
Neutral Current and
Day/Night Measurements
from the Pure-D_2O Phase of
SNO
SNO Collaboration
Aksel Hallin,
Queen's University
Neutrino 2002

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Solar Neutrinos

Solar Neutrinos

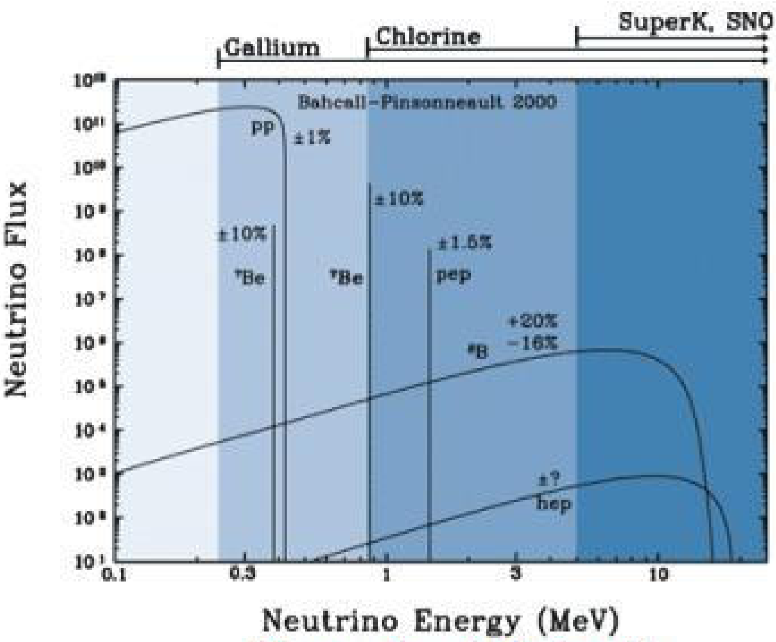


Figure by J. Bahcall

Experimental Results

SAGE+GALLEX/GNO

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

Flux = 0.58 SSM

Homestake

$$\nu_e +^{37} Cl \rightarrow^{37} Ar + e^-$$

Flux = 0.33 SSM

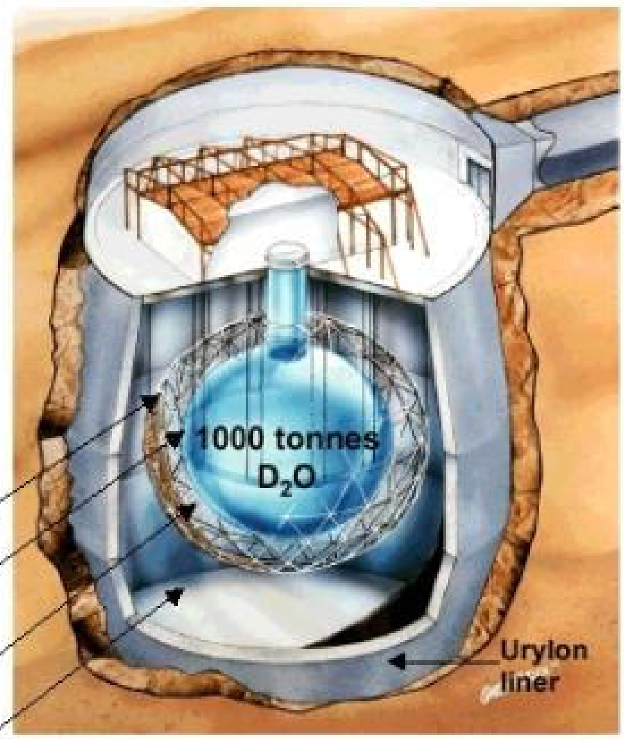
Kamiokande + Superkamiokande

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \sigma_{\mu\tau}=\frac{1}{6} \times \sigma_e$$

Flux = 0.46 SSM

Neutrino Flavor Change ?

The SNO Detector



17.8m dia. PMT Support Structure
9456 PMTs, 56% coverage

12.01m dia. acrylic vessel

1700 tonnes of inner shielding H_2O

5300 tonnes of outer shielding H_2O

Host: INCO Ltd., Creighton #9 mine
Coordinates: 46°28'30"N 81°12'04"W
Depth: 2092 m (~6010 m.w.e., ~70 μ day^{-1})

Nucl. Inst. and Meth. A449, p172 (2000)

ν Reactions in SNO

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

- Good measurement of ν_e energy spectrum
- Weak directional sensitivity $\propto 1 - 1/3\cos(\theta)$
- ν_e only.

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

- Equal cross section for all ν types
- Measure total ^8B ν flux from the sun.

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

- Low Statistics
- Mainly sensitive to ν_e, some sensitivity to ν_μ and ν_τ
- Strong directional sensitivity

Neutrino Physics From SNO

June 2001

$$\frac{\Phi_{cc}}{\Phi_{es}} = \frac{\nu_e}{\nu_e + 0.154(\nu_\mu + \nu_\tau)} = 1\ ?$$

$$\frac{\Phi_{cc}}{\Phi_{nc}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau} = 1\ ?$$

Perform a Hypothesis Test for Flavor Change by assuming pure ^8B Spectral shape and testing if flux ratios equal 1.

$$\Phi_{day} = \Phi_{night}\ ?$$

Test if interaction with electrons in the Earth changes Mu and Tau neutrinos back to Electron neutrinos

Solar Neutrino Flux From SNO Data

Total ^{8}B Solar Neutrino Flux Originating in the Sun

June 2001

$$\Phi_x = \Phi_{cc} + (\Phi_{es} - \Phi_{cc}) \times (1/\varepsilon)$$

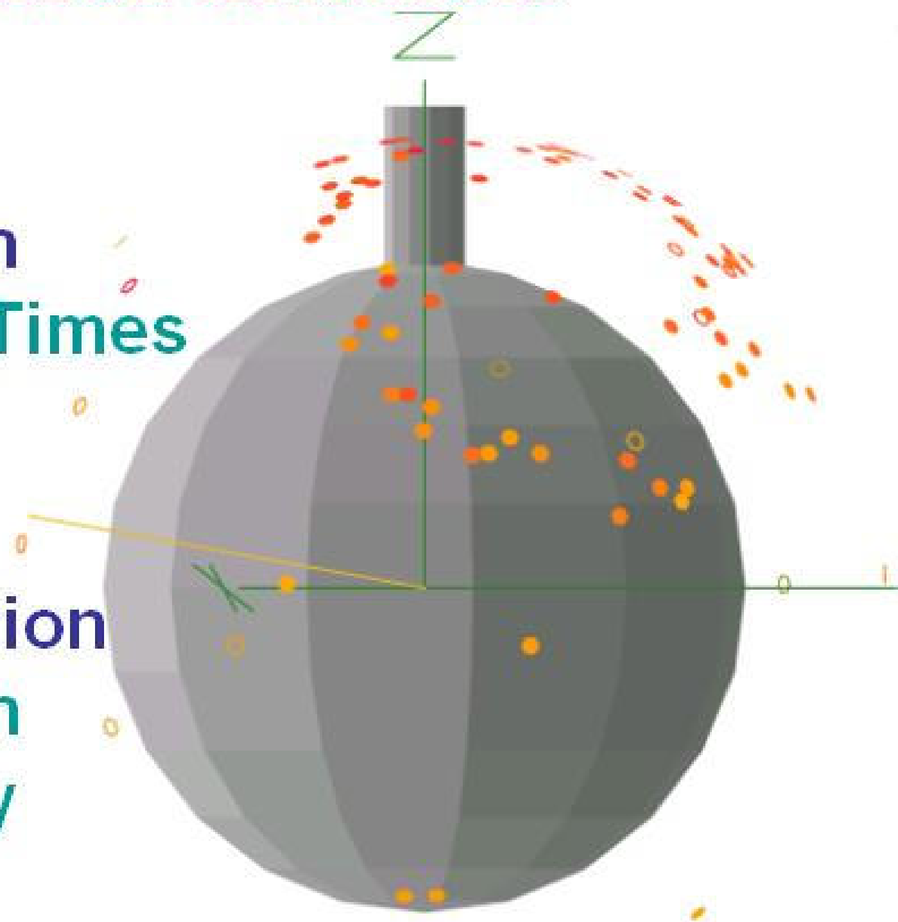
April 2002

$$\Phi_x = \Phi_{nc}$$

Event Information

PMT Information
Positions, Charges, Times

Event Reconstruction
Vertex, Direction
Energy, Isotropy

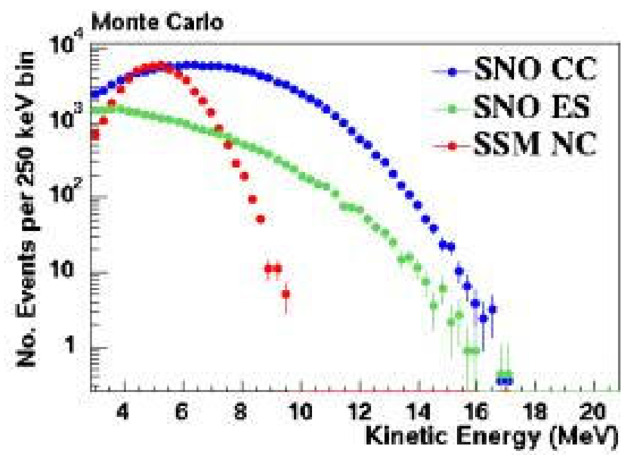


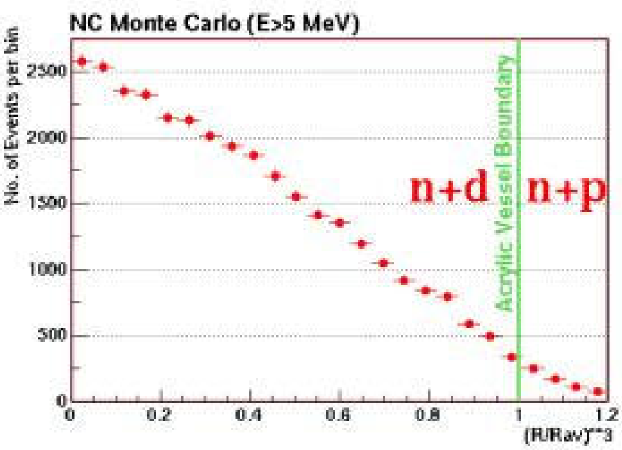
^{8}Li Electron

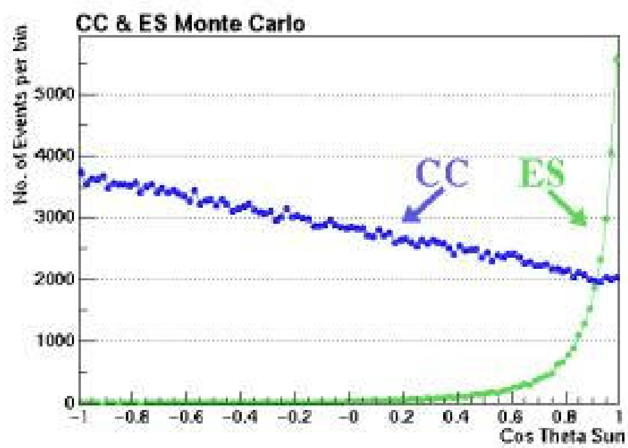
Signal Information

- Hits and Energy
- Direction from Sun
- Radial Response

$n + d \rightarrow t + \gamma \ldots \rightarrow e^-$ (E_γ = 6.25 MeV)







Backgrounds

Sources

High Energy Rock Gammas
Uranium Chain
Thorium Chain
Muon spallation products
PMT $\beta-\gamma$
Instrumental Backgrounds

Consequences

Low Energy Threshold

Fiducial Volume Cut

Photo Disintegration

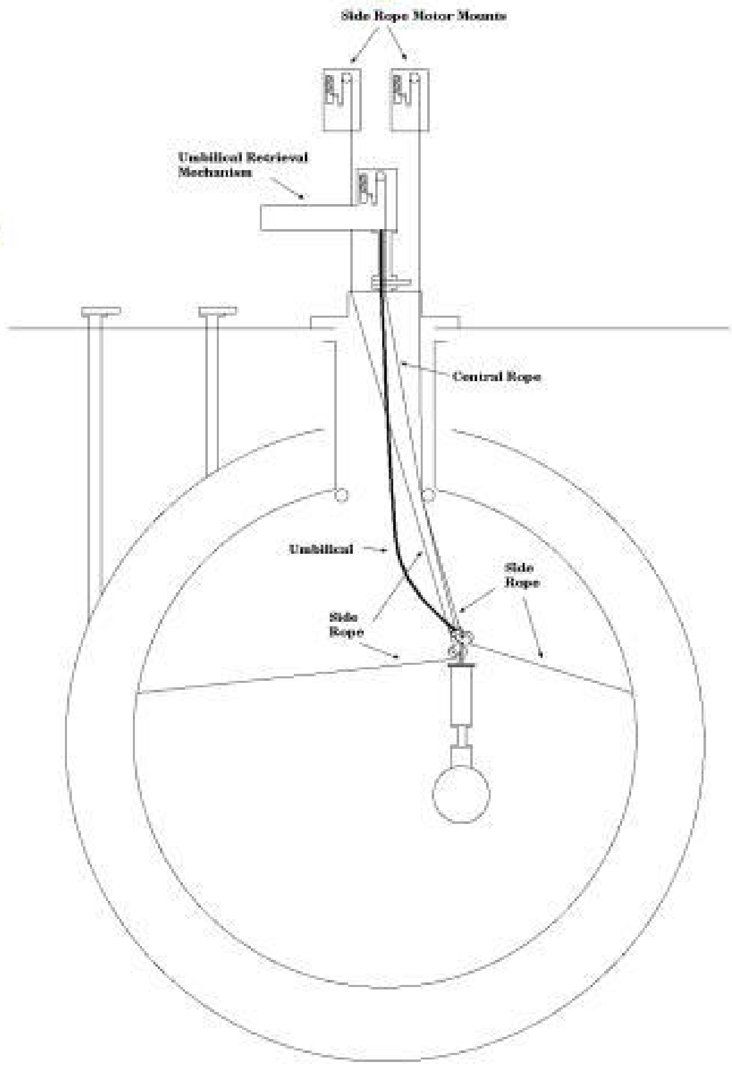
$$\gamma + d \rightarrow p + n$$

NC Bkg

Understanding Detector Response

Monte Carlo

Cherenkov production (e^-, γ, β–γ)
Photon propagation and detection
Neutron transport and capture
Reconstruction
(position, direction, energy)



Calibration

Pulsers	
Pulsed Laser	337nm to 620 nm
^{16}N	6.13 MeV γ's
$^{3}H(p,\gamma)^{4}He$	19.8 MeV γ's
^{8}Li	<13.0 MeV β's
^{252}Cf	neutrons
U/Th	^{214}Bi & ^{208}Tl β–γ's

Energy

Calibration

PMT & Optics

^{16}N Normalization

Response Uncertainties

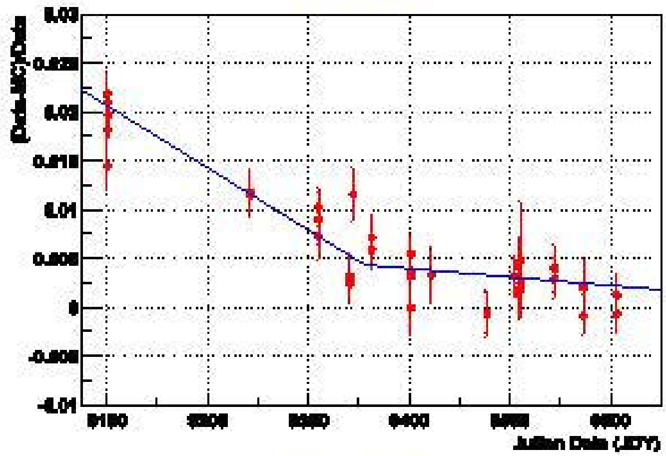
Scale, Resolution, Linearity

$\Delta E = 1.21\ \%$ $\quad \Delta\sigma = 4.5\ \%$

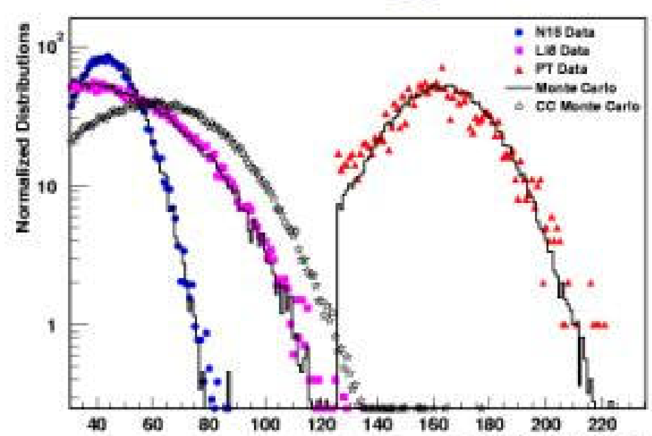
Flux Uncertainties (%)

	ΔCC/CC	ΔNC/NC
ΔE	−4.2,+4.3	−6.2,+6.1
Δσ	−0.9,+0.0	−0.0,+4.4

Time

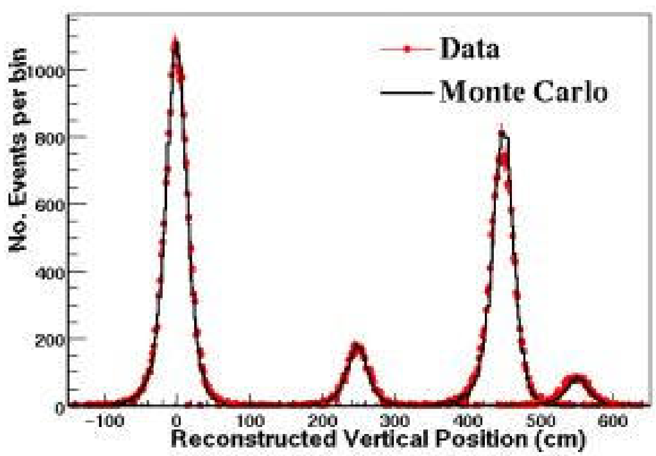


Energy

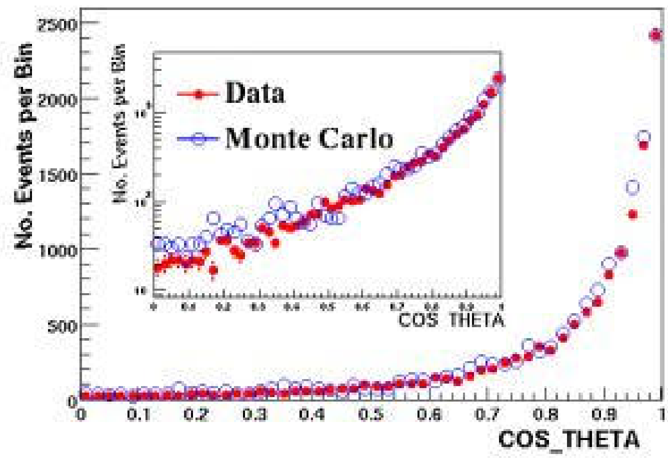


Reconstruction

^{8}Li at different positions



^{16}N events far from source

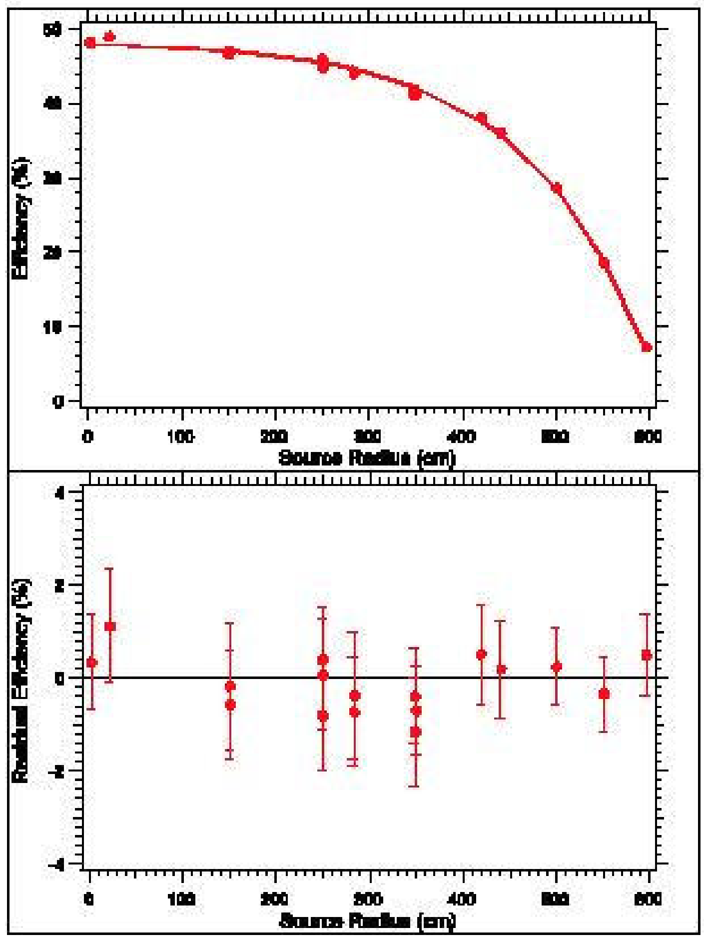


Flux Uncertainties →

	ΔCC/CC	ΔNC/NC
Vertex Accuracy	−2.8,+2.9	−1.8,+1.8
Vertex Resolution	−0.0,+0.0	−0.1,+0.1
Angular Resolution	−0.2,+0.2	−0.3,+0.3

Neutron Capture Efficiency & Uncertainties

Response vs Radius



Capture Efficiency

Total	29.90 +/- 1.10 %
With threshold & fiducial cut	14.38 +/- 0.53 %

Flux Uncertainty

ΔNC/NC

–4.0,+3.6 %

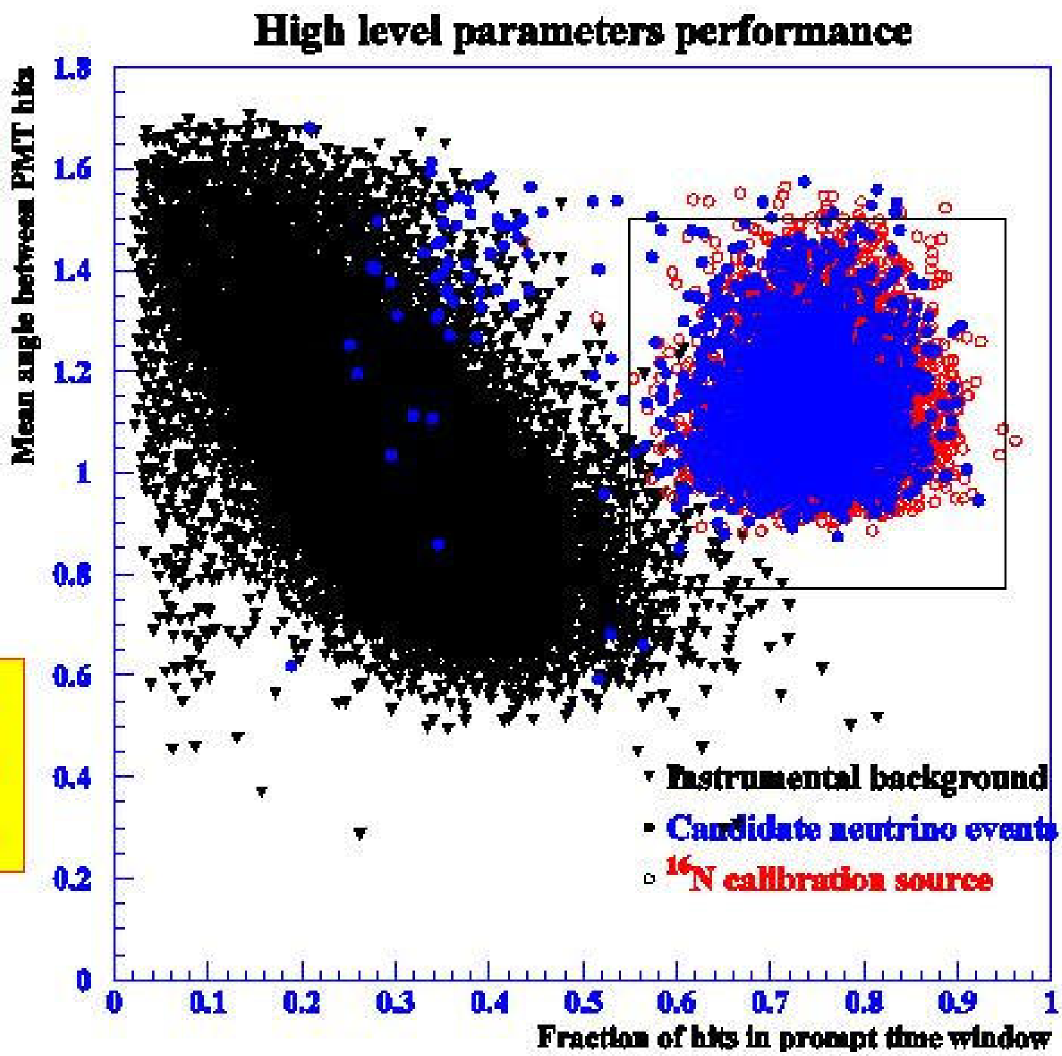
Data Reduction Cuts

Event Cuts

Instrumental
Fitter inefficiency
Cherenkov

Signal Loss

CC:	$1.43^{+0.39}_{-0.21}$ %
ES:	$1.46^{+0.40}_{-0.21}$ %
Neutrons:	$2.28^{+0.41}_{-0.23}$ %



Measuring U/Th Content

Ex-situ

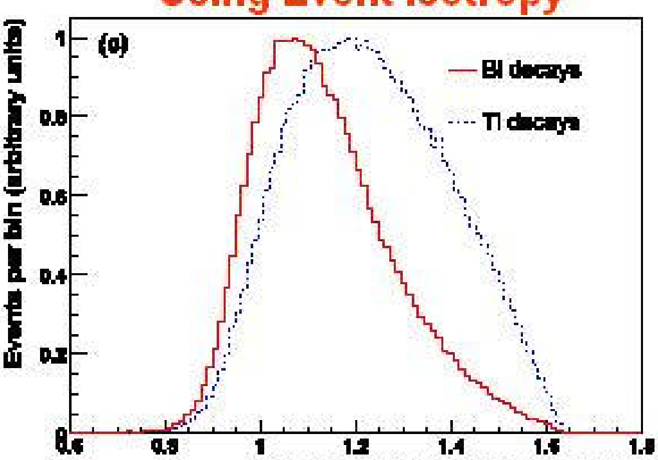
- Ion exchange (^{224}Ra, ^{226}Ra)
- Membrane Degassing (^{222}Rn)

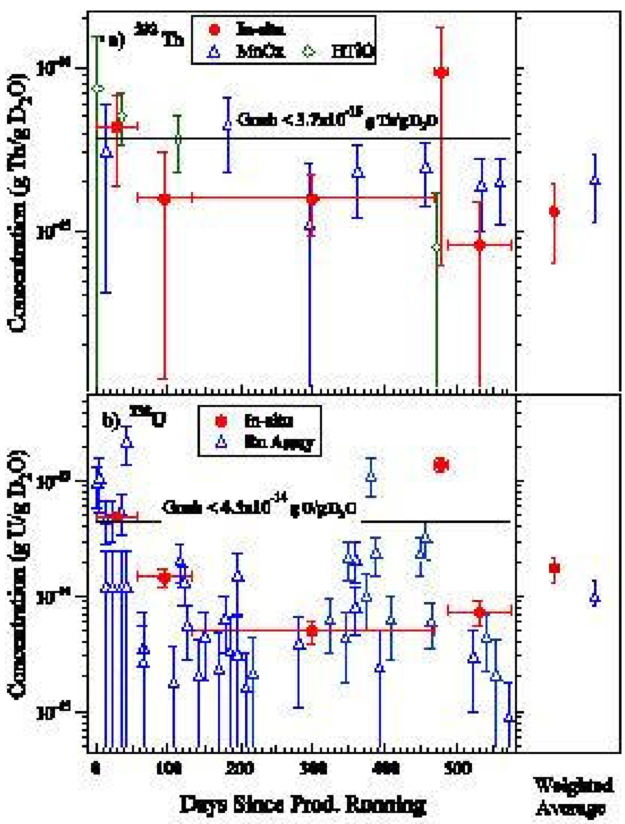
count daughter product decays

In-situ

- Low energy data analysis
- Separate ^{208}Tl & ^{214}Bi

Using Event isotropy

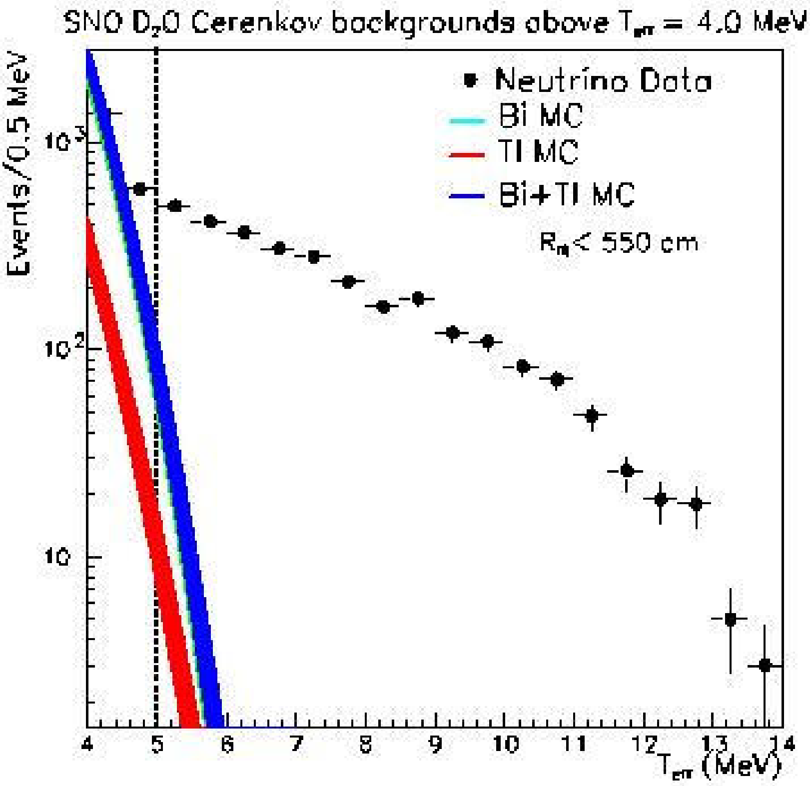


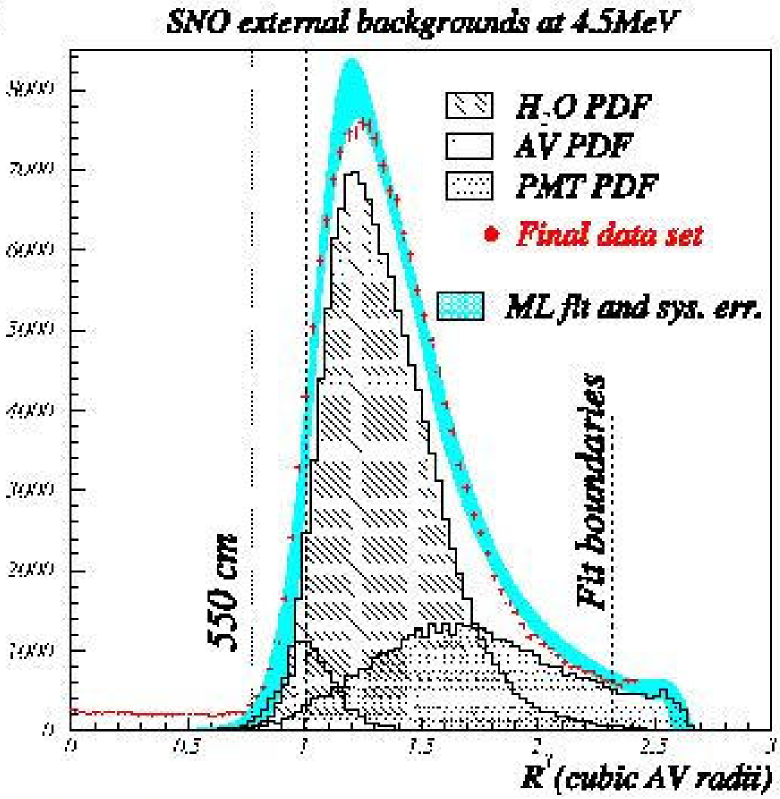


	D_2O	H_2O/AV
Neutron Events	44^{+8}_{-9}	27^{+8}_{-8}

Cherenkov Tails

Energy & Misreconstruction





	D_2O	H_2O	Acrylic	PMTs
Cherenkov Events	20^{+13}_{-6}	3^{+4}_{-3}	6^{+3}_{-6}	16^{+11}_{-8}

The Pure D_2O Phase Dataset

- Livetime: 306.4 days (November 2, 1999 ➡ May 27, 2001)
  Day: 128.5 days   Night: 177.9 days

- Energy Threshold: 5 MeV Kinetic

- Fiducial Volume Cut: 550 cm

- Total Number of Events after cuts: 2928
  Neutron Bkg 78^{+12}_{-12} Cherenkov Bkg 45^{+18}_{-12}

Signal Extraction Method

➤ Use Signal PDFs: R^3, $\cos\theta_{Sun}$, Energy < Monte Carlo / Analytic Functions

Signals	CC, NC, ES or Φ_e, $\Phi_{\mu\tau}$	Amplitudes Free	Perturb Observables $\vec{x}$, $\vec{u}$, E
Backgrounds	Photodisintegration Cherenkov	Amplitudes Fixed	Shift Amplitudes σ_{bkg}

↓

Maximum Likelihood Fit

↓

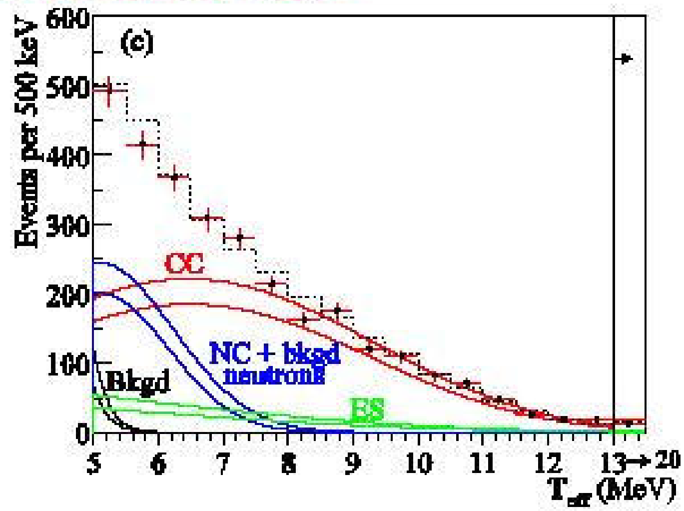
Signal Events | Systematic Error

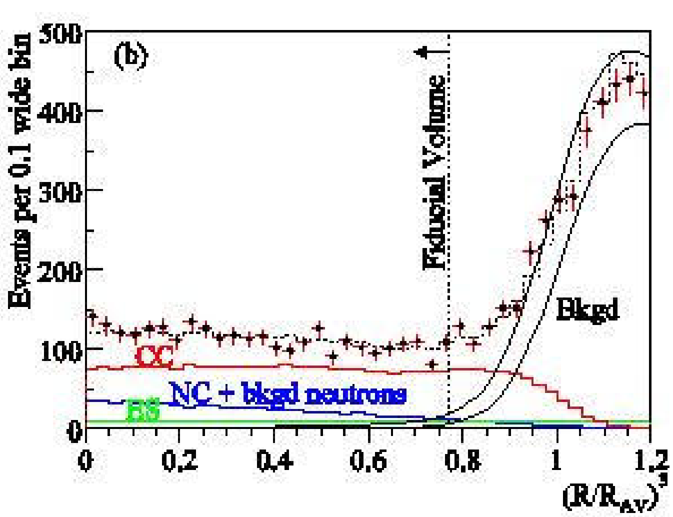
^{8}B CC Shape Constraint
No CC Shape Constraint
$A_{tot} = 0$ Day = Night

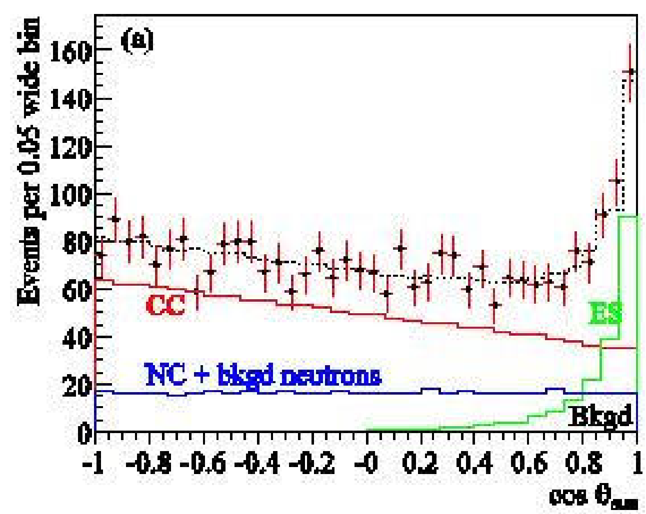
Shape Constrained Signal Extraction Results

#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}. $E_{Theshold} > 5$ MeV

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

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

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

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

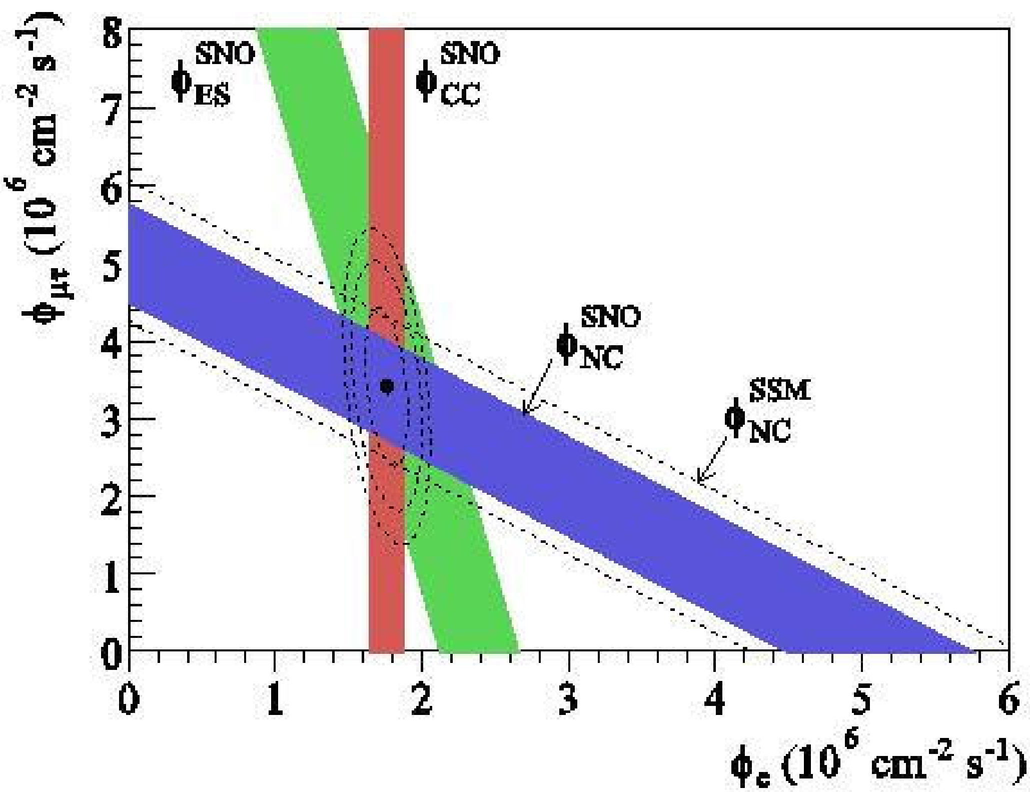
$\Phi_e = 1.76^{+0.05}_{-0.05}$ (stat.) $^{+0.09}_{-0.09}$ (syst.) $\times 10^6$ cm^{-2}s^{-1}

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

High threshold results agrees with first publication.

Physics Implication Flavor Content

$$\Phi_{ssm} = 5.05^{+1.01}_{-0.81} \quad \Phi_{sno} = 5.09^{+0.44}_{-0.43}{}^{+0.46}_{-0.43}$$



Strong evidence of flavor change

Solar Neutrino Flux

- ^{8}B SSM Flux

  BP01

  $\Phi(\nu_x) = 5.05^{+1.01}_{-0.81} \times 10^{6}\ cm^{-2}s^{-1}$

- ^{8}B SSM Flux: First SNO Result

  SNO + SK

  $\Phi(\nu_x) = 5.44^{+0.99}_{-0.99} \times 10^{6}\ cm^{-2}s^{-1}$

- Energy Constraint in ^{8}B Energy shape

  Signal extraction in R^3, $\cos\theta_{Sun}$, Energy

  $\Phi(\nu_x) = 5.09^{+0.44}_{-0.43}\ (stat.)^{+0.46}_{-0.43}\ (syst.) \times 10^{6}\ cm^{-2}s^{-1}$

- No Energy Constraint

  Signal extraction in R^3, $\cos\theta_{Sun}$

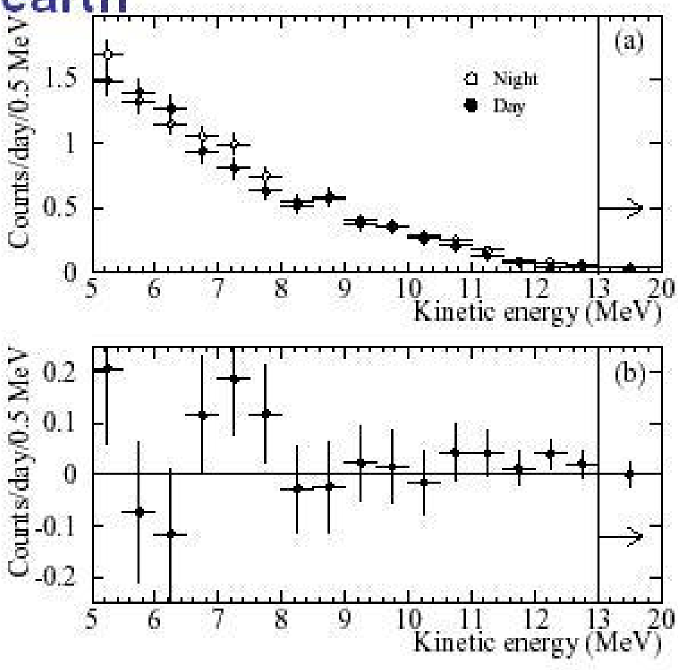
  $\Phi(\nu_x) = 6.42^{+1.57}_{-1.57}\ (stat.)^{+0.55}_{-0.58}\ (syst.) \times 10^{6}\ cm^{-2}s^{-1}$

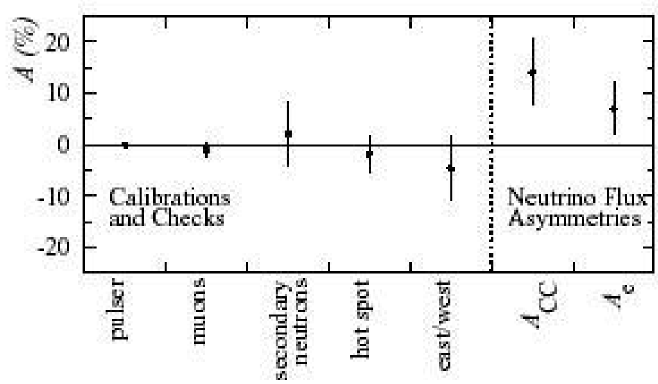
MSW and Day-Night Fluxes

Certain MSW oscillation solutions predict ν_s can change flavor while passing through the earth

Define Asymmetry

$$A_x = \frac{2^*(\Phi_{N,X} - \Phi_{D,X})}{(\Phi_{N,X} + \Phi_{D,X})}$$





A_e versus A_{total}

Signal Extraction in Φ_{CC}, Φ_{NC}, Φ_{ES}.

$$A_{cc} = 14.0 \pm 6.3^{+1.5}_{-1.4}$$

$$A_{nc} = 20.4 \pm 16.9^{+2.4}_{-2.5}$$

Signal Extraction in Φ_e, Φ_{total},

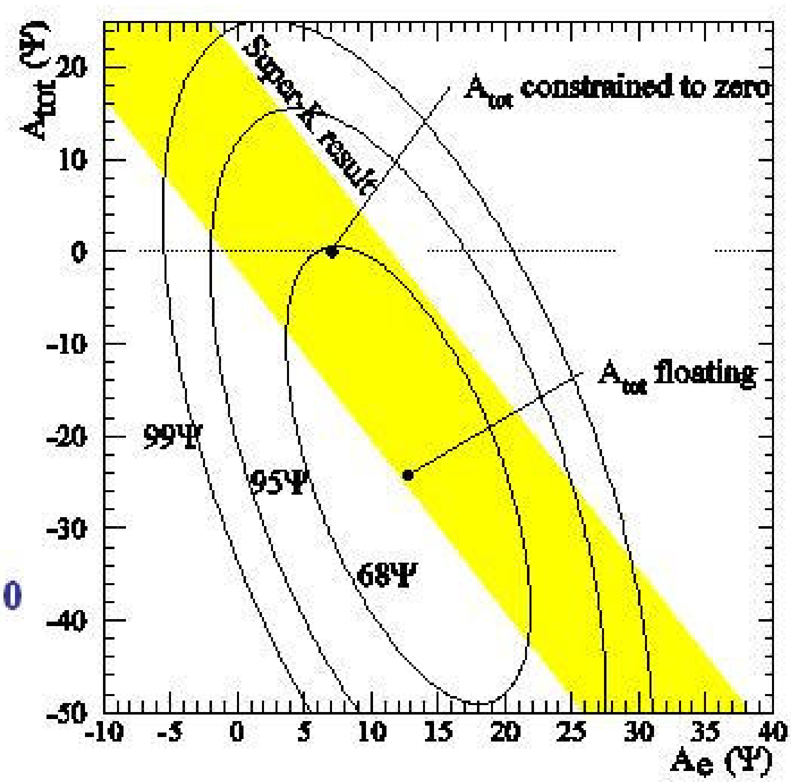
$$A_e = 12.8 \pm 6.2^{+1.5}_{-1.4}$$

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

Signal Extraction in Φ_e, Φ_{total}, + $A_{total} = 0$

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

$$A_e^{sk} = 5.3 \pm 3.7^{+2.0}_{-1.7}$$

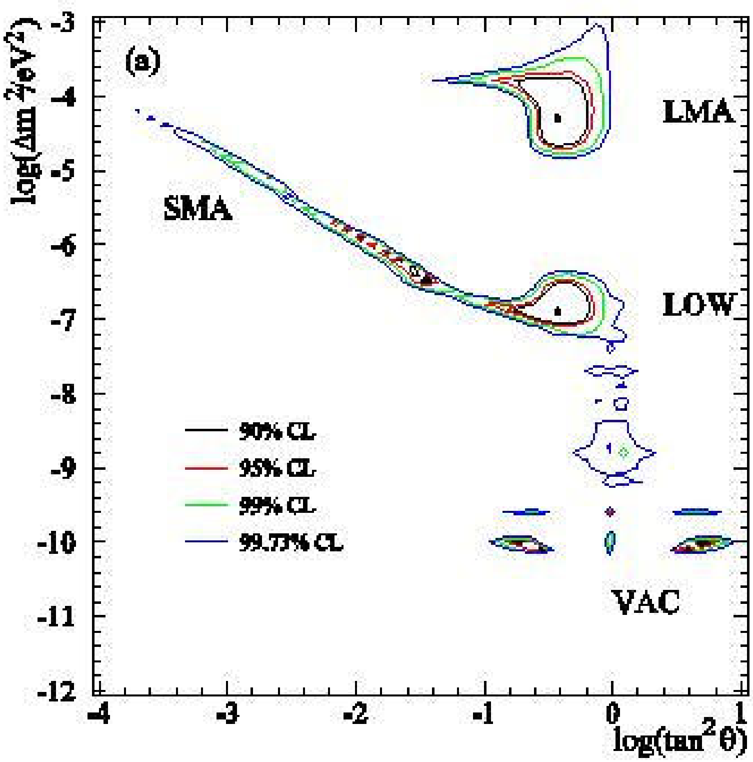


Inputs to Global Solar ν Analysis

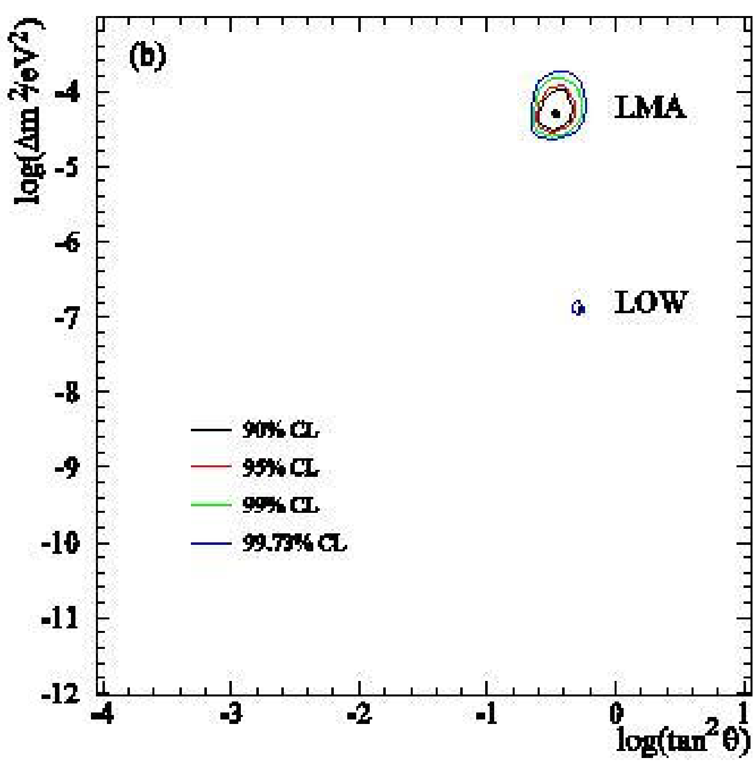
- Cl, latest Gallex/GNO, new SAGE, SK 1258-day dataset day spectrum and night spectrum
- SNO day spectrum (total: CC+NC+ES+bkgnd)
- SNO night spectrum (total: CC+NC+ES+bkgnd)
- ^{8}B floats free in fit, hep 1 SSM
- pp, pep, ^{7}Be, CNO SSM; solar model correlated uncertainties based upon Fogli, Lisi prescription
- MSW (Petcov) and QVO analytic approximation (Lisi et al.)
- numerical Earth MSW calculation (PREM)

Physics Interpretation Neutrino Oscillations

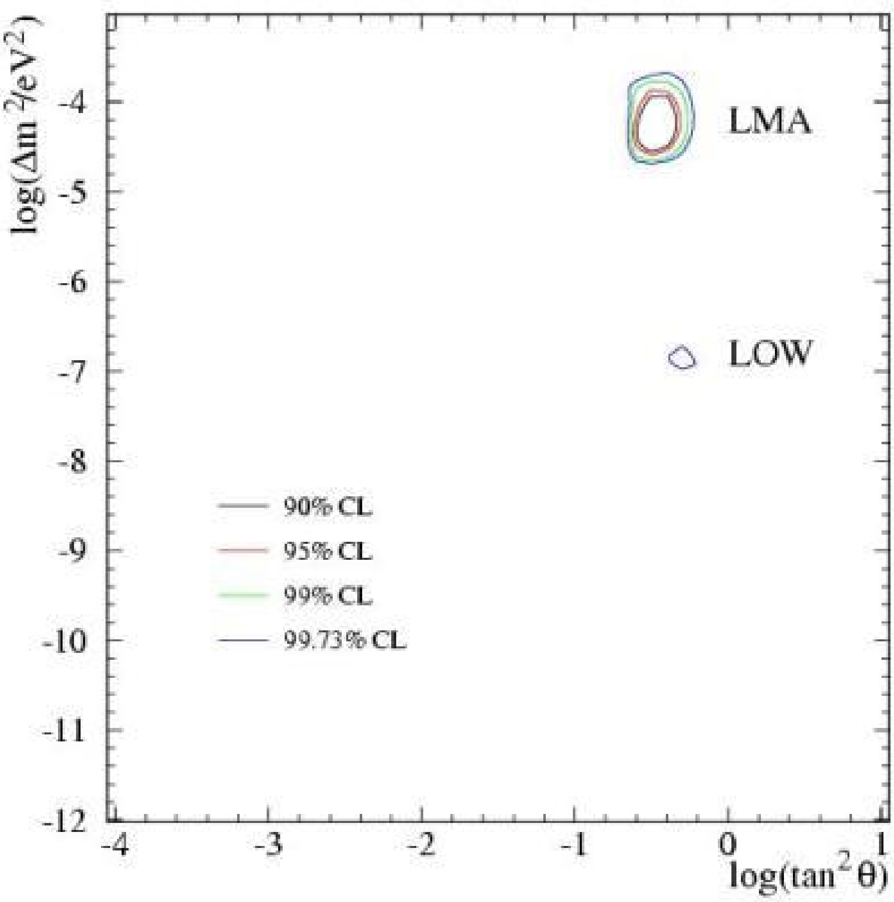
SNO Day and Night Energy Spectra Alone



Combining All Experimental and Solar Model information



Global Fit with total SNO spectrum



without separate day and night spectra

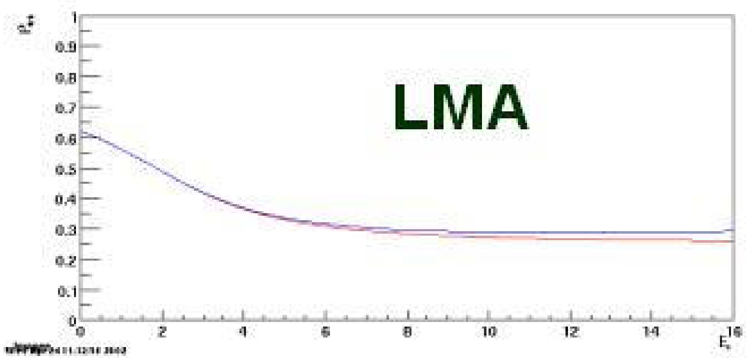
most of the MSW model constraints comes from SNO CC/NC!

Global Analysis Fit Results

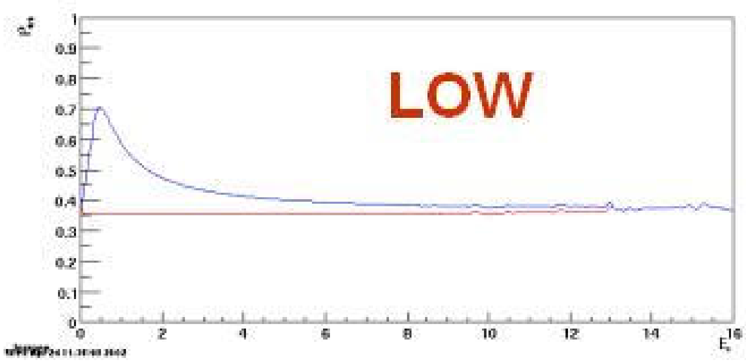
region	χ^2/dof	ϕ_B/SSM	A_e	Δm^2 (eV^2)	$\tan^2\theta$	CL
LMA	57.0/72	1.16	6.4%	5.0×10^{-5}	0.34	---
LOW	67.7/72	0.98	5.9%	1.3×10^{-7}	0.55	99.5%

- **SNO CC/NC measurement directly constrains the survival probability at high energy**
- **The LOW solution cannot accommodate the combined SNO and Ga experimental results**

LMA versus LOW



SNO NC: $5.86 \times 10^6\ cm^{-2}\ s^{-1}$
SNO CC day: $1.66 \times 10^6\ cm^{-2}\ s^{-1}$
SNO A_e: 6.4%
SK ES: $2.30 \times 10^6\ cm^{-2}\ s^{-1}$
SK A_{ES}: 3.5%
Ga rate: 72.8 SNU
Cl rate: 3.0 SNU



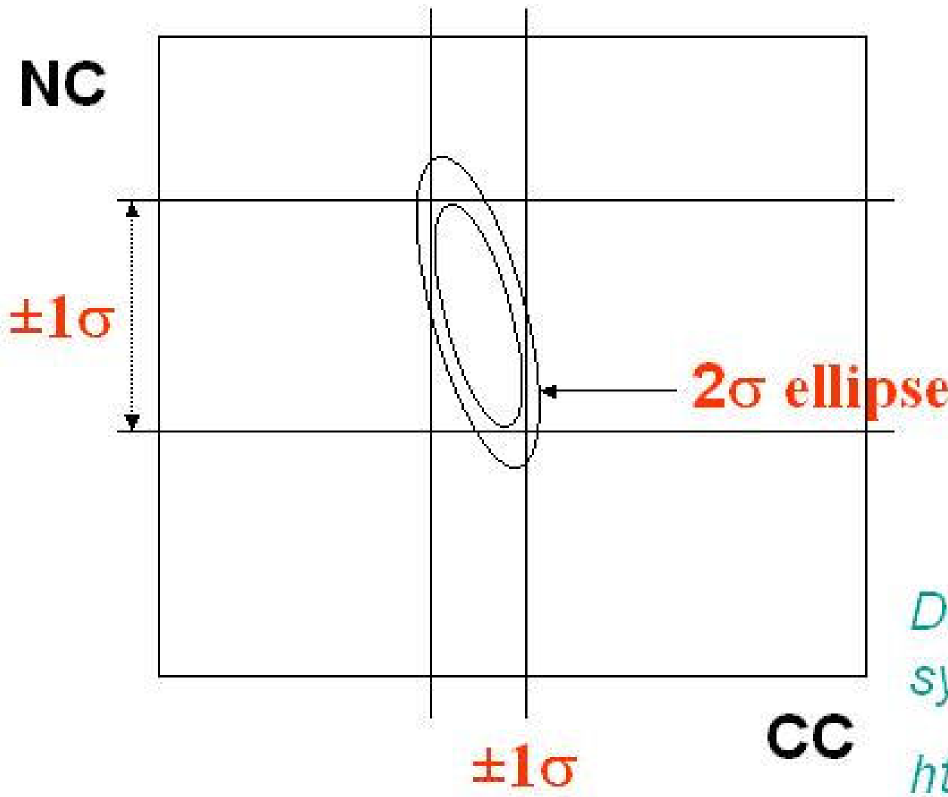
SNO NC: $4.95 \times 10^6\ cm^{-2}\ s^{-1}$
SNO CC day: $1.83 \times 10^6\ cm^{-2}\ s^{-1}$
SNO A_e: 5.9%
SK ES: $2.30 \times 10^6\ cm^{-2}\ s^{-1}$
SK A_{ES}: 4.4%
Ga rate: 61.2 SNU
Cl rate: 3.0 SNU

experimental: SK ES $2.32 \times 10^6\ cm^{-2}\ s^{-1}$; Ga 72.0 ± 4.5 SNU; Cl 2.56 ± 0.23 SNU

Many Reactions, One Experiment

- SNO reports three rate measurements
  - CC, NC, ES
  - statistically correlated since the rates are extracted from the same parent data distribution (e.g. energy spectrum, radial distribution, cos θ_{Sun})
  - detector-related systematics also introduce correlated uncertainties when comparing SNO rates (e.g. CC to NC)
  - theoretical uncertainties also have correlations
    - comparing CC to NC, cross section uncertainties partially cancel
- this is new in the global solar neutrino analysis (previously each experiment reported just one rate)

SNO CC and NC Correlations

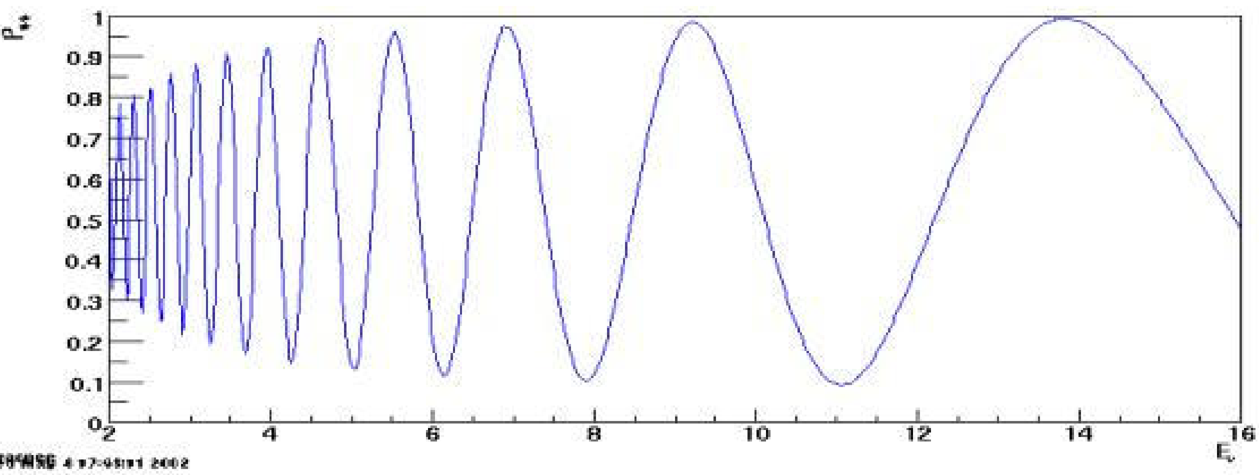


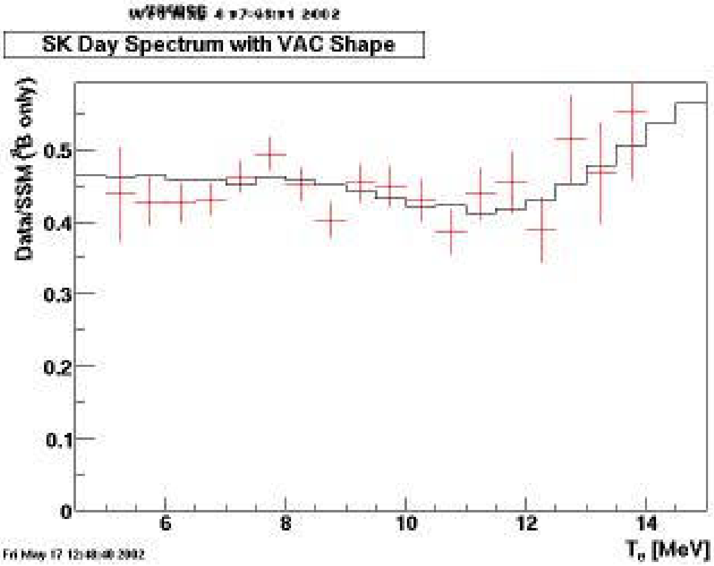
for illustration only...not an accurate plot of the correlation

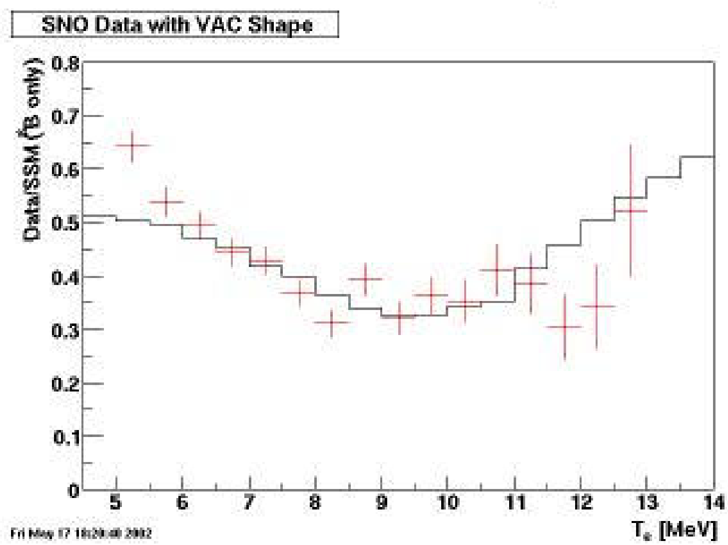
Details of SNO data and systematics available at:

http://sno.phy.queensu.ca

The Vacuum Region







Present and Future of SNO

The Salt Phase

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

- Higher n-capture efficiency
- Higher event light output
- Event isotropy differs from e^-
- Running since June 2001

Neutral Current Detectors

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

- Event by event separation

Nucl-ex/0204008, Nucl-ex/0204009

Conclusions

- **First NC Flux measurements yield clear evidence that the majority of ν_e produced in the Sun are transformed to ν_μ and/or ν_τ**
  - Null hypothesis - "No Weak Flavor Mixing" ruled out at 5.3 σ
  - Lowest Detection threshold yet for a real-time solar ν detector
  - Total ^8B flux measurement agrees well with Solar Models
  - Data in good agreement with previous SNO - SK CC/ES result

- **First SNO measurements of the Day-Night Asymmetries**
  - SNO Data is consistent with MSW oscillation interpretation
  - combined with global solar neutrino data favors LMA solution
  - "Dark side" solutions not allowed, indicating $m\nu_2 > m\nu_1$

Enhanced NC measurement, with NaCl underway since June 2001