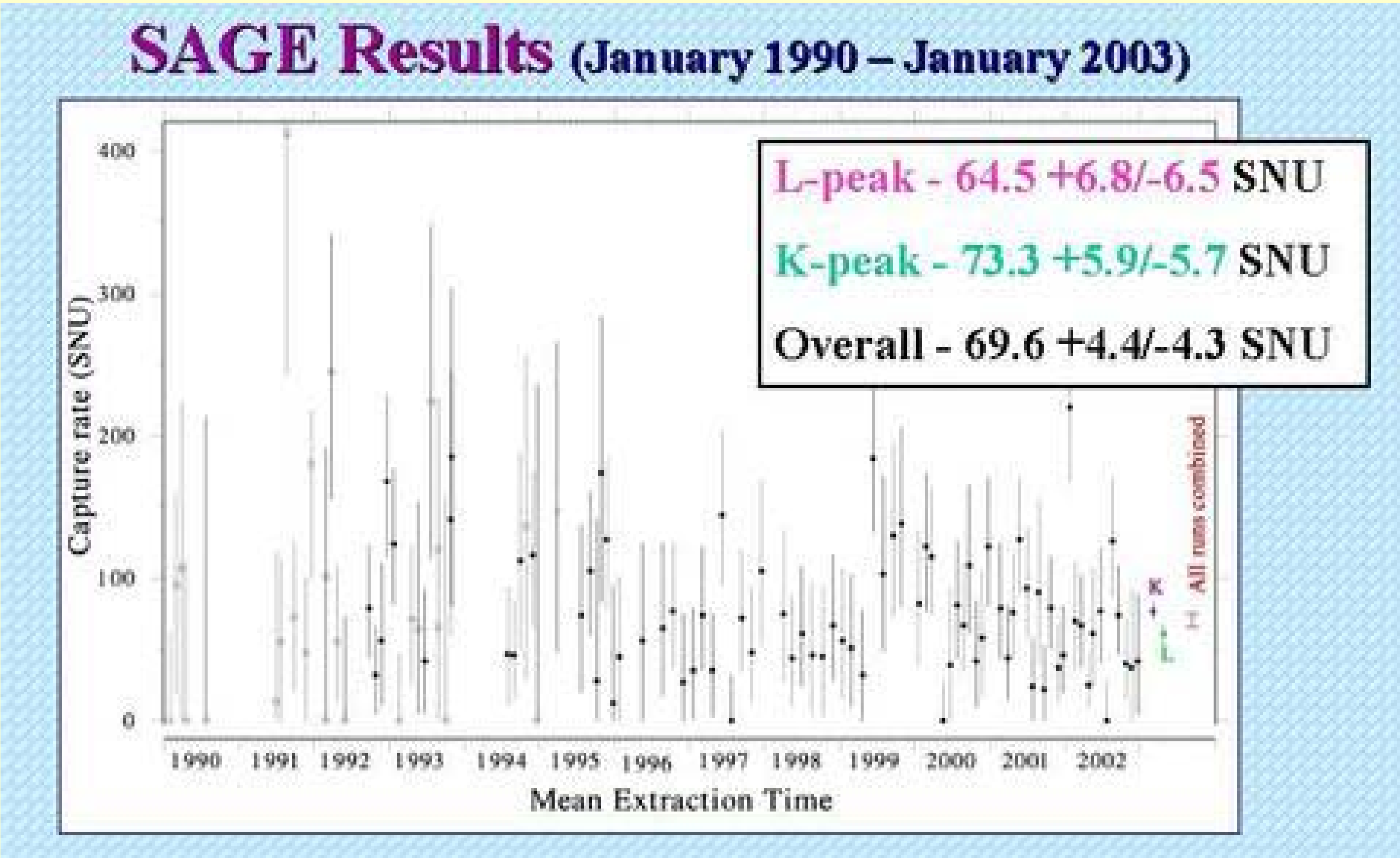
Gallium Measurements: SAGE (LowNu03)

SAGE overall 1990-2003 NEW

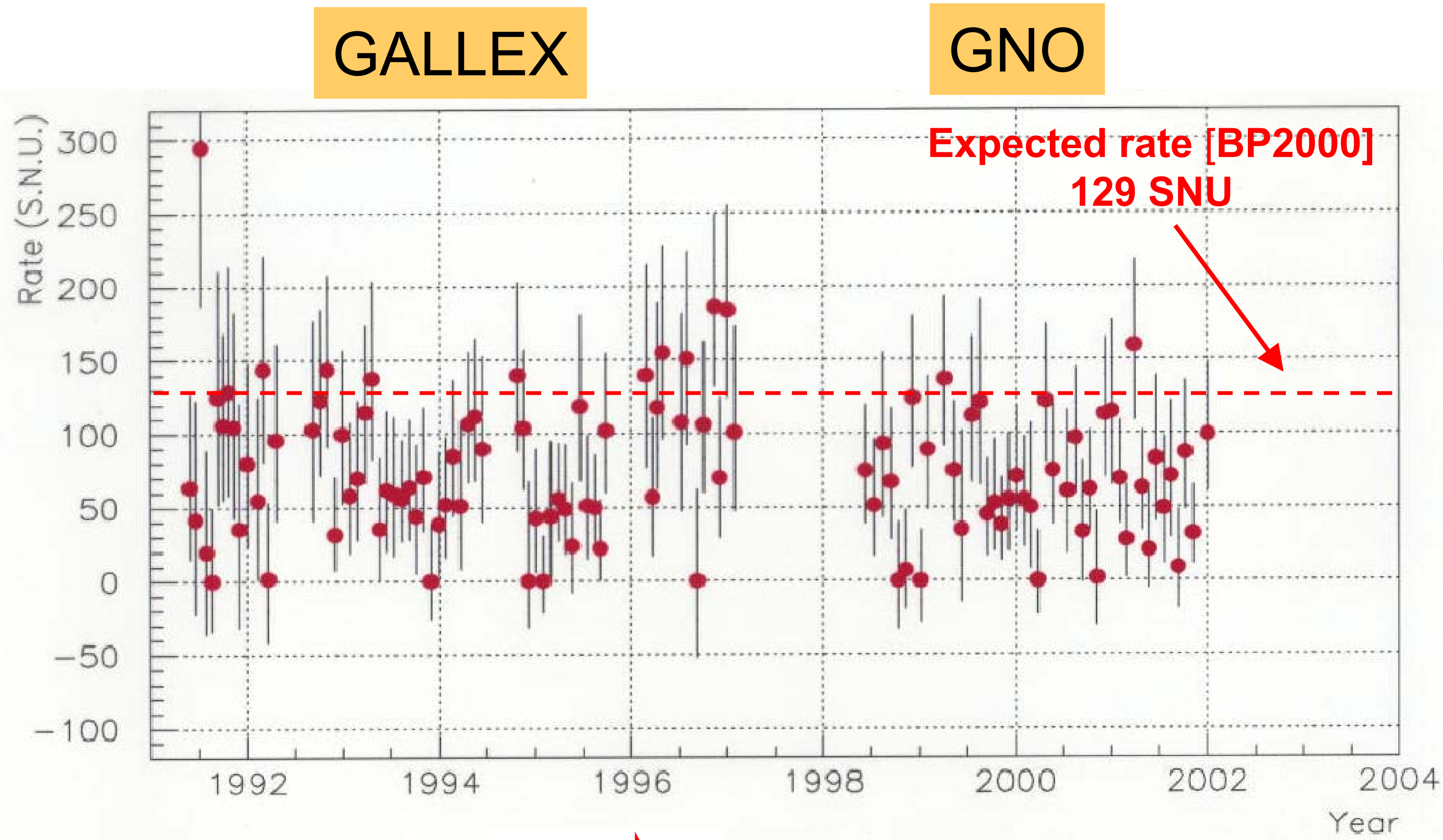
$69.6\ ^{+4.4}_{-4.3}$ (stat) $^{+3.7}_{-3.2}$ (syst) SNU

Expected rate [1σ from BP2000]

$129\ ^{+9}_{-7}$ SNU



Gallium Measurements: GALLEX + GNO



GALLEX → 77.5 +– 6.2 (stat) +– 4.5 (sys) SNU

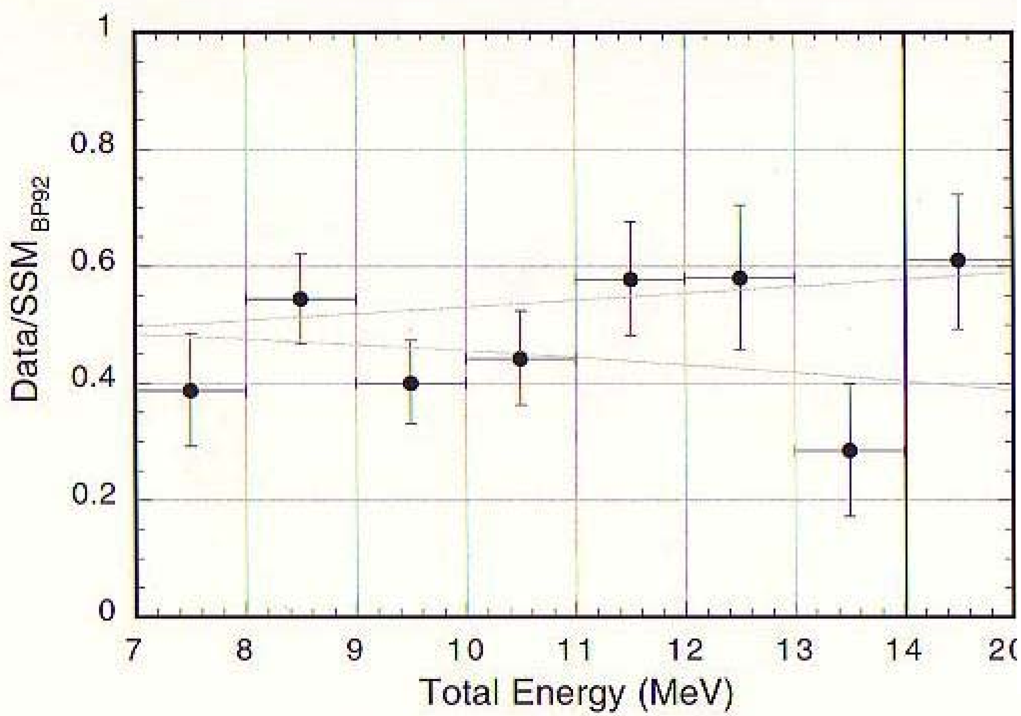
GNO → 65.2 +– 6.4 (stat) +– 3.0 (sys) SNU

GNO+GALLEX → 70.8 +– 4.5 (stat) +– 3.8 (sys) SNU

Water Measurements: Kamiokande

Energy spectrum of solar neutrino events

January 87 – February 95 $\Rightarrow$ Kamiokande II and III (2079 days)



Real-time Cerenkov Detector

2140 tons of water
948 PMTs

Energy Thresold
7 MeV

Sensitive to ^8B neutrinos

Based on ~600 solar ν events $\Rightarrow$ mainly ν_e

ES

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

Y.Fukuda et al., Phys. Rev. Lett. 77 (1996) 1683

Water Detector: Super-Kamiokande

- ^{8}B neutrino measurement by

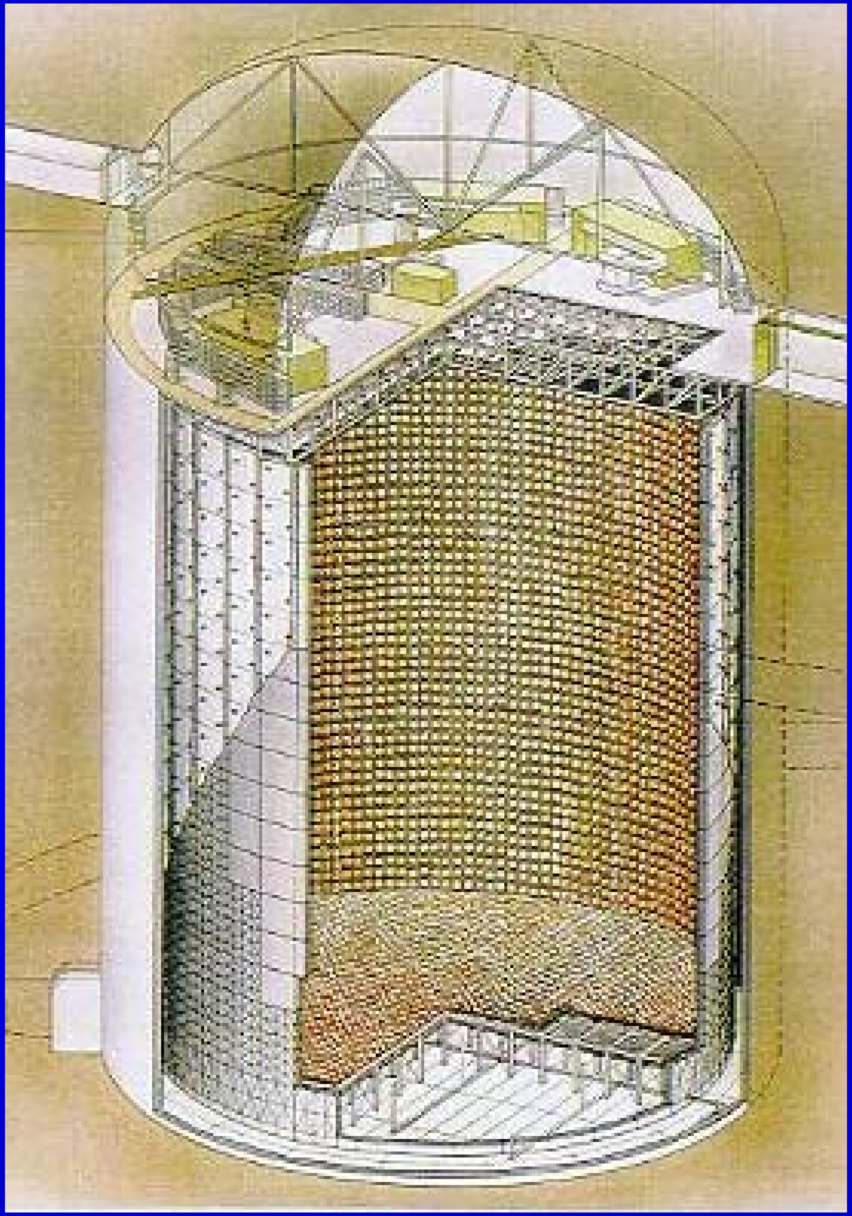
  $$\nu_x + e^- \rightarrow \nu_x + e^-$$

- Sensitive to ν_e, ν_μ, ν_τ

  $\sigma(\nu_{\mu,\tau} + e^-) \approx 0.15 \times \sigma(\nu_e + e^-)$

- High statistics ~15ev./day
- Real time measurement allow studies on time variations
- Studies energy spectrum

- 50 ktons of pure water with 11,146 PMTs (fiducial volume of 22.5 ktons for analysis)



Water Measurements: Super-Kamiokande

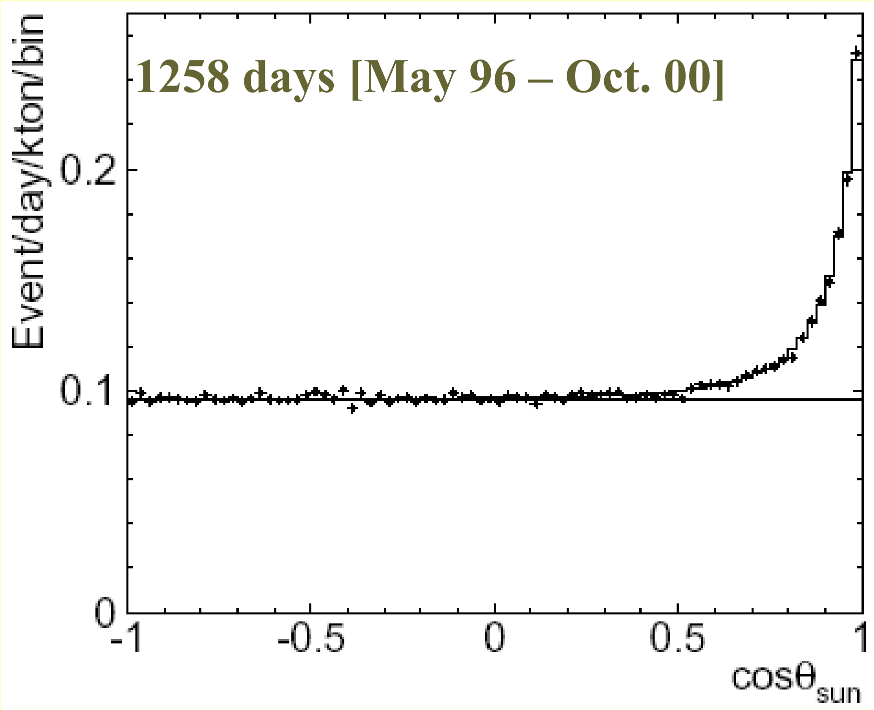
$$\Phi = 2.32 \pm 0.03\ (\text{stat})^{+0.08}_{-0.07}\ (\text{syst}) \times 10^{6}\ \text{cm}^{-2}\ \text{s}^{-1}$$

$$(\Phi_{night} - \Phi_{day}) / \Phi_{average} = 0.033 \pm 0.022\ (\text{stat})^{+0.013}_{-0.012}\ (\text{syst})$$

- Kamiokande & SuperK provided the first evidence of neutrino production in the core of the Sun with directional information
- Energy threshold:

  6.5 MeV (1996)

  5.5 MeV (1997-2000)



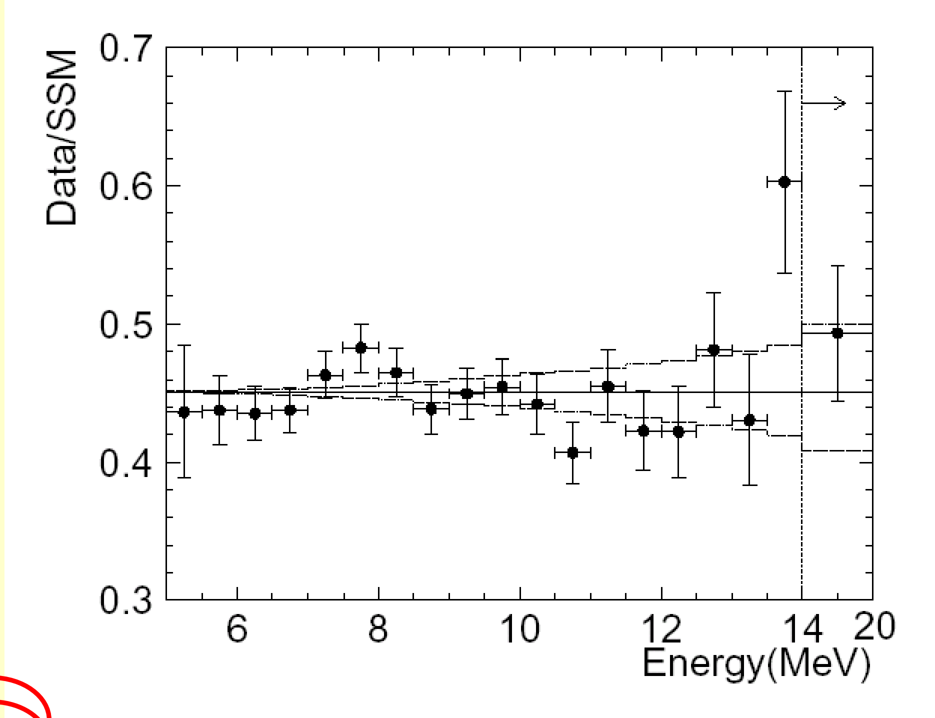
Phys.Rev.Lett.86:5651-5655,2001

Water Measurements: Super-Kamiokande

$$\Phi = 2.32 \pm 0.03\ (\text{stat})\ ^{+0.08}_{-0.07}\ (\text{syst})\ \text{x}\ 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$$

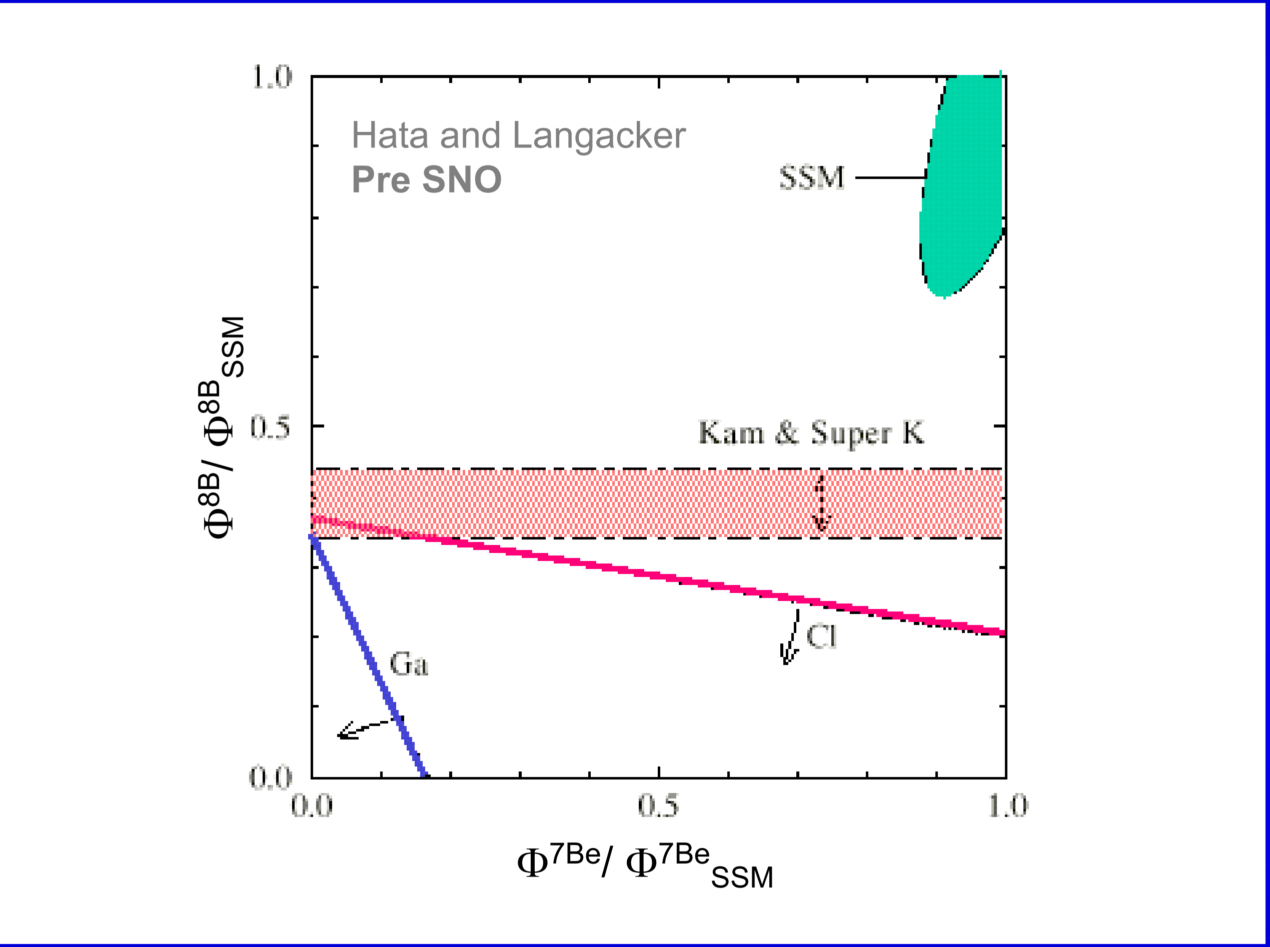
$$(\Phi_{night} - \Phi_{day}) / \Phi_{average} = 0.033 \pm 0.022\ (\text{stat})\ ^{+0.013}_{-0.012}\ (\text{syst})$$

- Kamiokande & SuperK provided the first evidence of neutrino production in the core of the Sun with directional information
- Energy threshold:
  - 6.5 MeV (1996)
  - 5.5 MeV (1997-2000)
- No spectral distortion
- hep (90% C.L. UL) $40\text{x}10^3\ \text{cm}^{-2}\ \text{s}^{-1}$
  i.e. 4.3 the expected rate (BP2000)



Phys.Rev.Lett.86:5651-5655,2001

Astrophysical Solutions?



The data are incompatible with the Standard Solar Model !!!

Solar ν Flux Measurement Results

Experiment	Year	Detection Reaction	Ratio Exp/BP2000
Chlorine (127 t)	1970-1995	$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$	0.34 ± 0.03
Kamiokande (680t)	1986-1995	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.54 ± 0.08
SAGE (23 t)	1990-	$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$	0.55 ± 0.05
Gallex + GNO (12 t)	1991-	$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$	0.57 ± 0.05
SuperK (22kt)	1996-	$\nu_x + e^- \rightarrow \nu_x + e^-$	$0.451^{+0.017}_{-0.015}$

Chlorine – Gallium – Water experiments have different energy threshold

!!! The data suggest an energy dependence !!!

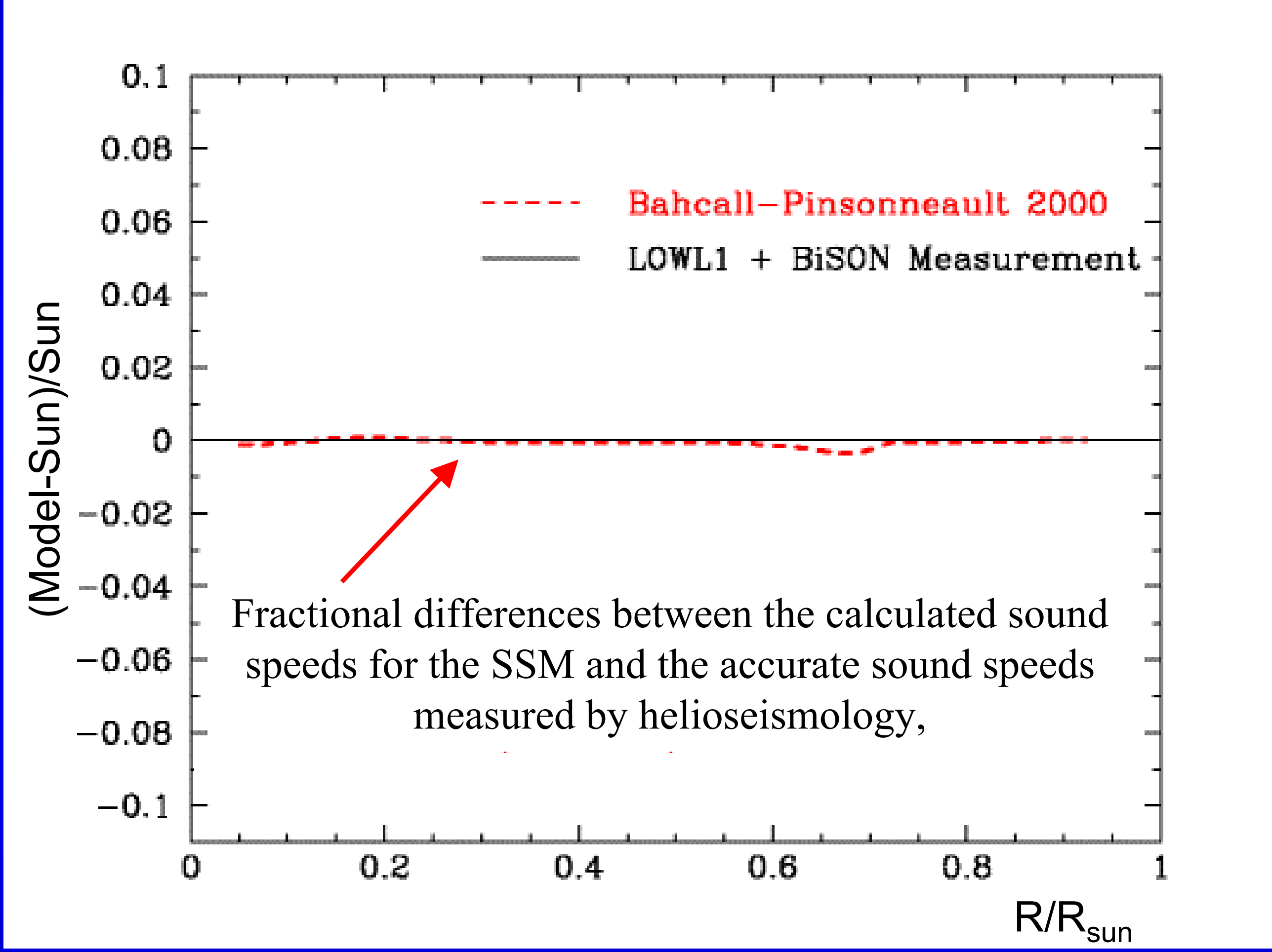
??? What could explain such a variation ???

Solar Neutrino Problem

- Historically the first culprit was assumed to be the method of determining the solar ν flux.
- In fact, the last 30 years showed that the SSM provides and accurate description of the macroscopic properties of our Sun.
- The mass, radius, shape, luminosity, age, chemical composition, and photon spectrum of the Sun are precisely determined and used as input parameters.
- Equation of state relates pressure and density; while the radiative opacity dictates photon transport.
- Experimental fusion cross sections used to determined the nuclear reaction rates.

Test of Standard Solar Model

SSM determines the present distribution of physical variables inside the Sun (like the core temperature and density), photon spectrum, the speed of sound, , and the neutrino fluxes.



Neutrino Mixing: Pontecorvo

- As in the quark sector, it is possible to define a neutrino mixing matrix which relates the mass and weak eigenstates

Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{\alpha i} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$

Solar Neutrino Oscillations

$P_{ee} = \sin^2(2\theta)\,\sin^2(1.27\Delta m^2\, L / E)$

- **Physics:**

  Δm^2 & $\sin(2\theta)$

- **Experiment:**

  Distance (L) & Energy (E)

$$\Delta m^2 \equiv \Delta m_{12}^2 \text{ and } \theta \equiv \theta_{12}$$

3 Parameters !

$$\Delta m^2 = m_2^2 - m_1^2$$

$$\theta = \text{Mixing angle}$$

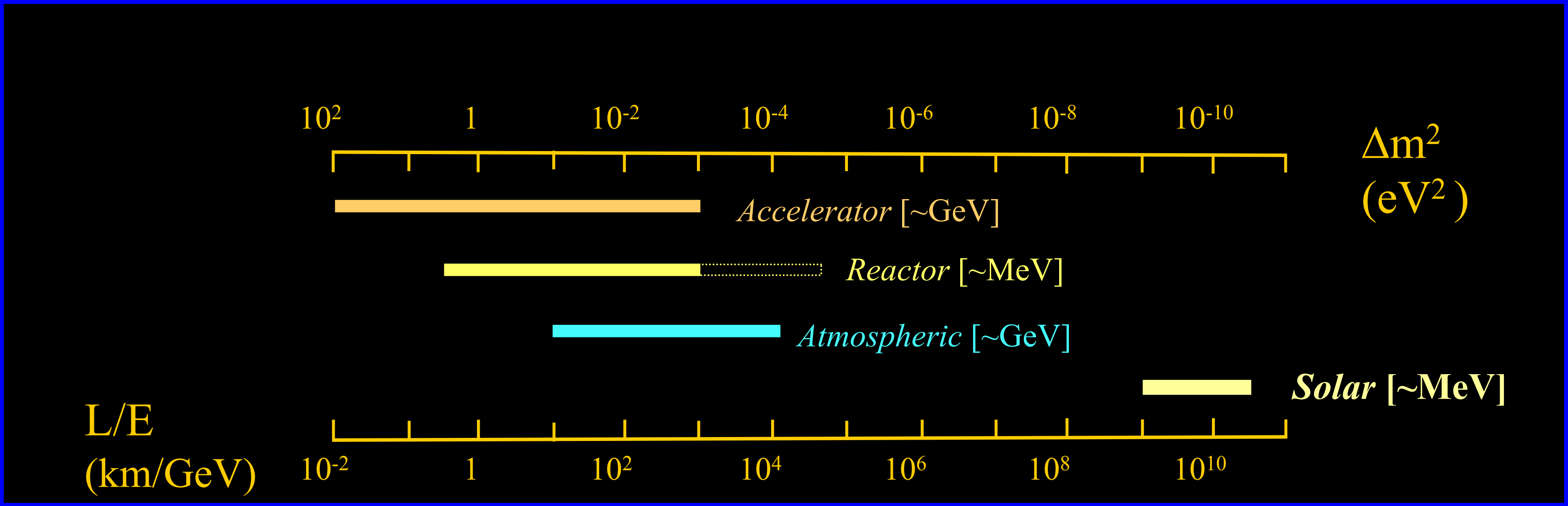
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The state evolves with time or distance

Sensitivity to ν oscillations

Vacuum Oscillations

- Different types of experiments sensitive to different aspects of oscillation space



MSW = Mikheyev – Smirnov - Wolfenstein

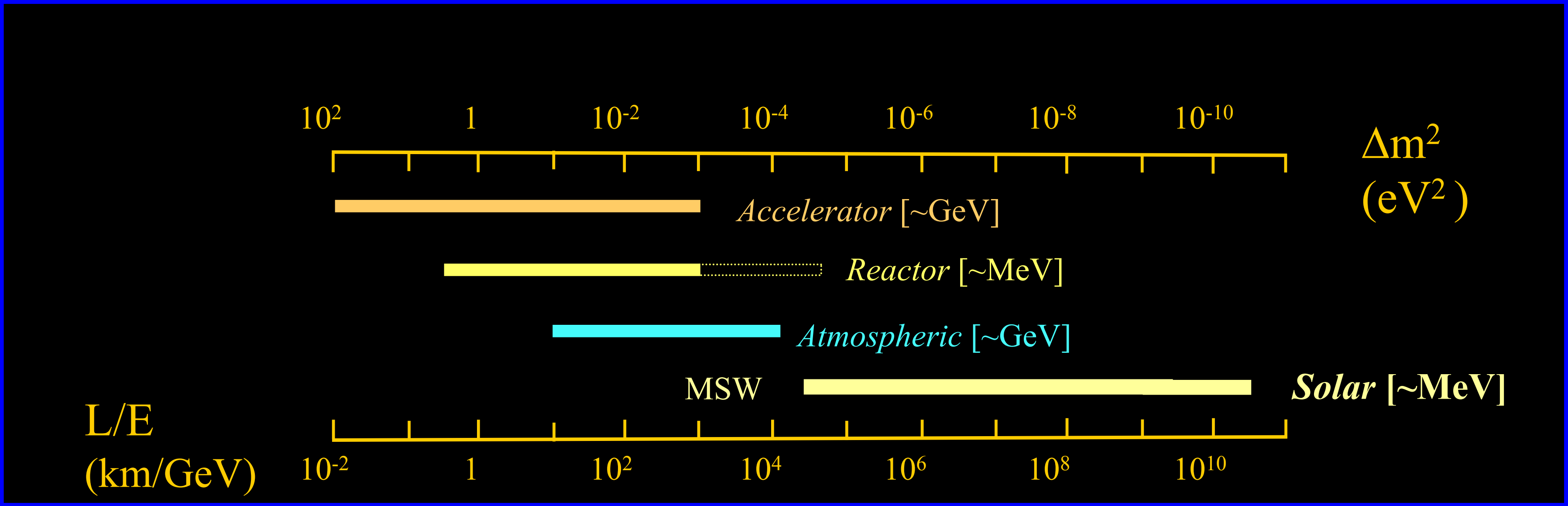
Sensitivity to ν oscillations

Vacuum Oscillations

- Different types of experiments sensitive to different aspects of oscillation space

MSW Oscillations

- For ν's in matter can acquire an effective mass through scattering, enhancing oscillations



MSW = Mikheyev – Smirnov - Wolfenstein

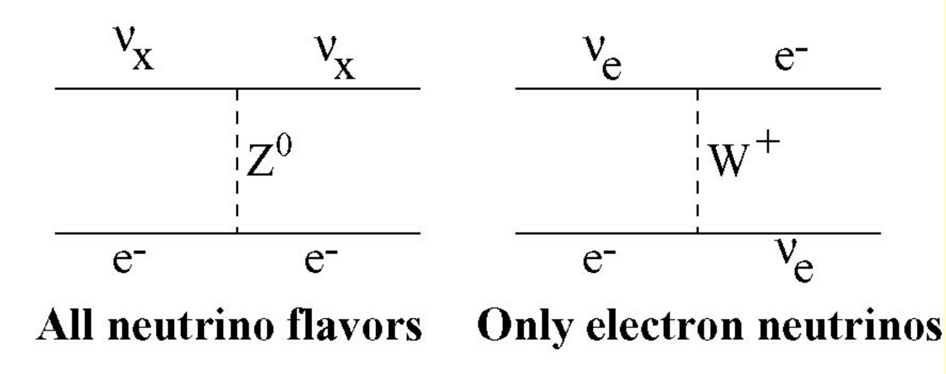
Matter-Enhanced Neutrino Oscillations

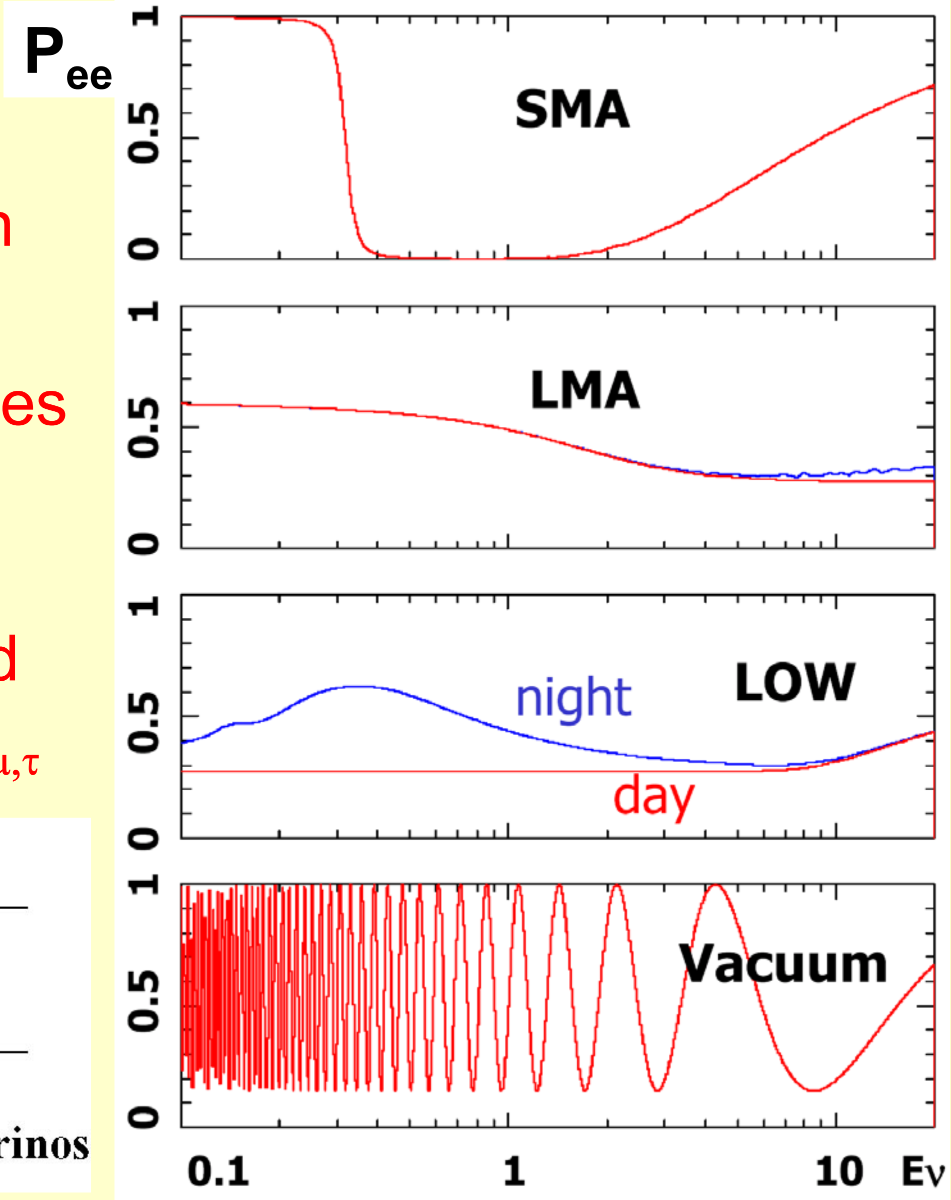
Neutrinos produced in weak state ν_e

$\Rightarrow$ High density of electrons in the Sun

$\Rightarrow$ Superposition of mass states $\nu_{1,2,3}$ changes through the MSW resonance effect

$\Rightarrow$ Solar neutrino flux detected on Earth consists of $\nu_e + \nu_{\mu,\tau}$

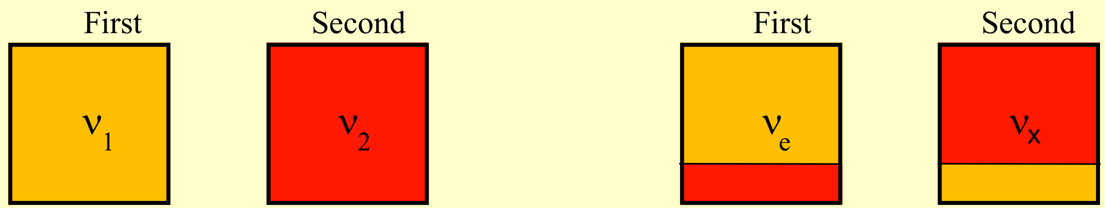




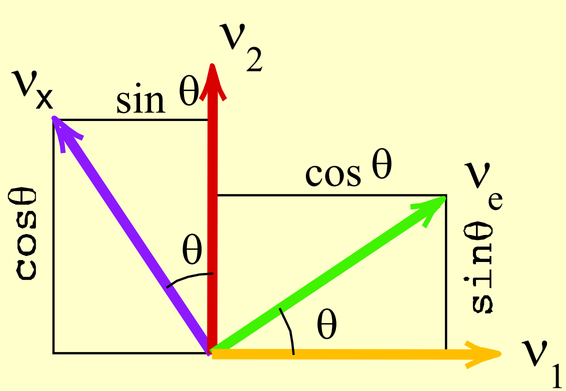
Neutrino Oscillations

Neutrino States

Mass States **Weak States**



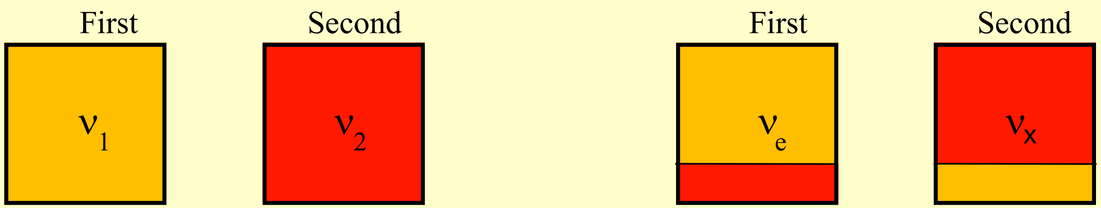
$$\begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



Neutrino Oscillations

Neutrino States

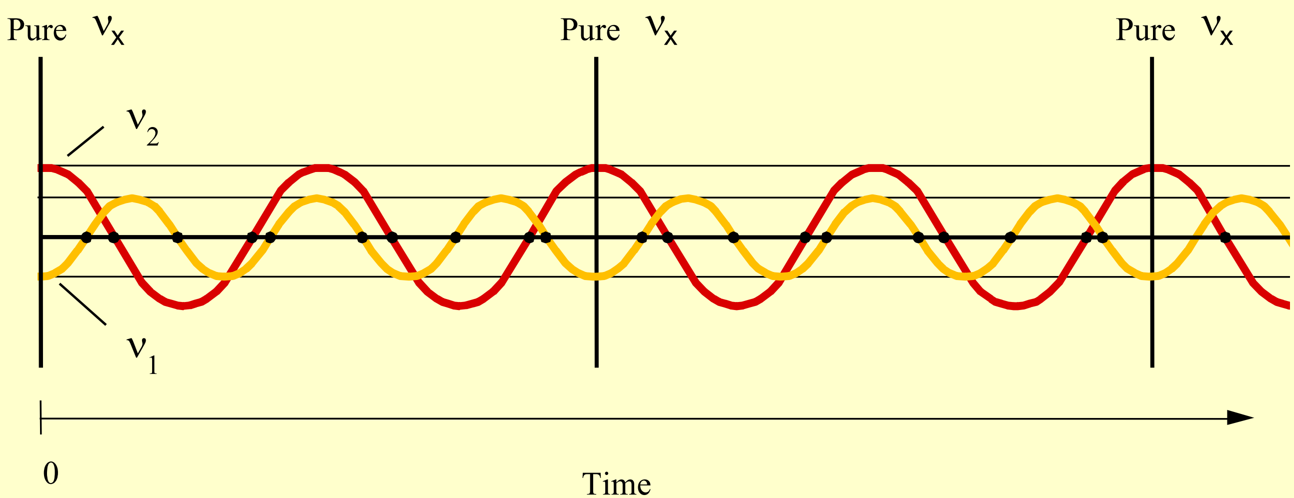
Mass States **Weak States**



$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix}=\frac{1}{2}\mathrm{T}\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix}$$

$$\mathrm{T}=\begin{pmatrix}-\dfrac{\Delta m^2}{4E}\cos 2\theta & \dfrac{\Delta m^2}{4E}\sin 2\theta\\ \dfrac{\Delta m^2}{4E}\sin 2\theta & \dfrac{\Delta m^2}{4E}\cos 2\theta\end{pmatrix}$$

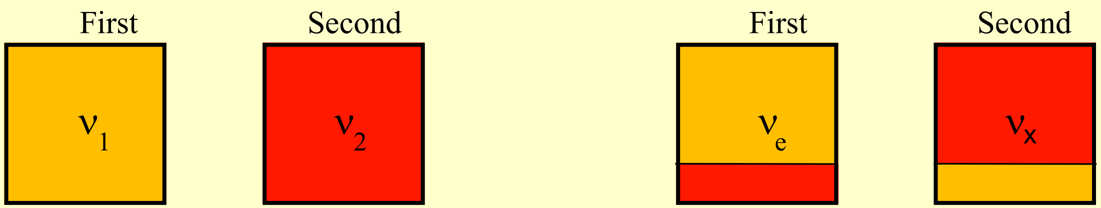
Time Evolution



Neutrino Oscillations in matter

Neutrino States

Mass States **Weak States**



Time Evolution

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix}$$

$$\mathrm{T} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}$$

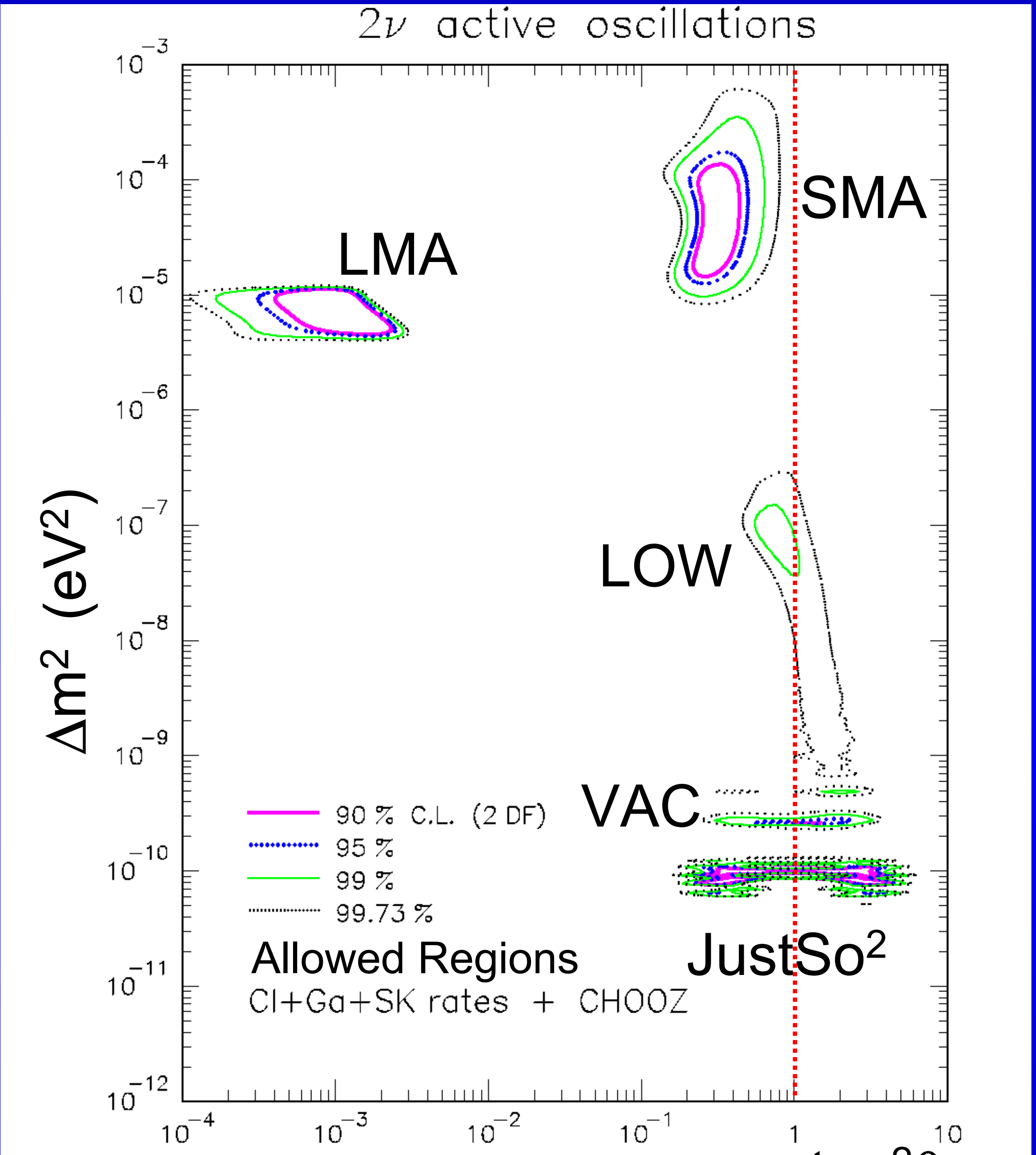
$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\omega - \cos 2\theta)^2 + \sin^2 2\theta}$$

$$\omega = -\sqrt{2}G_F N_e E / \Delta m^2$$

Mixing Parameters

Combination of the Chlorine, Gallium, SK, and CHOOZ restricted the mixing parameters

Pre SNO



Phys.Rev. D64 (2001) 093007

SK and SNO

SuperK

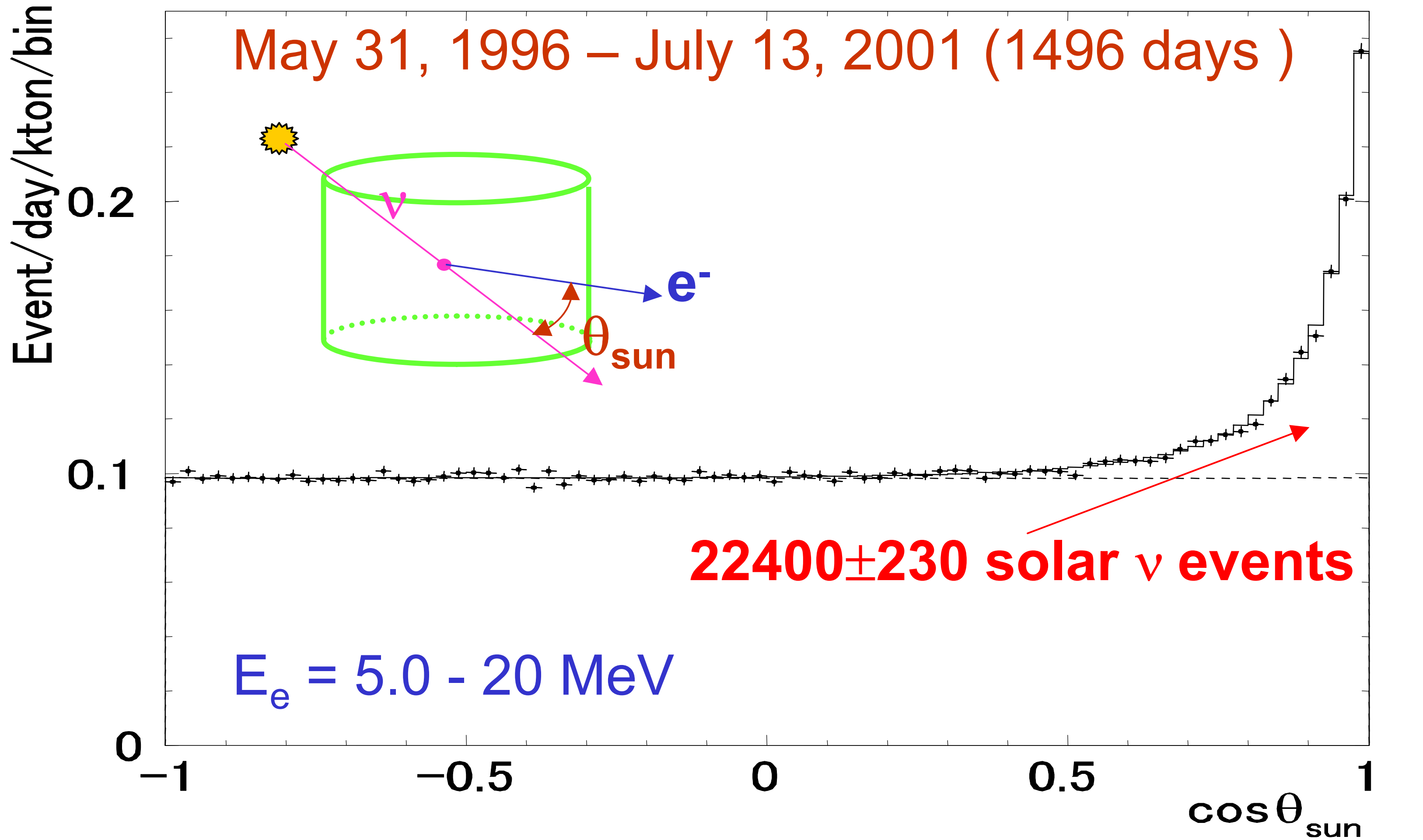
- Time variation and spectral distortion
- Search for anti-ν_e

SNO

- Measurement of Φ_e and Φ_{total}
- Day/Night fluxes

OVERAL PICTURE

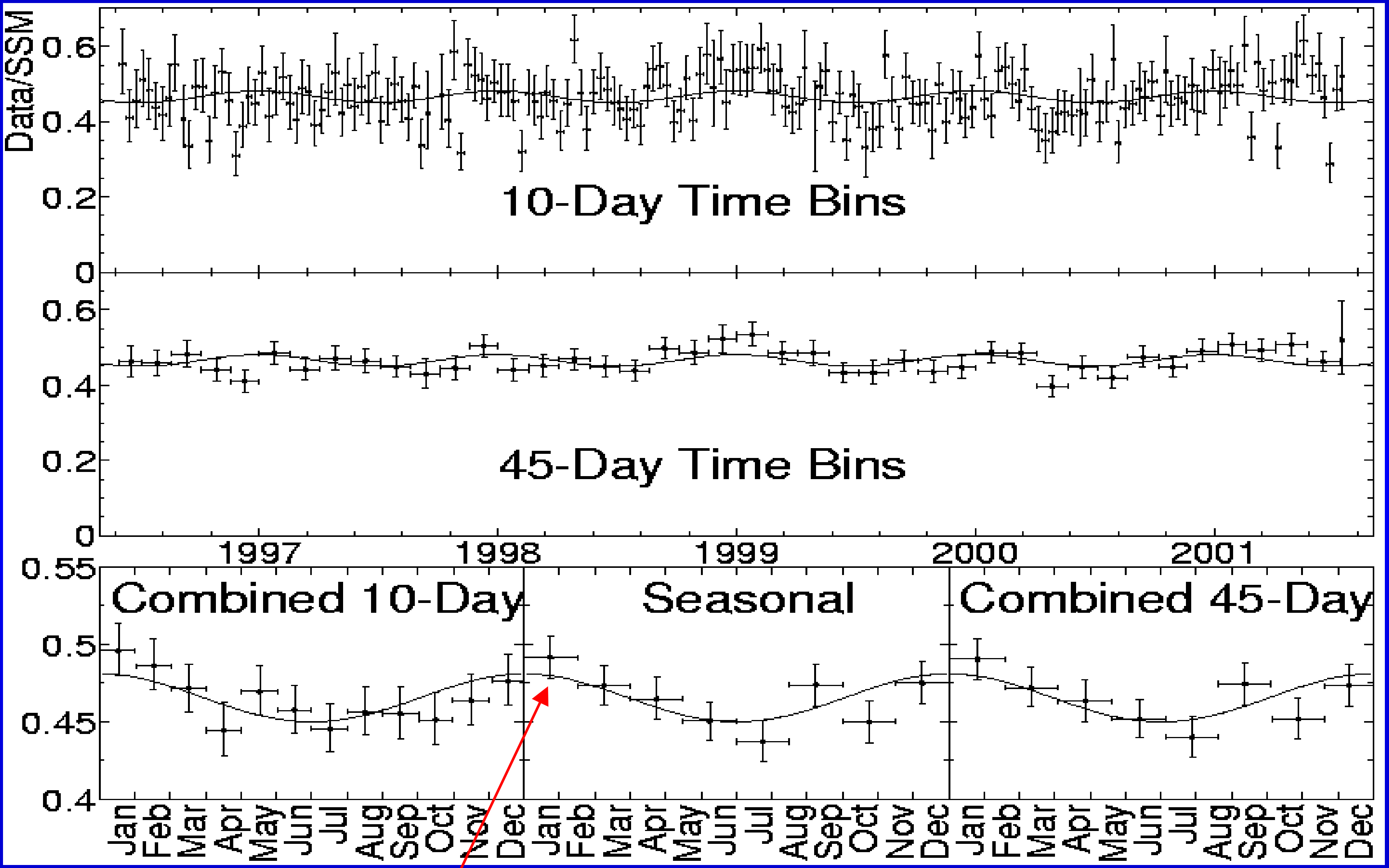
Solar neutrino data in SK (period I)



^{8}B flux : 2.35 ± 0.02 ± 0.08 [x 10^{6} /cm^{2}/sec]

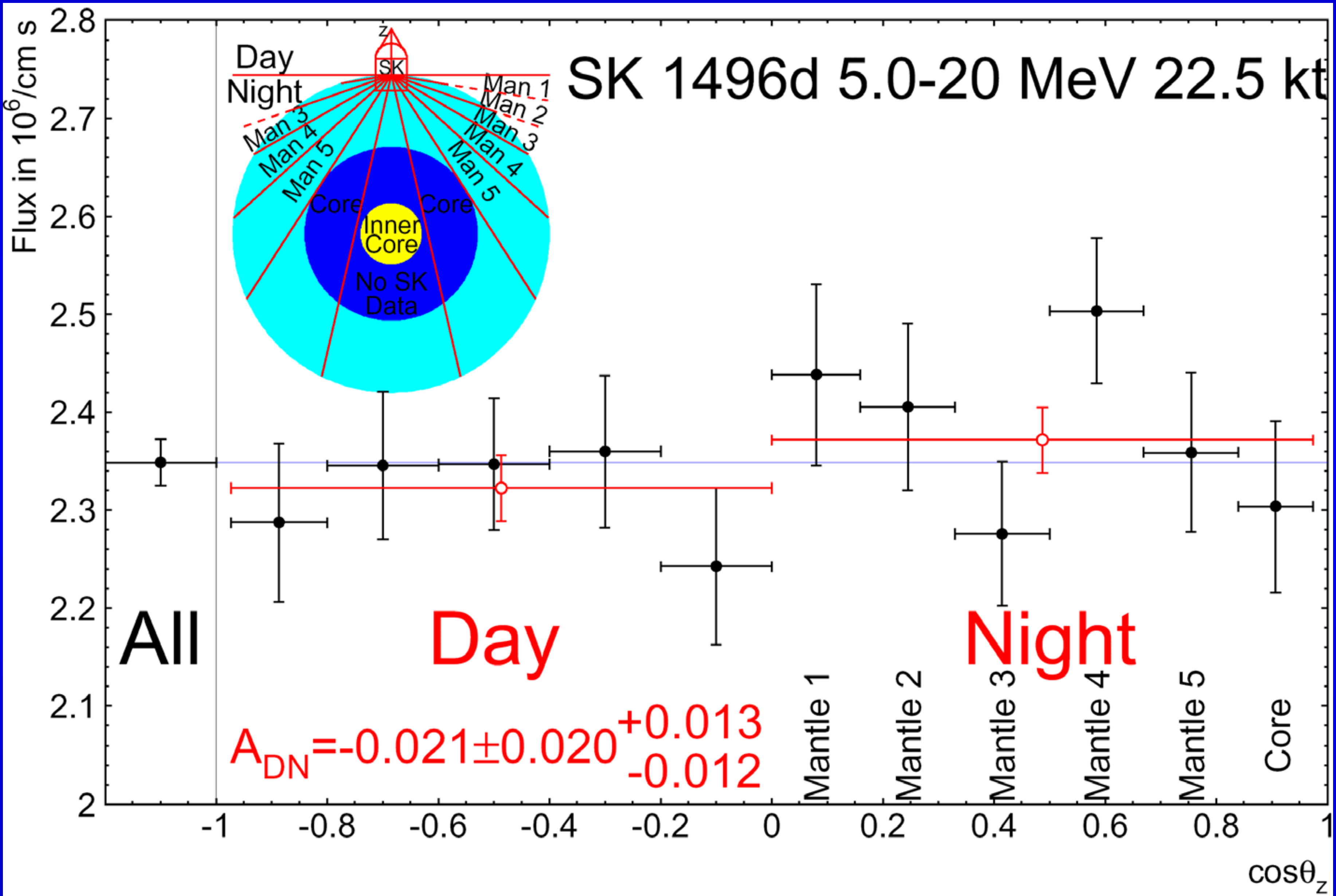
$$\frac{\text{Data}}{\text{SSM(BP2001)}} = 0.465 \pm 0.005 ^{+0.016}_{-0.015}$$

Time variation of the solar neutrino flux



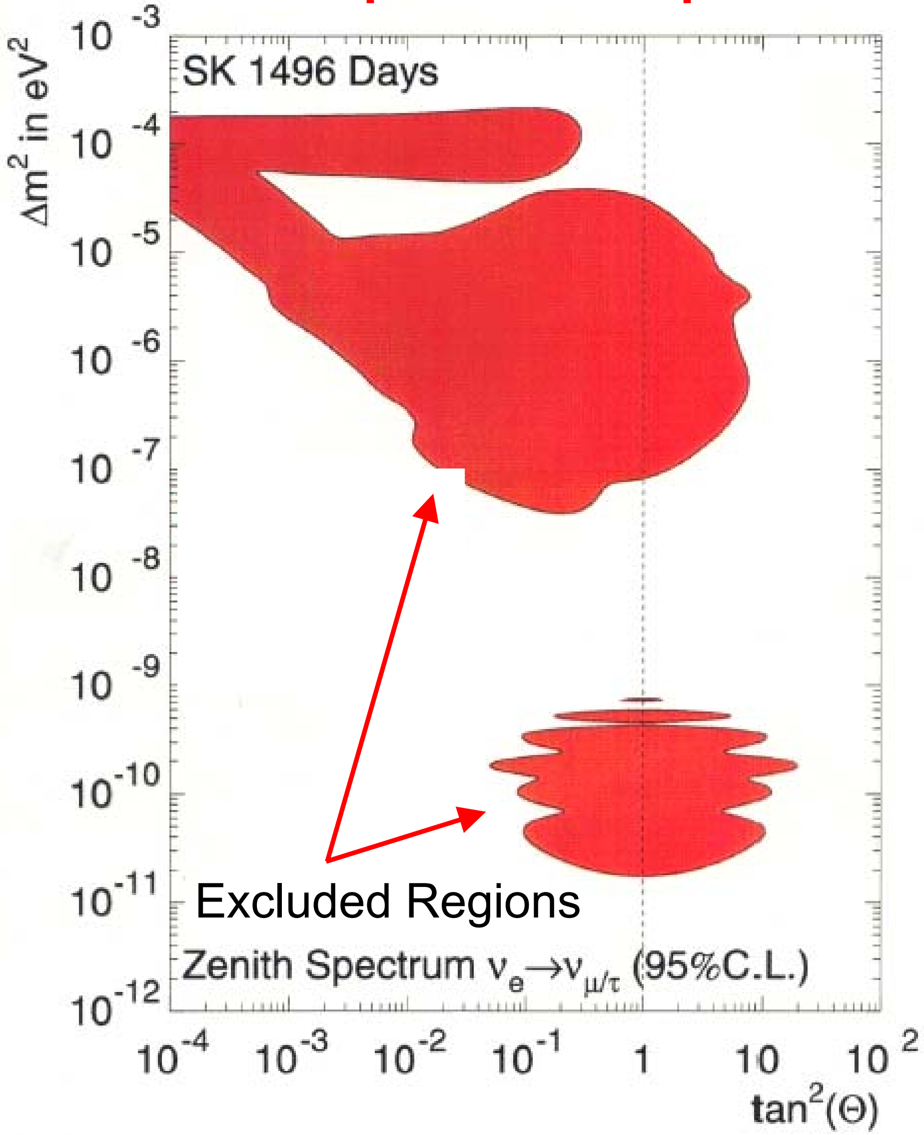
Expected time variation by eccentricity ($1/r^2$)

Daily Variation of SK Rate

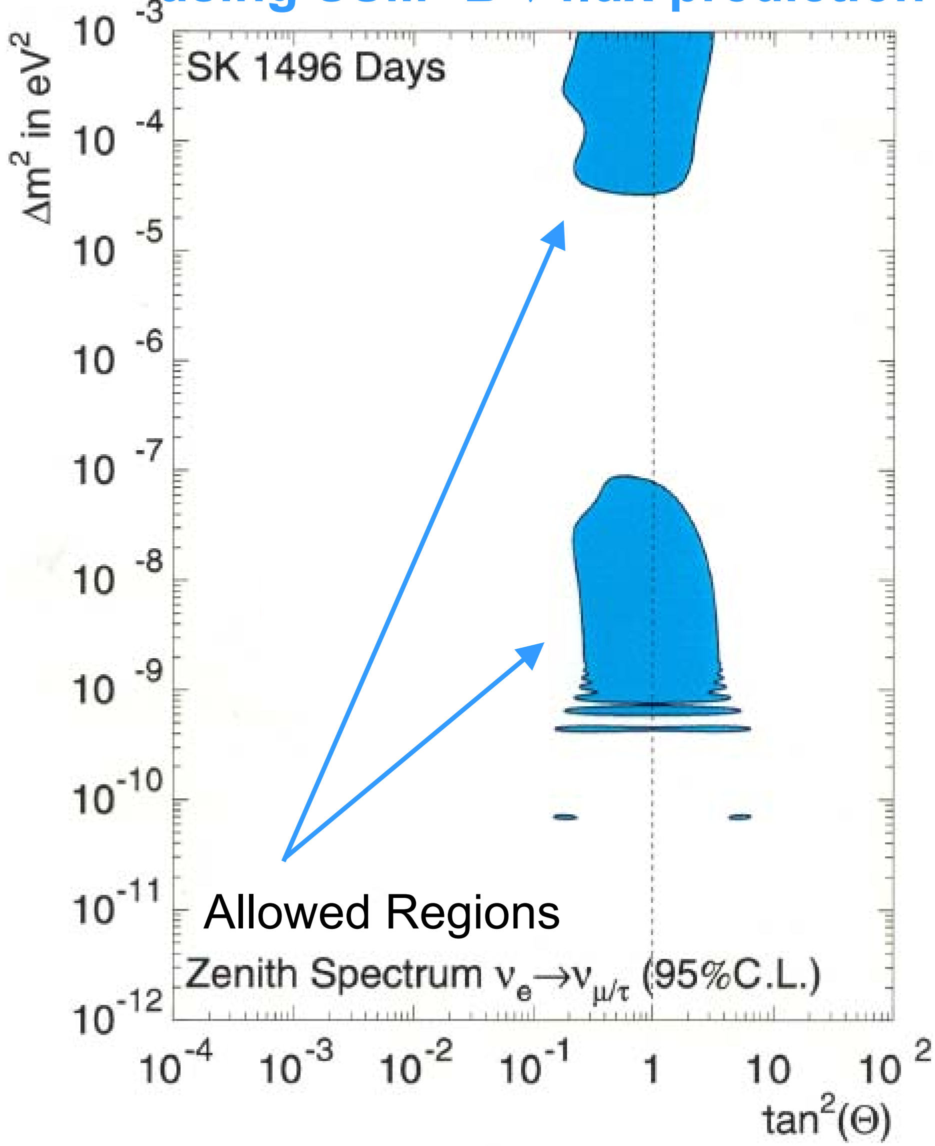


SK Constraint on mixing parameters

zenith spectrum shape alone



using SSM ^8B ν flux prediction

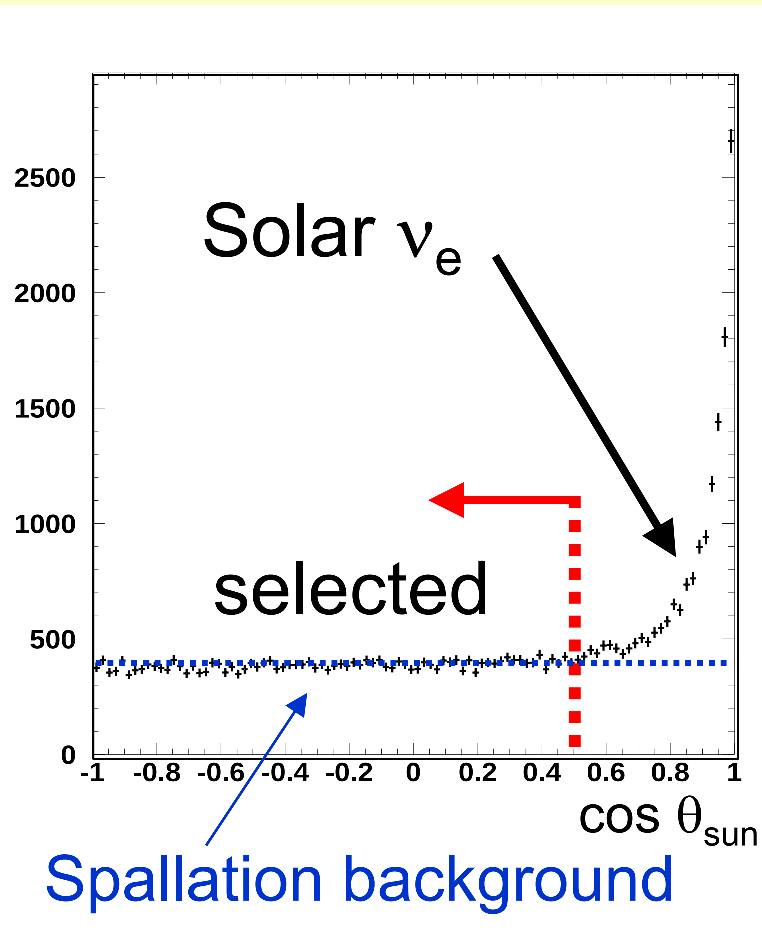


Phys. Lett. B (2002) 179

SK Search for solar $\bar{\nu}_e$

If neutrinos have magnetic moment,

$\nu_e \rightarrow \bar{\nu}_e$ **(Dirac ν)** $\nu_e \rightarrow \bar{\nu}_\mu, \bar{\nu}_\tau \rightarrow$ **osc.** $\rightarrow \bar{\nu}_e$ **(Majorana ν)**



Combine 8-20 MeV,

$\bar{\nu}_e$ flux < 0.8% of SSM

U.L. @ 90% C.L. NEW

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

Phys.Rev.Lett.90(2003)

Sudbury Neutrino Observatory

2092 m to Surface (6010 m w.e.)

PMT Support Structure, 17.8 m
9456 20 cm PMTs
~55% coverage within 7 m

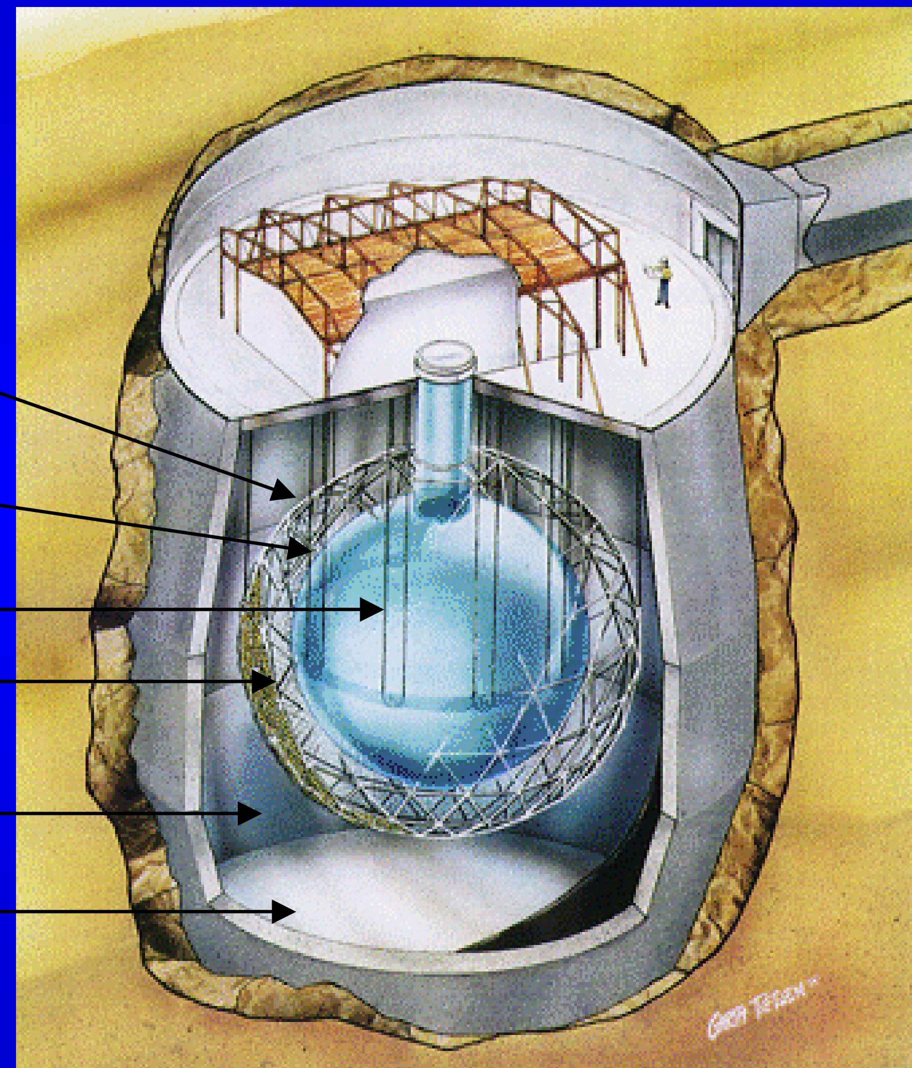
Acrylic Vessel, 12 m diameter

1000 tonnes D_2O
1700 tonnes H_2O, Inner Shield

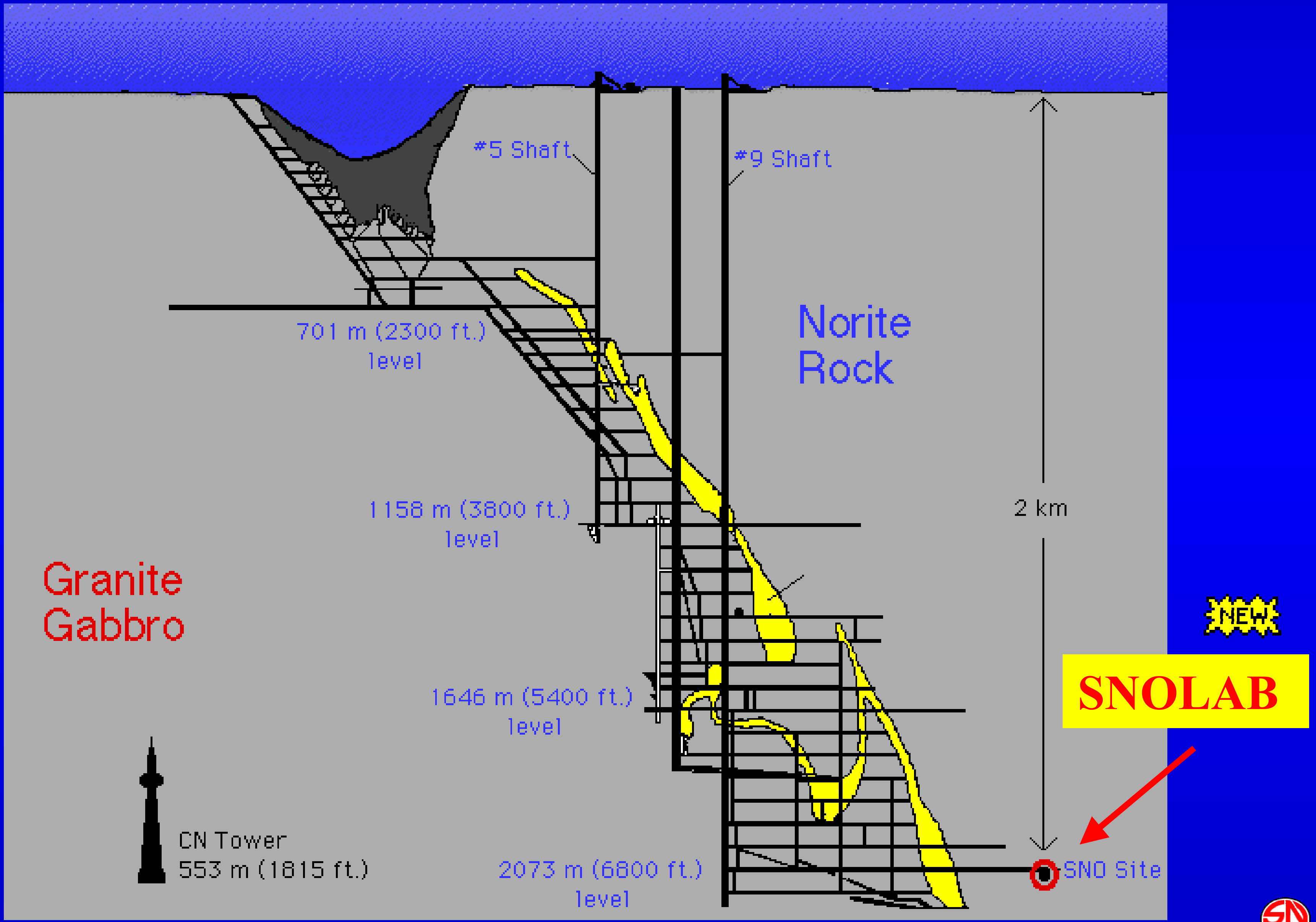
5300 tonnes H_2O, Outer Shield

Urylon Liner and Radon Seal

Energy Threshold = 5.511 MeV



Underground laboratory in Sudbury



The SNO detector observes the following interactions:

CC **Charged Current**

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

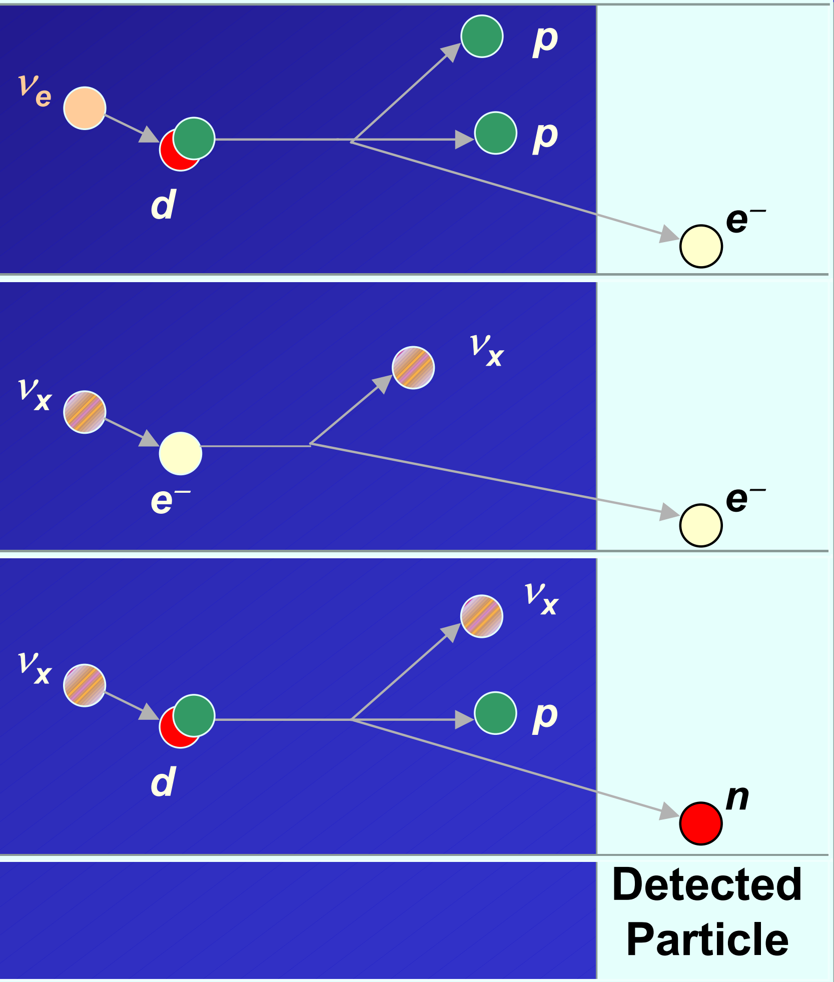
ES **Elastic Scattering**

$\nu_x + e^- \rightarrow \nu_x + e^-$

NC **Neutral Current**

$\nu_x + d \rightarrow \nu_x + p + n$

$x = e, \mu, \tau$



Neutrino Reactions in SNO

CC $\nu_e + d \rightarrow p + p + e^-$

Produces Cherenkov Light Cone in D_2O

- Q = 1.445 MeV
- good measurement of ν_e energy spectrum
- some directional info $\propto (1 - 1/3 \cos\theta)$
- ν_e only

NC $\nu_x + d \rightarrow p + n + \nu_x$

n captures on deuteron
$^2H(n, \gamma)^3H$
Observe 6.25 MeV γ

- Q = 2.22 MeV
- measures total ^8B ν flux from the Sun
- equal cross section for all ν types

ES $\nu_x + e^- \rightarrow \nu_x + e^-$

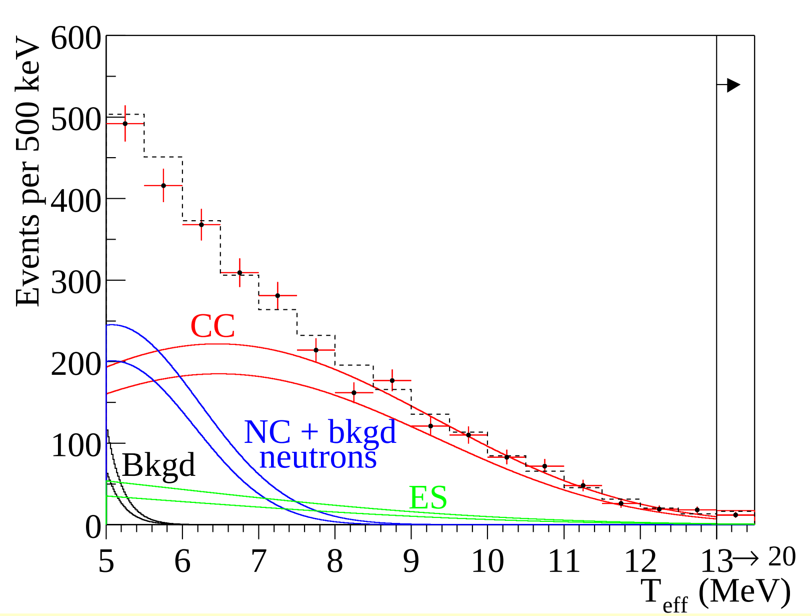
Produces Cherenkov Light Cone in D_2O

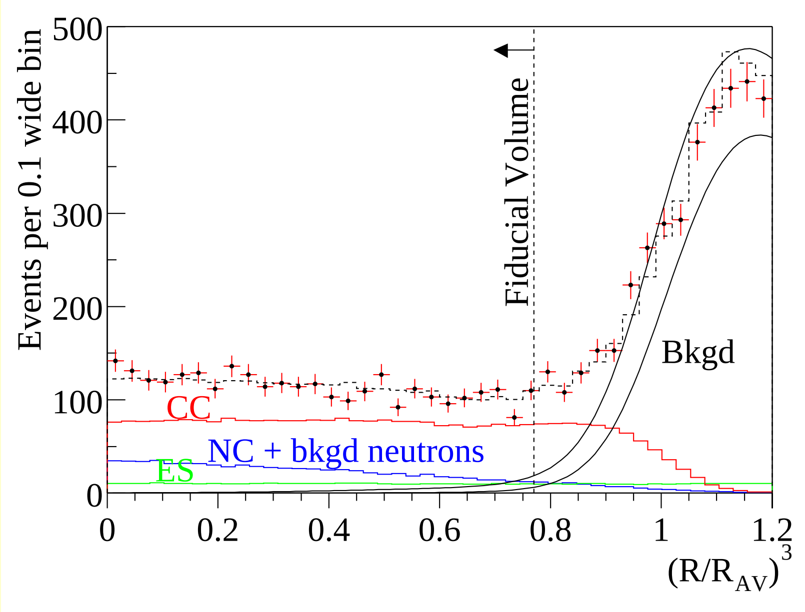
- low statistics
- mainly sensitive to ν_e, some ν_μ and ν_τ
- strong directional sensitivity

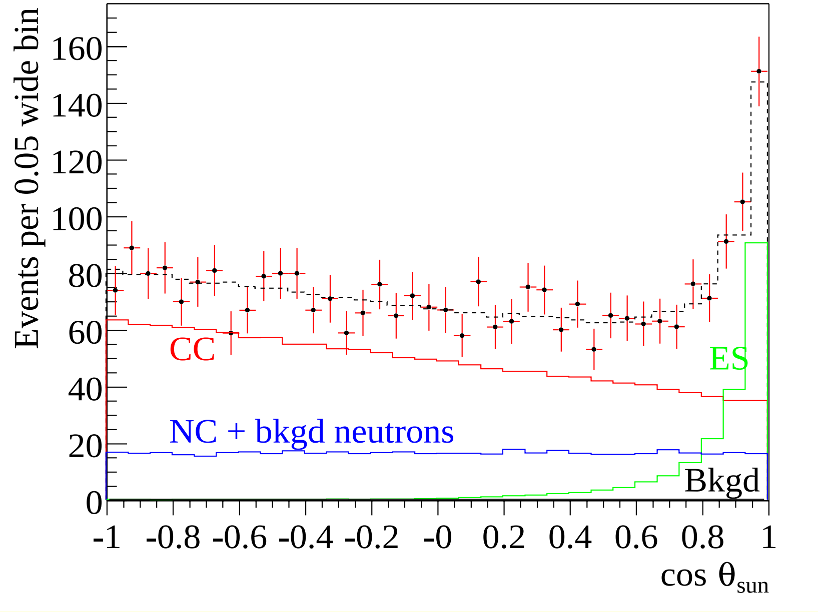
Shape Constrained Signal Extraction Results

#EVENTS

CC	$1967.7^{+61.9}_{+60.9}$
ES	$263.6^{+26.4}_{+25.6}$
NC	$576.5^{+49.5}_{+48.9}$







Shape Constrained Neutrino Fluxes

Signal Extraction in Φ_{CC}, Φ_{NC}, Φ_{ES} with E > 5.511 MeV

$$\Phi_{cc}(\nu_e) = 1.76^{+0.06}_{-0.05}\,(\mathrm{stat.})^{+0.09}_{-0.09}\,(\mathrm{syst.})\ \mathrm{x}10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$\Phi_{es}(\nu_x) = 2.39^{+0.24}_{-0.23}\,(\mathrm{stat.})^{+0.12}_{-0.12}\,(\mathrm{syst.})\ \mathrm{x}10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$\Phi_{nc}(\nu_x) = 5.09^{+0.44}_{-0.43}\,(\mathrm{stat.})^{+0.46}_{-0.43}\,(\mathrm{syst.})\ \mathrm{x}10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Signal Extraction in Φ_e, $\Phi_{\mu\tau}$

$\Phi_{cc}(\nu_e) = \Phi_e$ **and** $\Phi_{nc}(\nu_x) = \Phi_e + \Phi_{\mu\tau}$

$\Phi_{es}(\nu_x) = (1-\varepsilon)\,\Phi_e + \varepsilon\,\Phi_{\mu\tau}$ **with** $\varepsilon \approx 0.15$

Shape Constrained Neutrino Fluxes

Signal Extraction in Φ_{CC}, Φ_{NC}, Φ_{ES} with E > 5.511 MeV

$$\Phi_{cc}(\nu_e) = 1.76^{+0.06}_{-0.05}\,(\text{stat.})\,^{+0.09}_{-0.09}\,(\text{syst.})\ \text{x}10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\Phi_{es}(\nu_x) = 2.39^{+0.24}_{-0.23}\,(\text{stat.})\,^{+0.12}_{-0.12}\,(\text{syst.})\ \text{x}10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\Phi_{nc}(\nu_x) = 5.09^{+0.44}_{-0.43}\,(\text{stat.})\,^{+0.46}_{-0.43}\,(\text{syst.})\ \text{x}10^6\ \text{cm}^{-2}\text{s}^{-1}$$

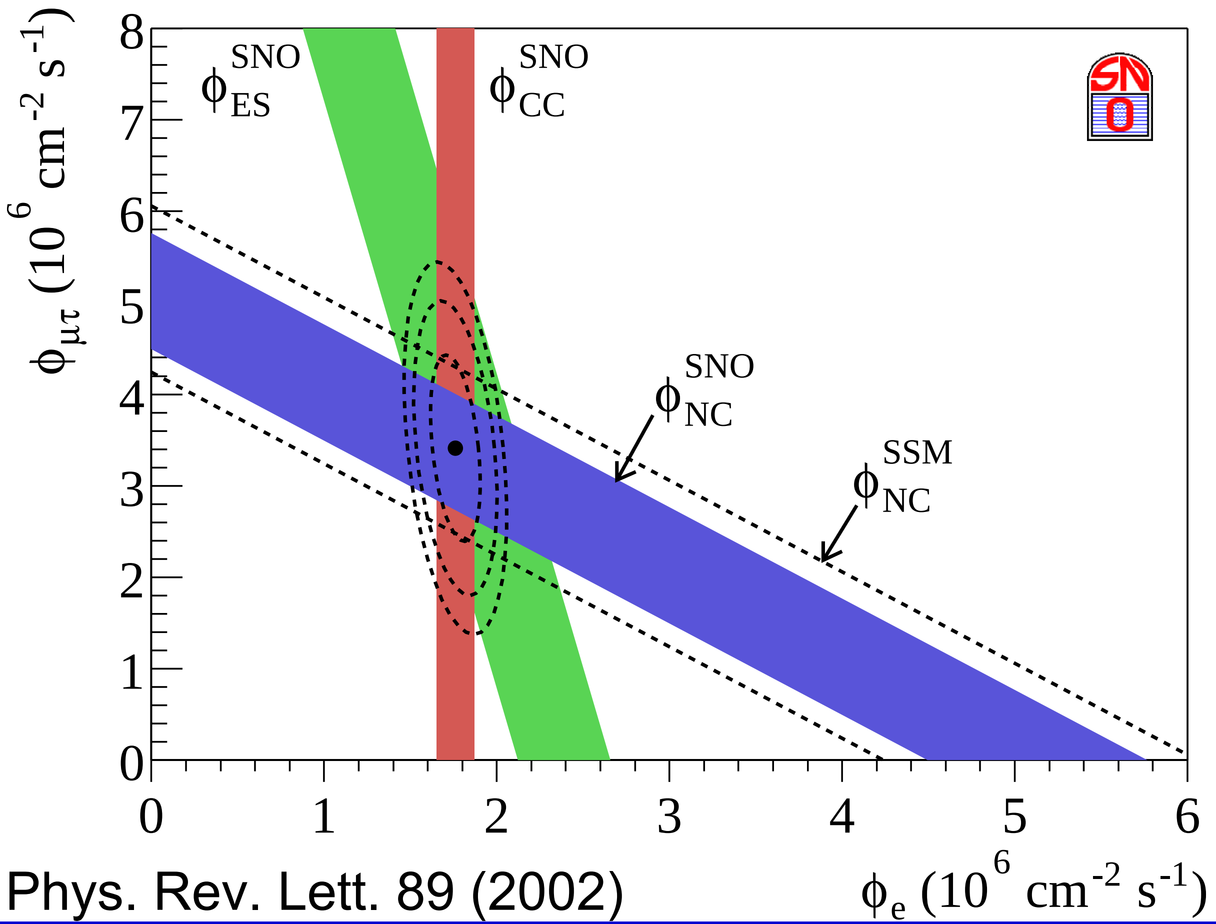
Signal Extraction in Φ_e, $\Phi_{\mu\tau}$

$$\Phi_e = 1.76^{+0.05}_{-0.05}\,(\text{stat.})\,^{+0.09}_{-0.09}\,(\text{syst.})\ \text{x}10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\Phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}\,(\text{stat.})\,^{+0.48}_{-0.45}\,(\text{syst.})\ \text{x}10^6\ \text{cm}^{-2}\text{s}^{-1}$$

SNO NC in D_2O (April 2002)

~ 2/3 of initial solar ν_e are observed at SNO to be $\nu_{\mu,\tau}$



Phys. Rev. Lett. 89 (2002)

Flavor change at 5.3 σ level.

Sum of all the fluxes agrees with SSM.

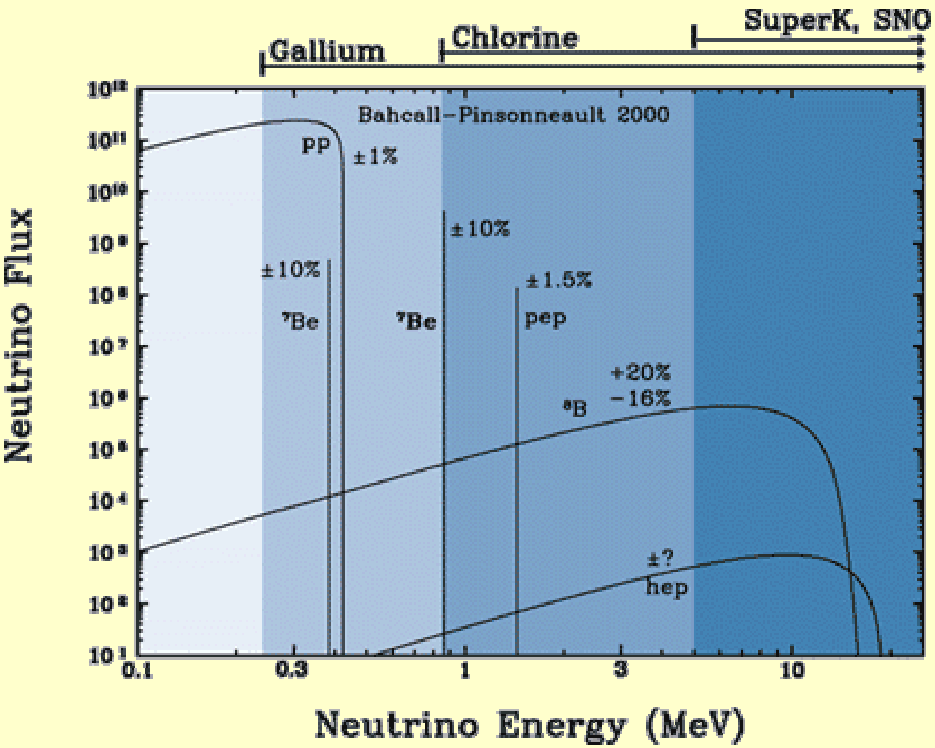
$$\Phi_{SSM} = 5.05^{+1.01}_{-0.81}$$

10^6 cm^{-2} s^{-1}

$$\Phi_{SNO} = 5.09^{+0.44}_{-0.43}{}^{+0.46}_{-0.43}$$

10^6 cm^{-2} s^{-1}

The Solar Neutrino Problem

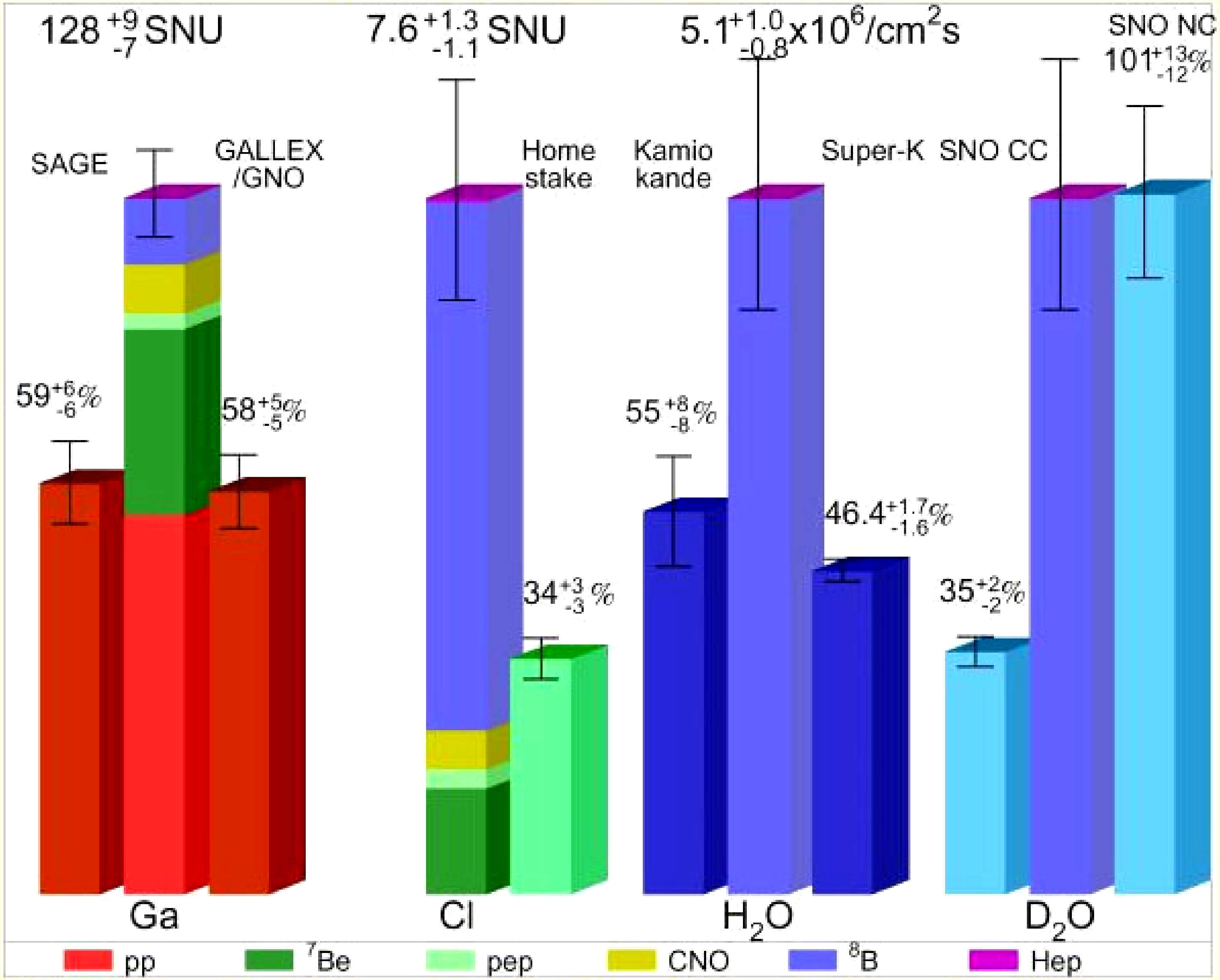


Experiment	Exp/SSM
•SAGE+GALLEX/GNO	0.55
•Homestake	0.34
•Kamiokande+SuperK	0.47
•SNO CC (June 2001)	0.35

SNO NC (April 2002) 1.01

SNO CC vs NC implies flavor change, which can then explain other experimental results.

Solar ν Problem



Michael Smy, UC Irvine

Day/Night Asymmetries

$$A_X = \frac{(\Phi_{night} - \Phi_{day})}{(\Phi_{night} + \Phi_{day})/2}$$

Signal Extraction for Φ_{CC}, Φ_{NC}, Φ_{ES} $\Rightarrow$ Φ_e and Φ_{TOT}

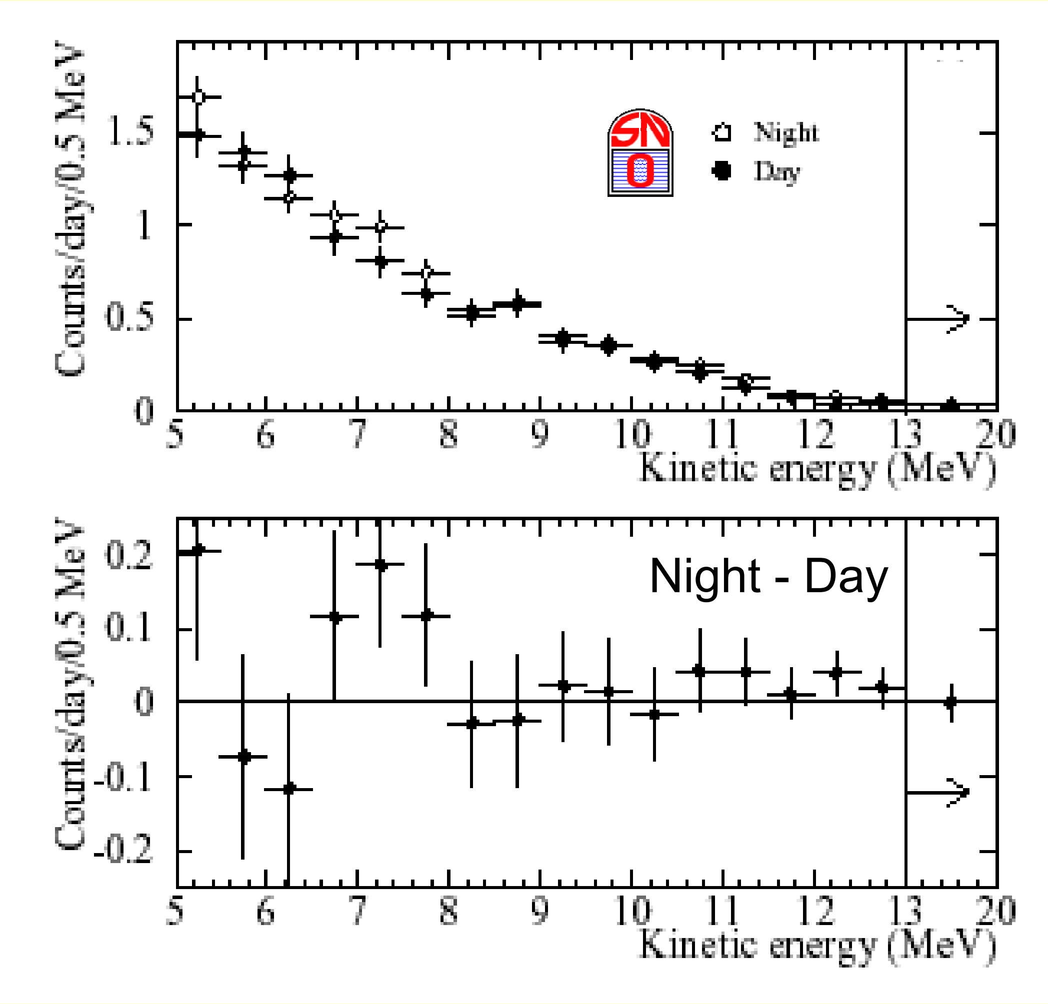
Allowing $A_{tot} \neq 0$

$A_{TOT} = -24.2 \pm 16.1 ^{+2.4}_{-2.5}$ %

$A_e = 12.8 \pm 6.2 ^{+1.5}_{-1.4}$ %

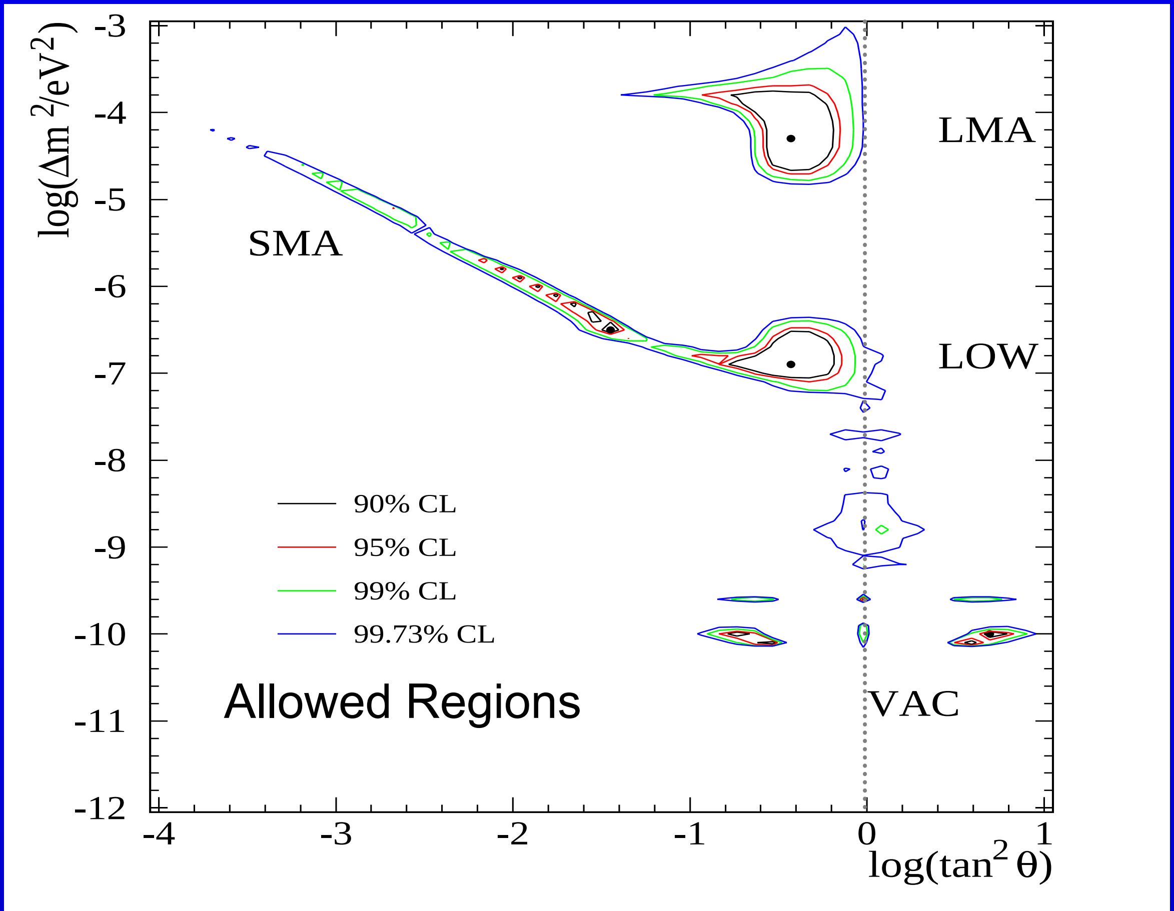
With constraint $A_{tot} = 0$

$A_e = 7.0 \pm 4.9 ^{+1.3}_{-1.2}$ %



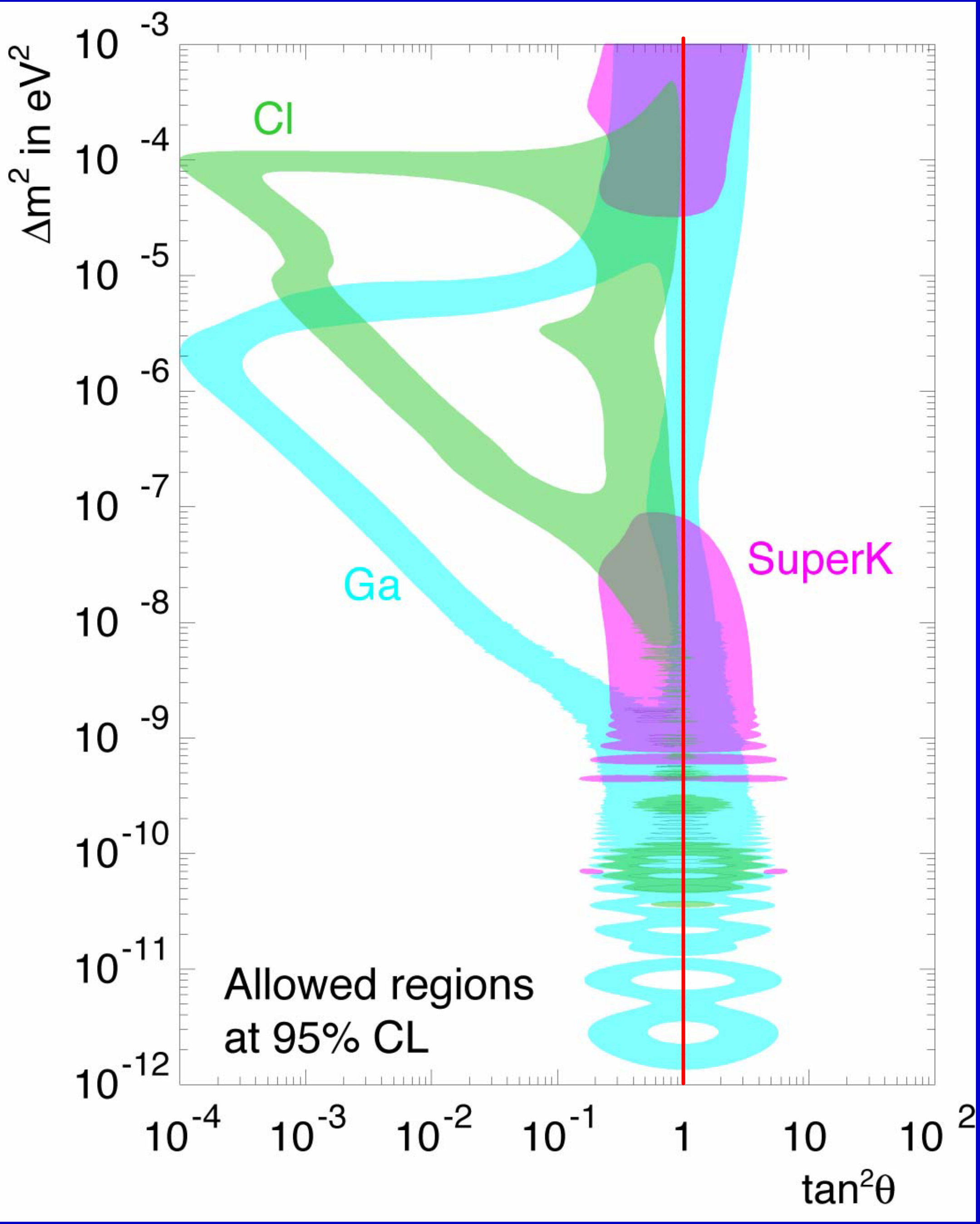
SNO: Constraint on mixing parameters

Day/Night and Energy Spectra SNO Alone



Progress in 2002 on the Solar Neutrino Problem

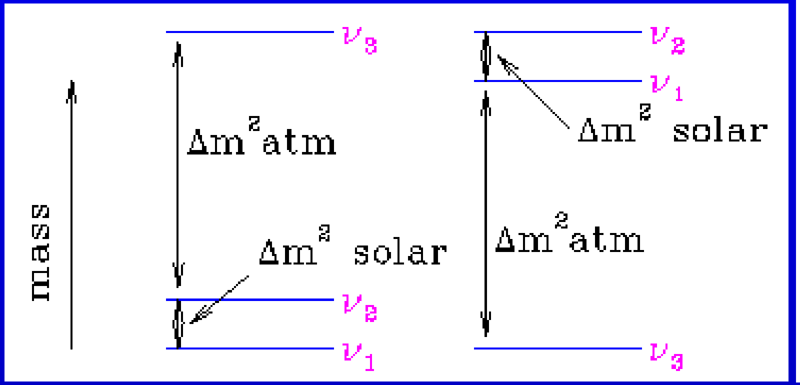
March 2002

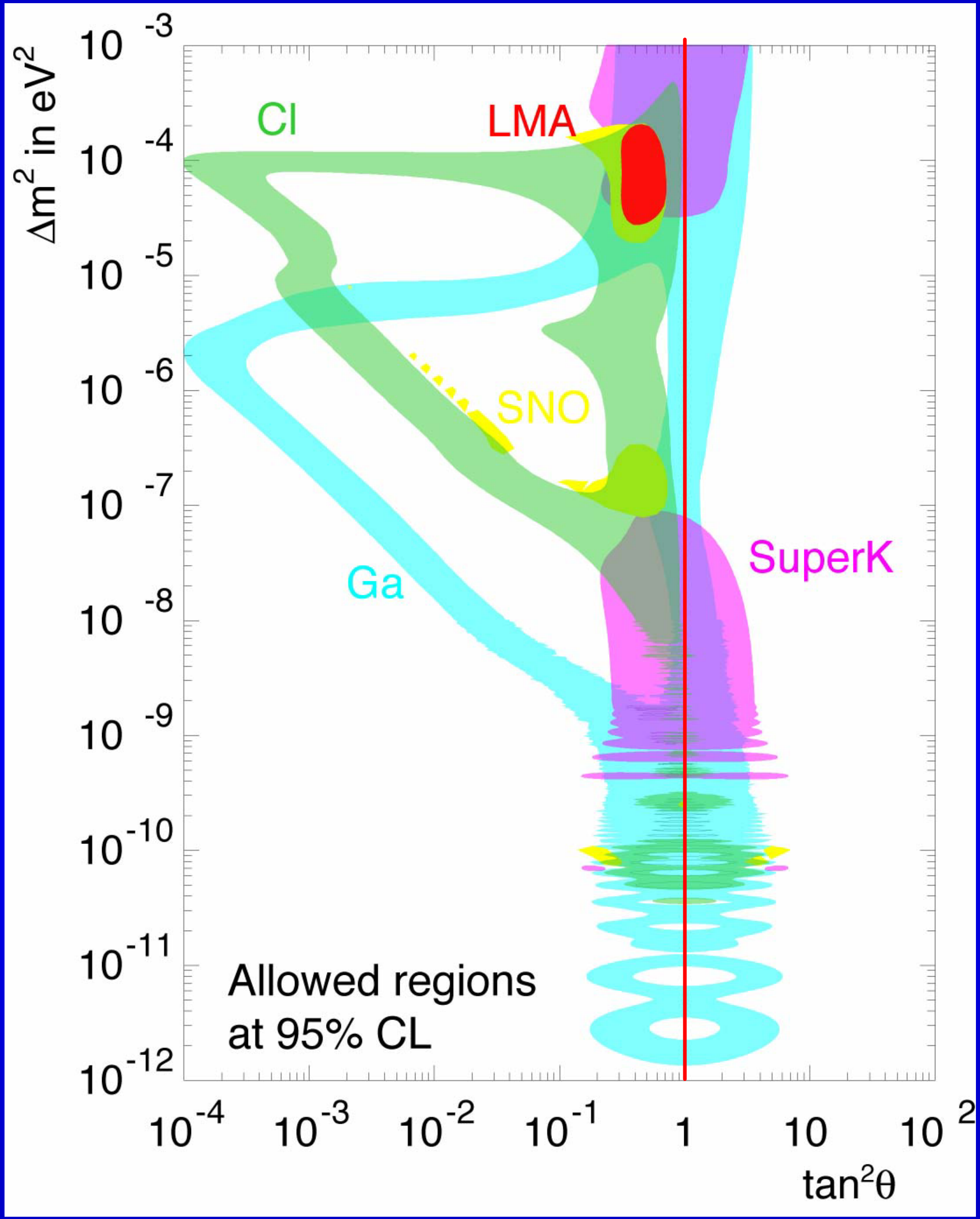


Progress in 2002 on the Solar Neutrino Problem

March 2002

April 2002 with SNO



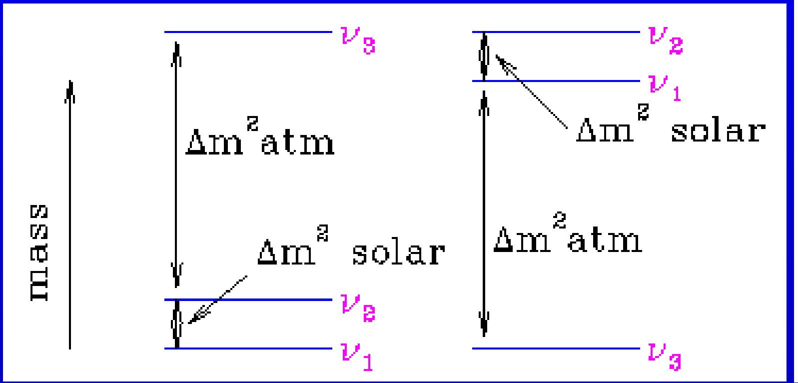


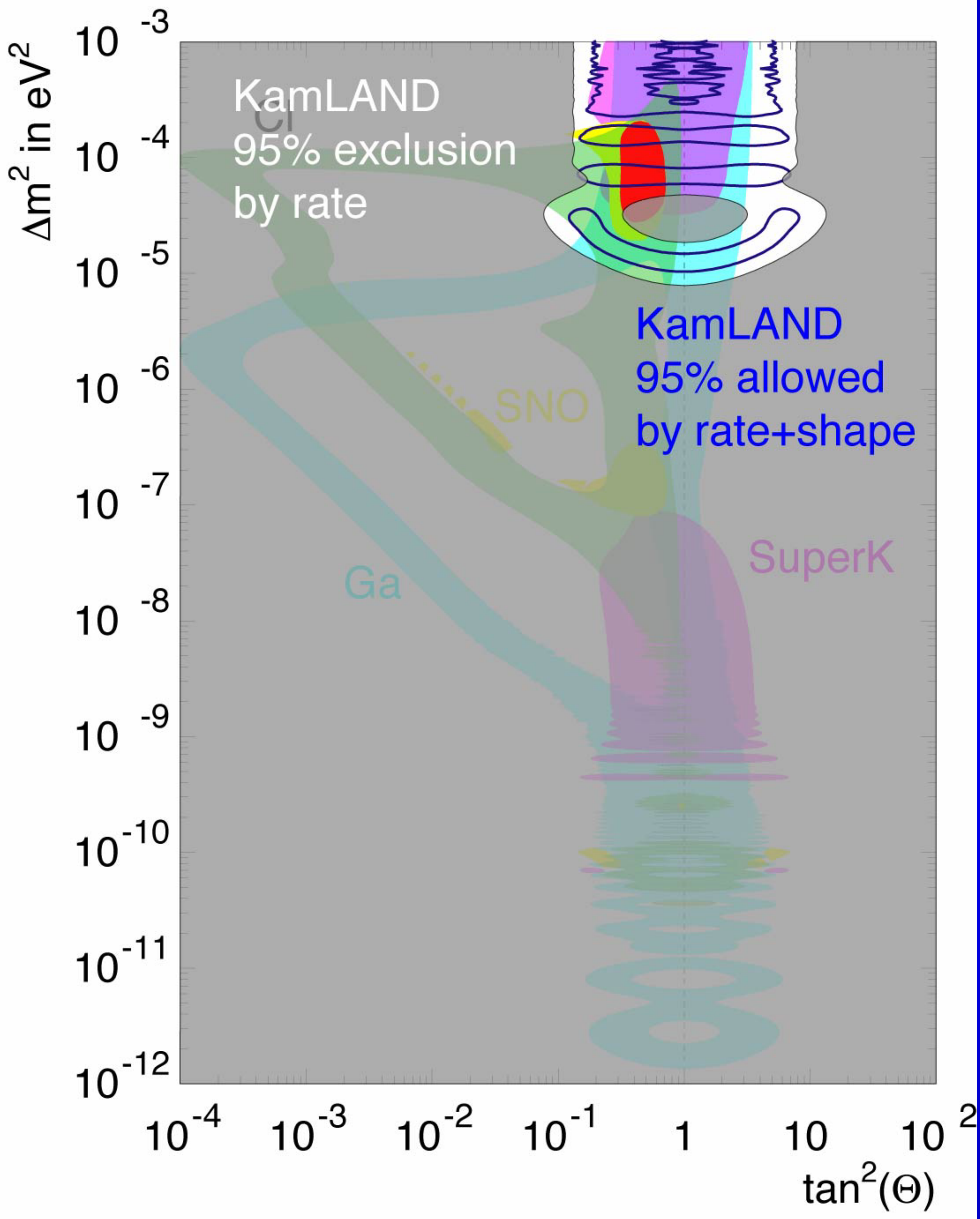
Progress in 2002 on the Solar Neutrino Problem

March 2002

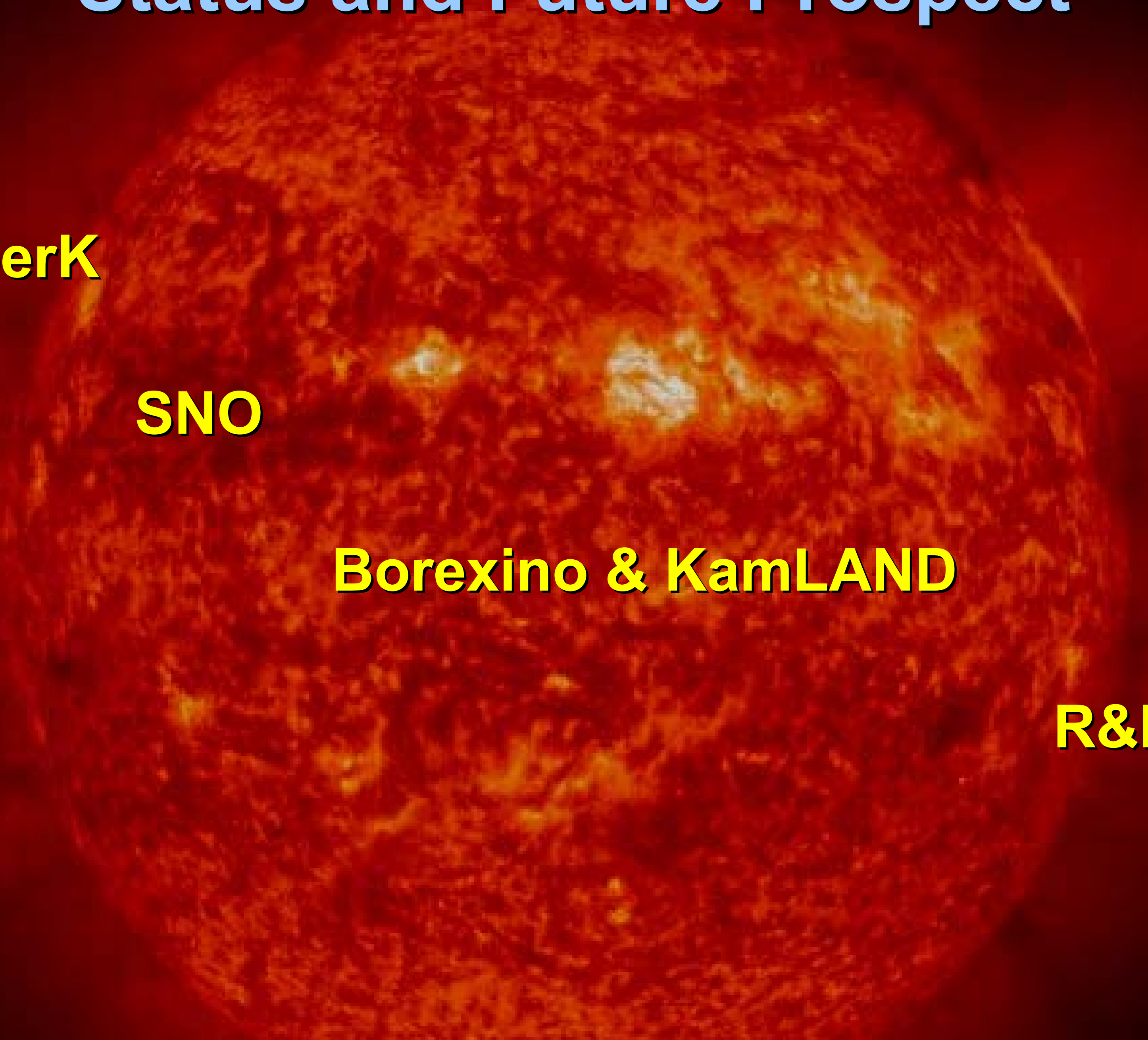
April 2002 with SNO

Dec 2002 with KamLAND





Status and Future Prospect



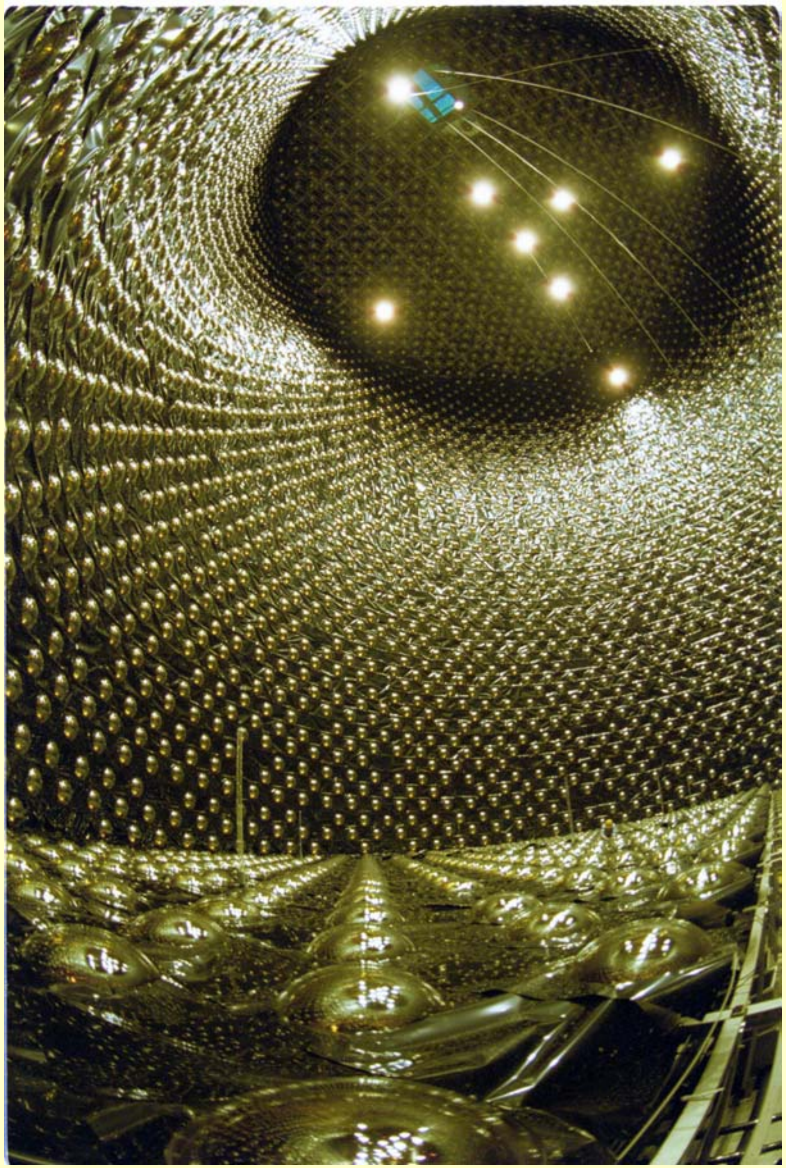
SuperK

SNO

Borexino & KamLAND

R&D

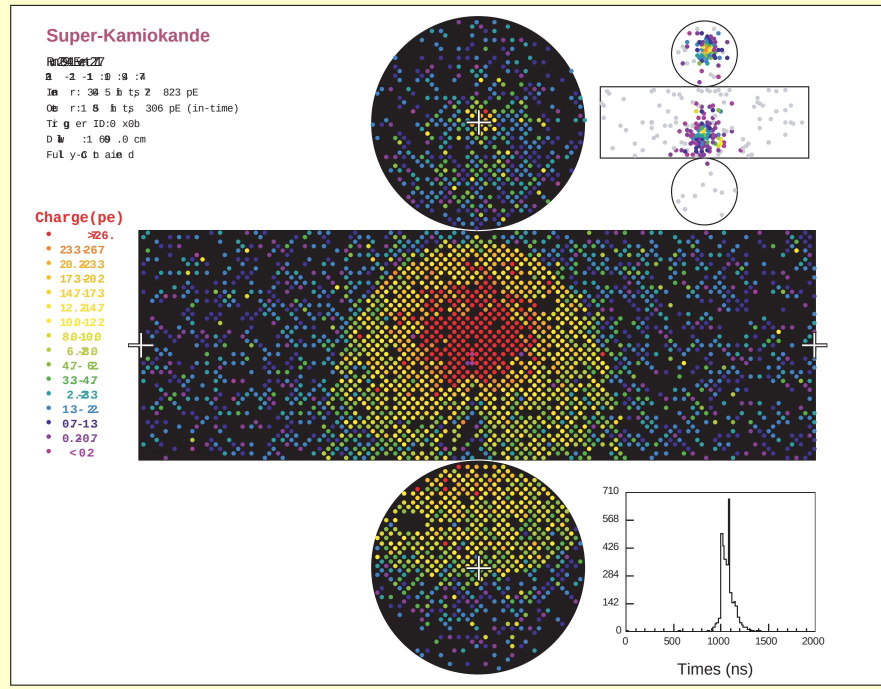
Super-Kamiokande restart (SK-II)



Pure water filling: Oct-Dec, 2002

Tank was full on Dec10, 2002

Only 13 months after the incident



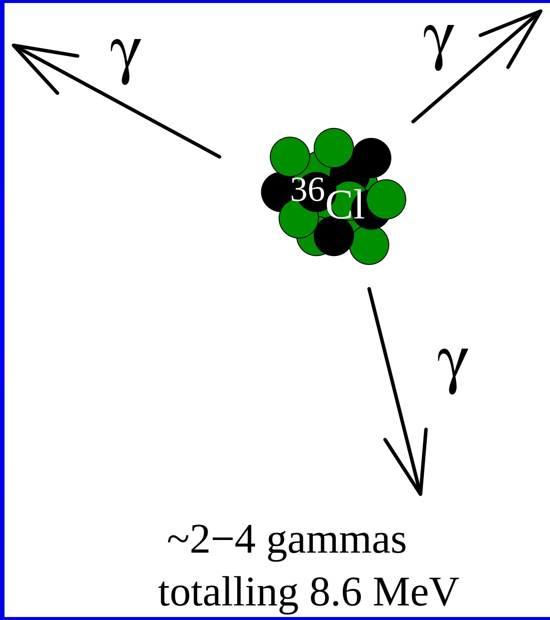
Typical cosmic ray muon in SK-II

Total number of PMTs in SK-II: ~5200 PMTs (~47% of SK-I)

SNO Salt Phase (in progress)

NC $\nu_x + d \rightarrow p + n + \nu_x$

- **Added 2 tons of salt (0.2%) in June 2001**
- **Higher n-capture efficiency**
- **Higher NC event light output**
- **Light pattern differs from e$^-$**



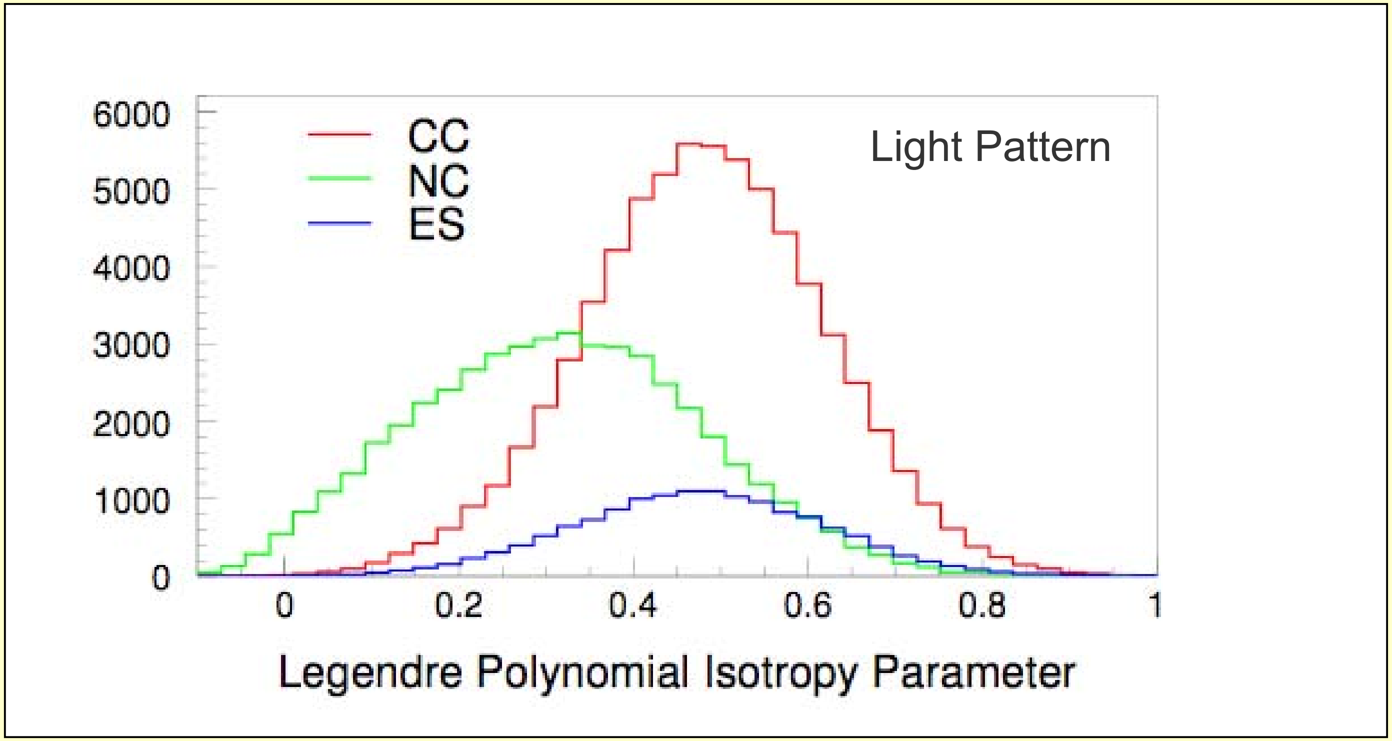
Results SOON (CC/NC, $\bar{\nu}_e$, hep)!

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

SNO Statistical Significance

CC: Single electron
Cerenkov signal less isotropic

NC: Multiple γ's from n capture on ^{35}Cl
Cerenkov signal more isotropic



SNO Statistical Significance

CC: Single electron
Cerenkov signal less isotropic

NC: Multiple γ's from n capture on ^{35}Cl
Cerenkov signal more isotropic

Variables	CC Stat. Error	NC Stat. Error	ES Stat. Error
* E, R, θ_{sun}	3.4 %	8.6%	10%
* R, θ_{sun}	9.5%	24%	11%
E, R, θ_{sun}	4.2%	6.3%	10%
E, R, θ_{sun}, Iso.	3.3%	4.6%	10%
R, θ_{sun}, Iso.	3.8%	5.3%	10%

Simulation

* Phys. Rev. Lett. 89 (2002)

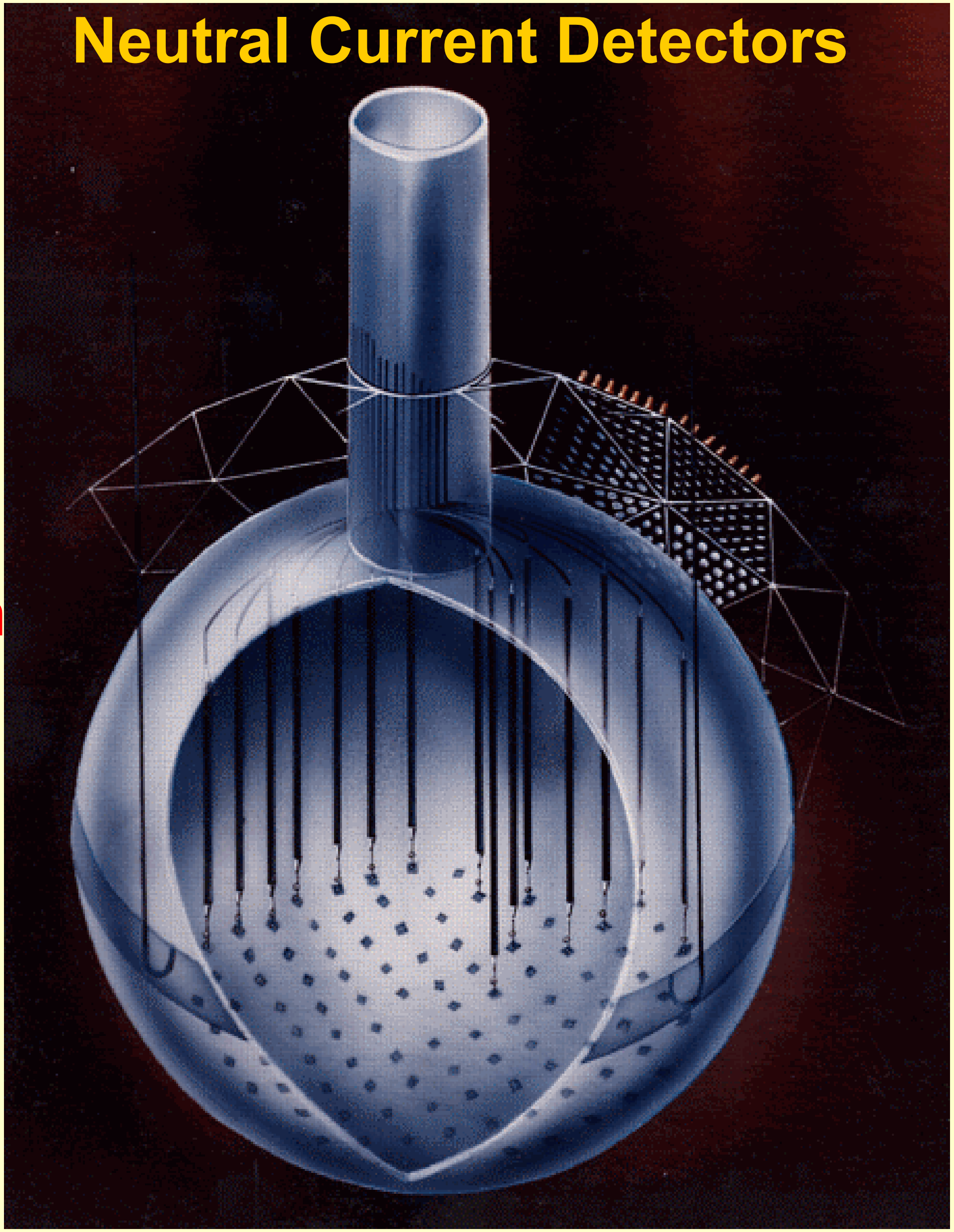
SNO Future Plans

NC

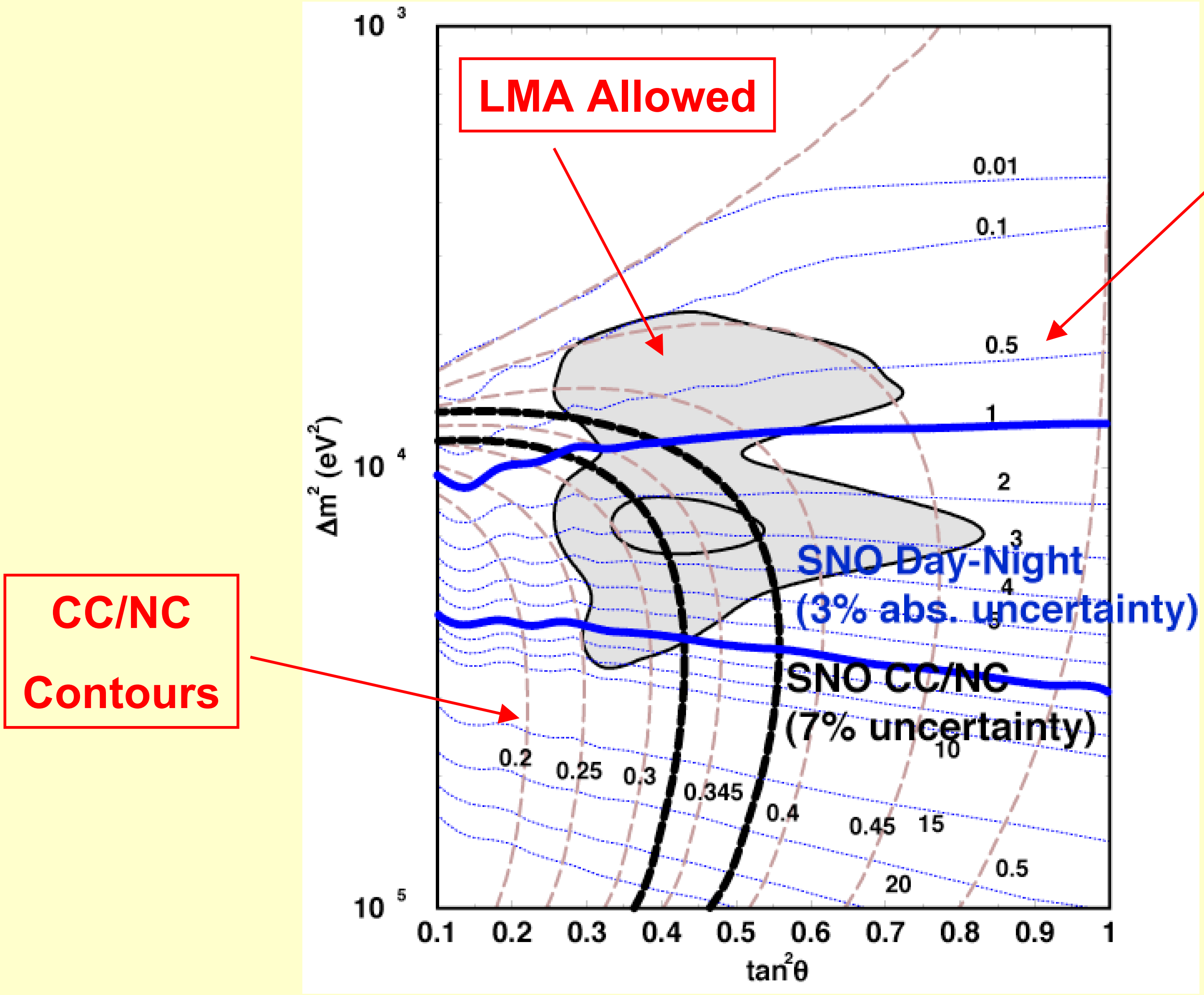
$$\nu_x + d \rightarrow p + n + \nu_x$$

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

- Event by event separation
- Break the correlation between NC & CC events
- Measure in separate data streams NC & CC events
- Different systematic errors than neutron capture on NaCl
- Deployment in September 03



What SNO might tell us in the future…



hep-ph/0212270
hep-ph/0204253

BOREXINO: Sensitivity to ^{7}Be ν's

Liquid Scintillator Spill Consequences (LOWNu03)

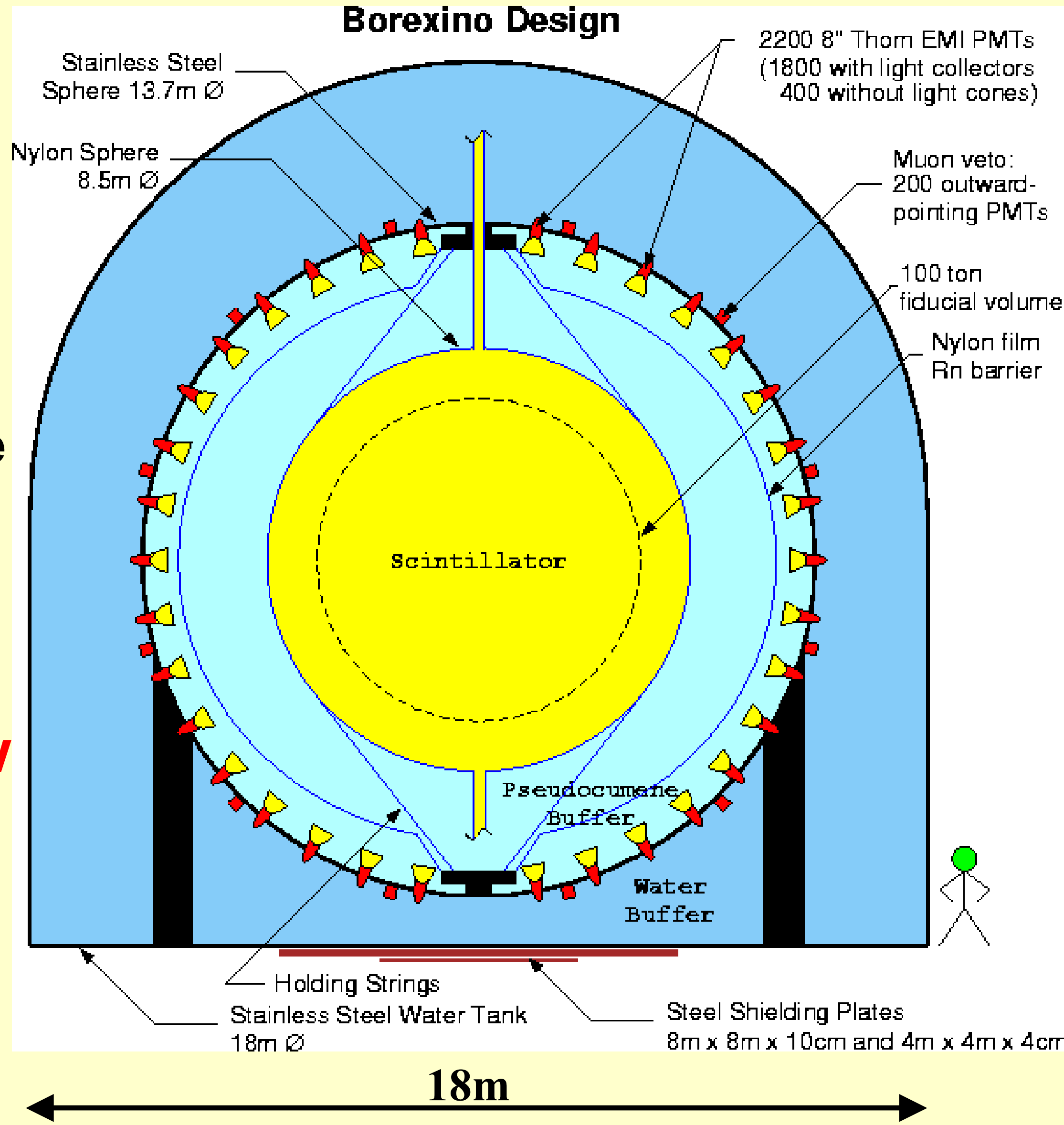
Dedication of BX to seal the detector and resume activities within 2003

Possibility that legal procedure will take longer should be seriously considered; implying no BX operations

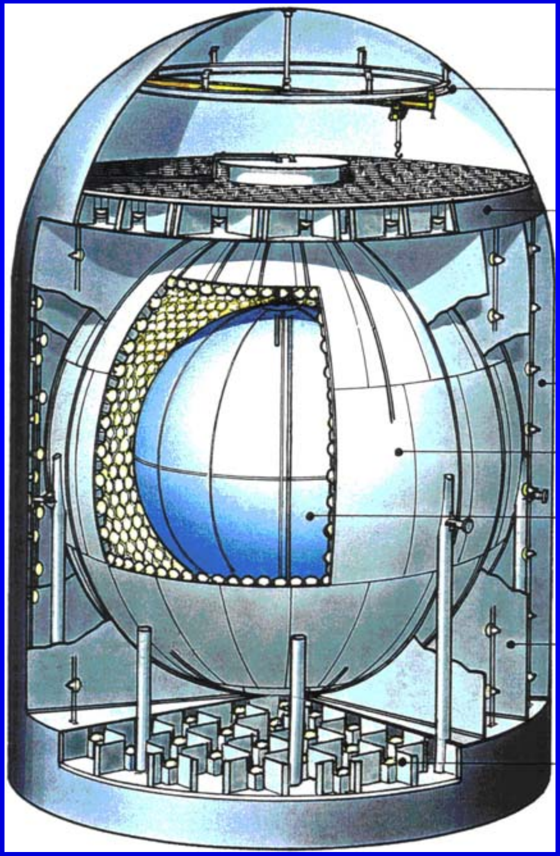
Challenge: Control of Low Energy Background

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

Energy window [0.25,0.8] MeV



KamLAND: Sensitivity to ^{7}Be ν's



- **1000 ton liquid scintillator**
- **13 m thin transparent balloon**
- **1325 inner looking PMT's**

Shift from a coincidence experiment to a ES low energy experiment

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

Backgrounds will be the main concern, especially radioactive krypton

Upcoming Experiments and R&D Efforts

- Ongoing Gallium experiments [important]
- More about the ^{8}B from SuperK and SNO
- Borexino & KamLAND real-time look at the ^{7}Be ν's
- Real-time low energy ν's are the ultimate probe of the Sun and test of the Standard Solar Model

pp ν's projects		^{7}Be ν's projects	
ES	CC	ES	CC
XMASS	LENS	BOREXINO	LENS
CLEAN	MOON	KamLAND	MOON
HERON	SIREN	TPC	SIREN
TPC		MUNU	
MUNU		LITHIUM	
GENIUS			

Conclusion

- Solar neutrino oscillation was established by Chlorine, Gallium, SuperK and SNO experiments
- SNO provided direct evidence of flavor conversion of solar ν_e's
- Real-time data do not show large energy distortion nor time-like asymmetry
- Matter Effect explains the energy dependence of solar oscillation
- Large mixing angle (LMA) solutions are favored
- Solar Neutrino Problem is now an industry for precise measurements of neutrino oscillation parameters

Implications and Outlook

- **Solar neutrinos demonstrate that neutrinos have mass and the minimum SM is incomplete**
  - **Unlike the quark sector where the CKM mixing angles are small, the lepton sector exhibits large mixing**
  - **The ν masses and mixing may play significant roles in determining structure formation in the early universe as well as supernovae dynamics and the creation of matter**
- **The coming decade will be exciting for neutrino physics helping delineate the *New* Standard Model that will include neutrino masses and mixing**
  - **Precision measurements of the leptonic mixing matrix**
  - **Determination of neutrino masses**
  - **Investigation of lepton sector CP and CPT properties**