Recent Results from the Sudbury Neutrino Observatory

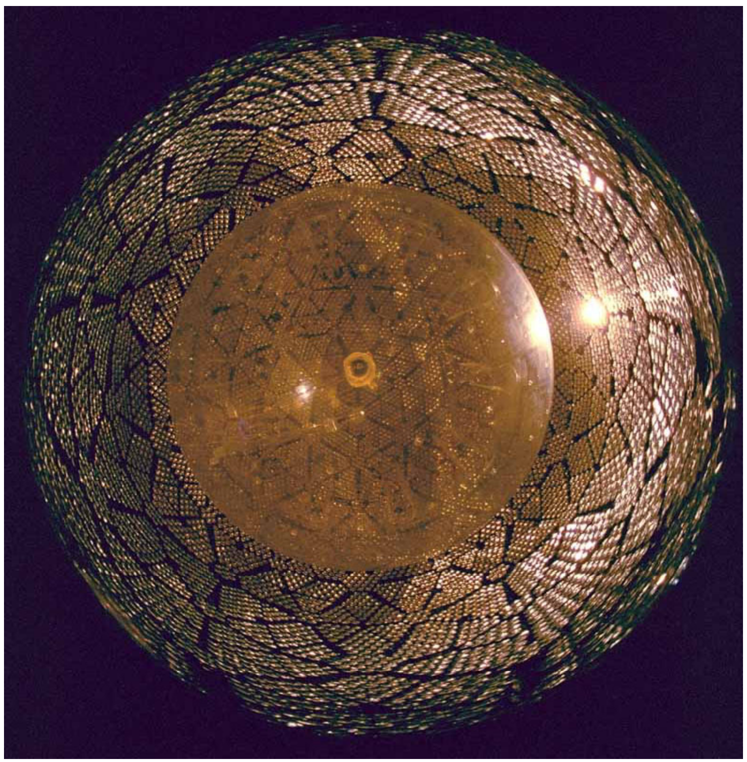

Photo courtesy of LBNL

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Outline

- The Solar Neutrino Problem
- The SNO Detector
- Calibration and Detector Response
- Signal Analysis of the SNO Data
- Physics Implications
- Conclusion

The Solar Neutrino Problem

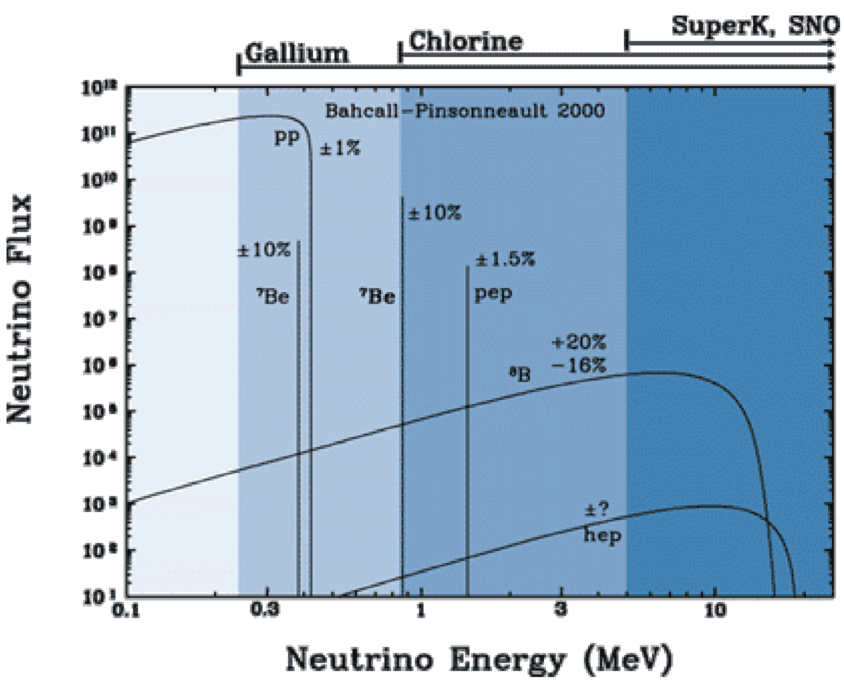


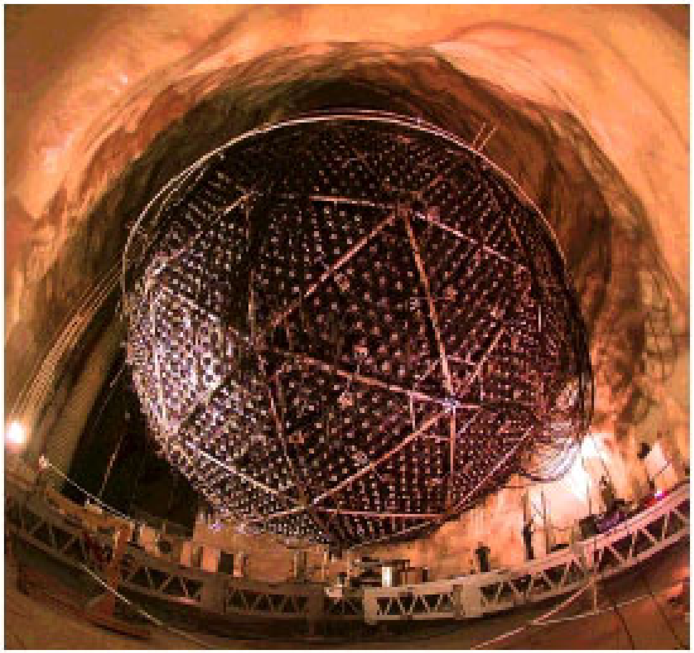
Figure by J. Bahcall

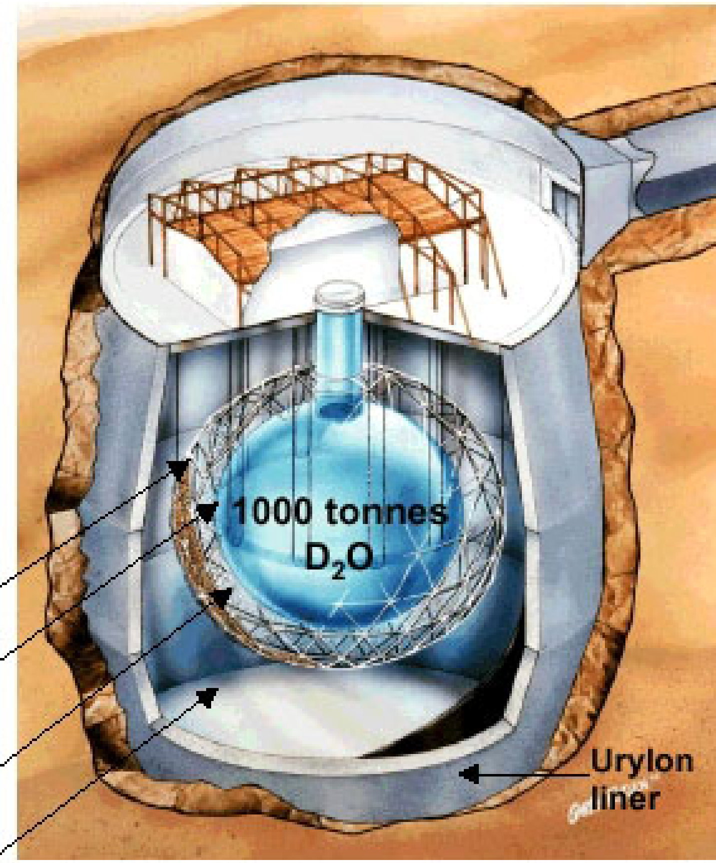
Experiment	Exp/SSM
•SAGE+GALLEX/GNO	0.58
•Homestake	0.33
•Kamiokande+SuperK	0.46
•SNO CC (June 2001)	0.35
SNO NC (April 2002)	~1

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

The SNO Detector

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





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})

ν Reactions in SNO

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

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

Beyond the Standard Model: Neutrino Mass and Mixing

Neutrino Flavor Transformation through Oscillations

If neutrinos have mass leptons can mix:

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

Flavor eigenstates are a mixture of mass eigenstates

$$\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$$

States evolve with time or distance

$$\nu_e = U_{e1}e^{-E_1 t}\nu_1 + U_{e2}e^{-E_2 t}\nu_2 + U_{e3}e^{-E_3 t}\nu_3$$

Matter Enhanced Oscillations (MSW)

Neutrinos in matter can acquire effective mass through forward scattering, ν_e can undergo both CC and NC scattering

→ MSW ν oscillations are dependent on ν energy and density of matter

Key signatures for ν oscillations

Measure total flux of solar neutrinos vs. the pure ν_e flux

Evidence for ν flavor change

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

June 2001

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

April 2002

Potential signal for ν oscillations

Φ_{day} vs Φ_{night}

April 2002

Comparing the solar ν flux at Day and Night

Certain ν oscillation models predict ν regeneration in Earth

$$\frac{[CC]_{DAY}}{[CC]_{NIGHT}} = \frac{[\nu_e]_{DAY}}{[\nu_e]_{NIGHT}} \neq 1$$

$$\frac{[NC]_{DAY}}{[NC]_{NIGHT}} = \frac{[\nu_e + \nu_\mu + \nu_\tau]_{DAY}}{[\nu_e + \nu_\mu + \nu_\tau]_{NIGHT}} \neq 1$$

Tests for Neutrino Oscillations

Solar Neutrino Physics with SNO

What can we learn from measuring the NC interaction rate and the Day/Night variations of the ^{8}B Flux?

- Total ^{8}B ν flux (NC)
  ν_e flux (CC)
  CC_{SNO}/NC_{SNO} → **Test of neutrino flavor change**

- Total flux of solar ^{8}B neutrinos
  → **Test of solar models**

- Diurnal time dependence
  → **Test of neutrino oscillations**

- Electron neutrino energy spectrum
  → **Distortions in ^{8}B spectrum?**

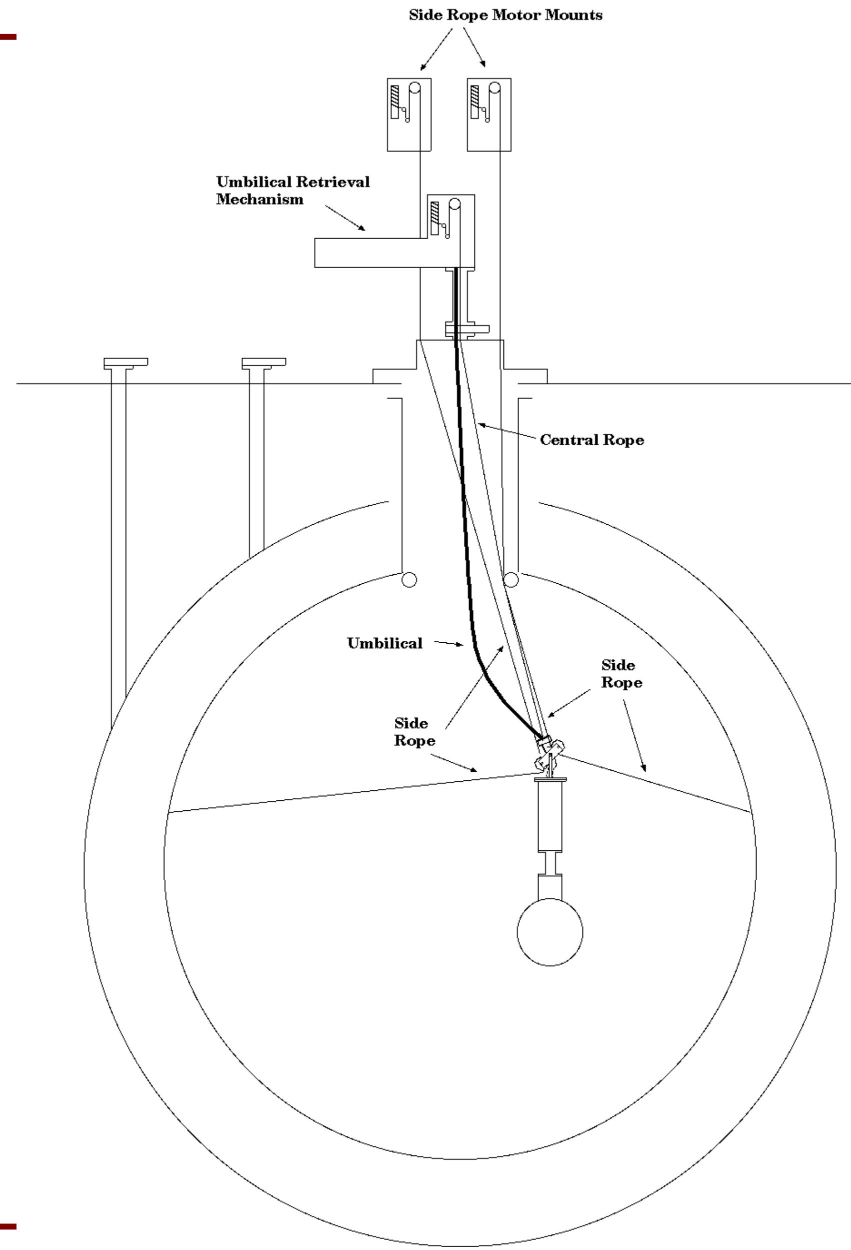
Monte Carlo

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

↕

Calibration

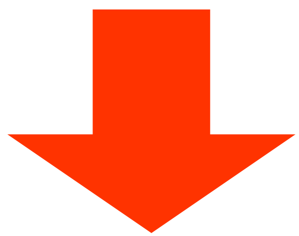
Pulsers	
Pulsed Laser	**337nm to 620 nm**
^{16}N	**6.13 MeV γ's**
$^{3}H(p,\gamma)^{4}He$	**19.8 MeV γ's**
^{8}Li	**<13.0 MeV β's**
^{252}Cf	**neutrons**
U/Th	**^{214}Bi & ^{208}Tl β–γ's**



Cherenkov Event Information

PMT Information

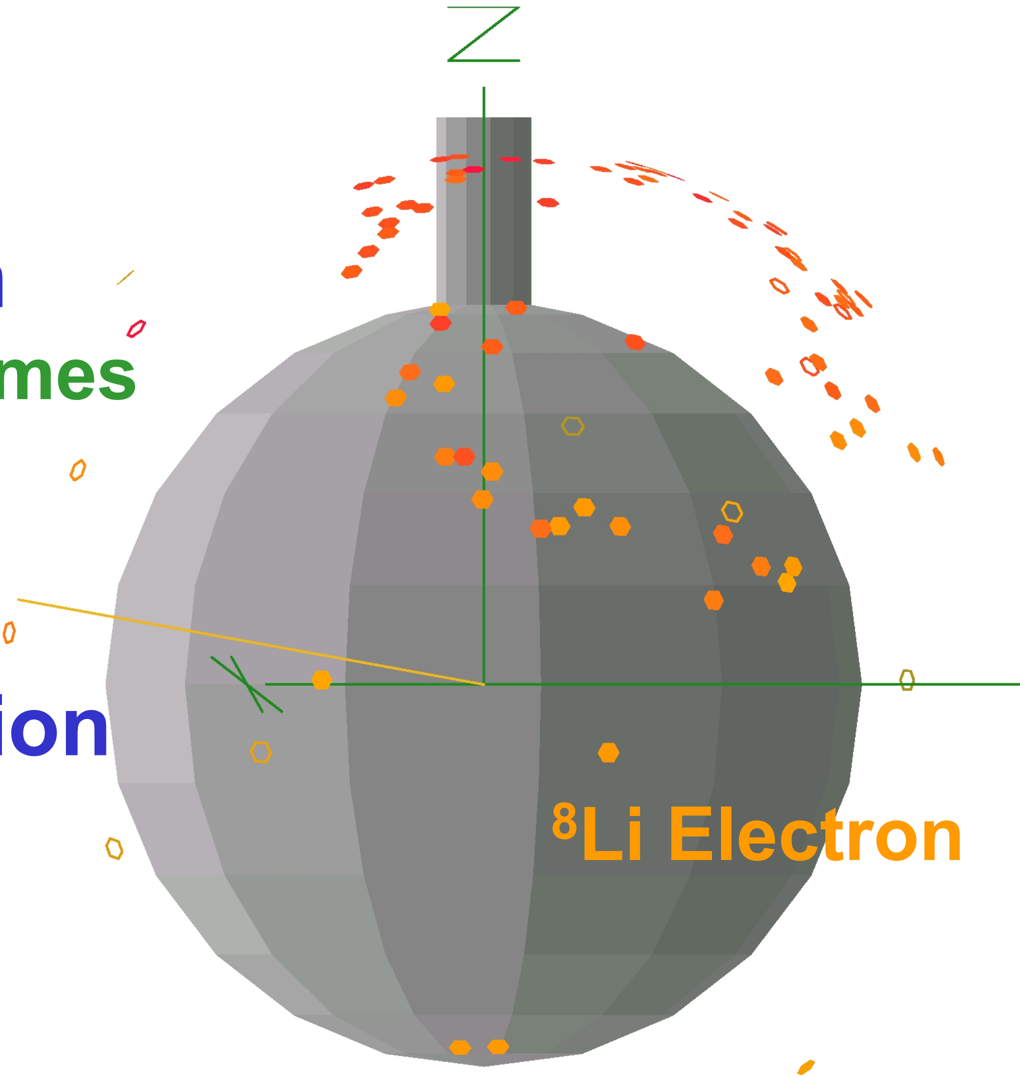
Positions, Charges, Times



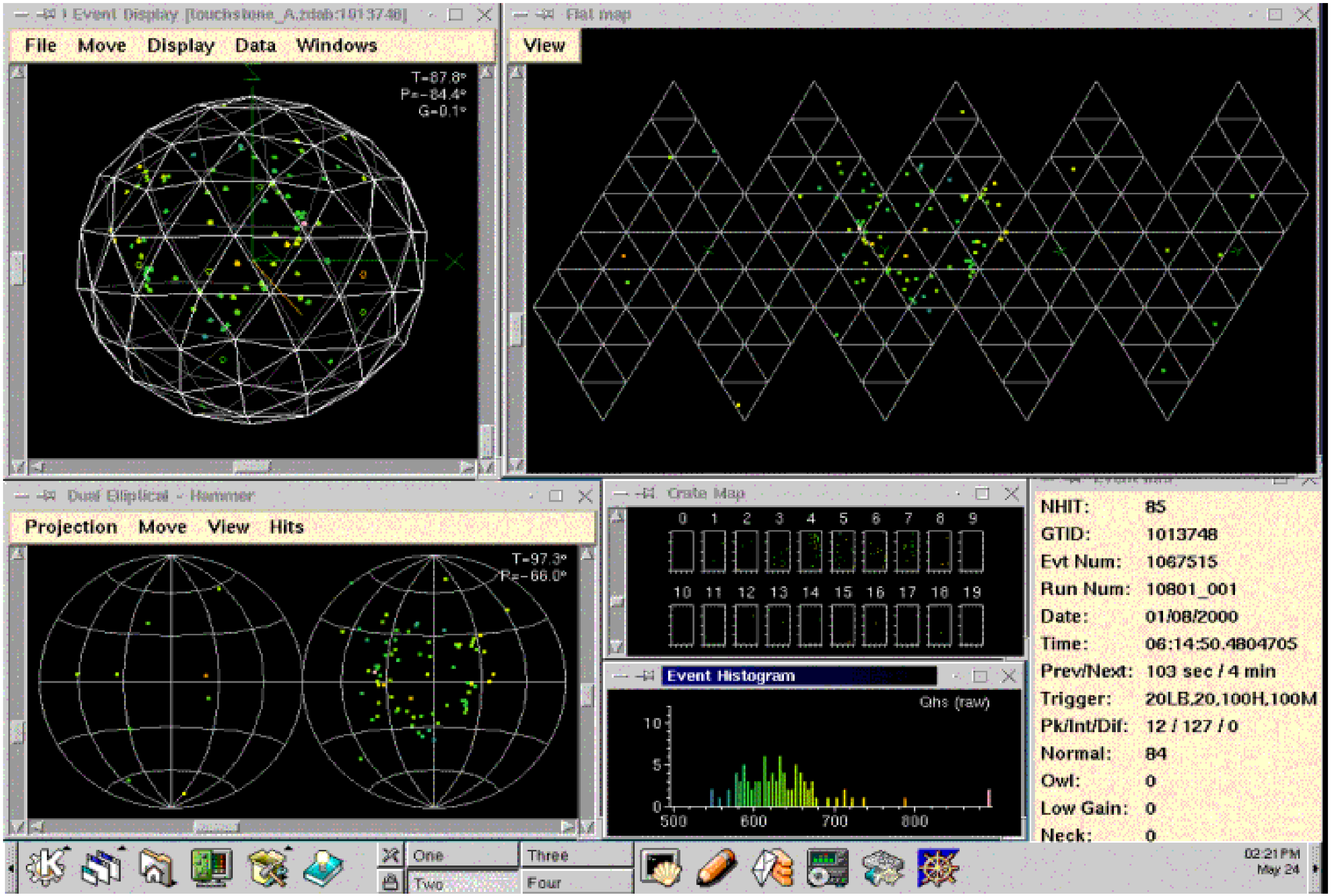
Event Reconstruction

Vertex, Direction

Energy, Isotropy



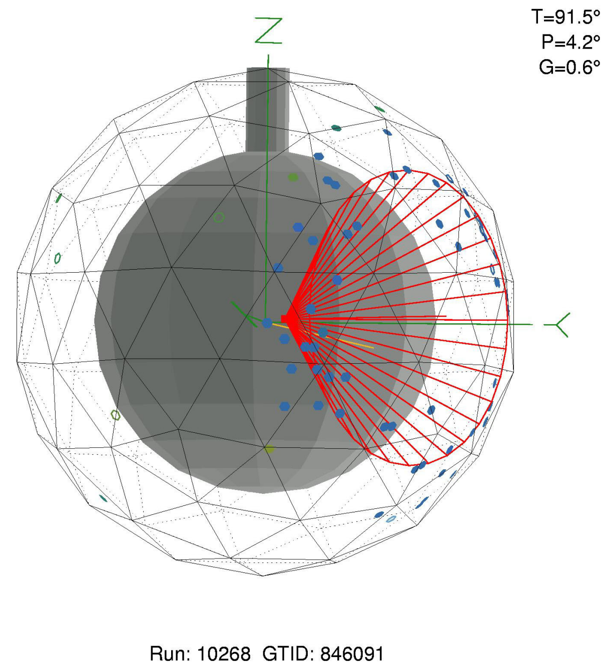
Candidate Neutrino Event

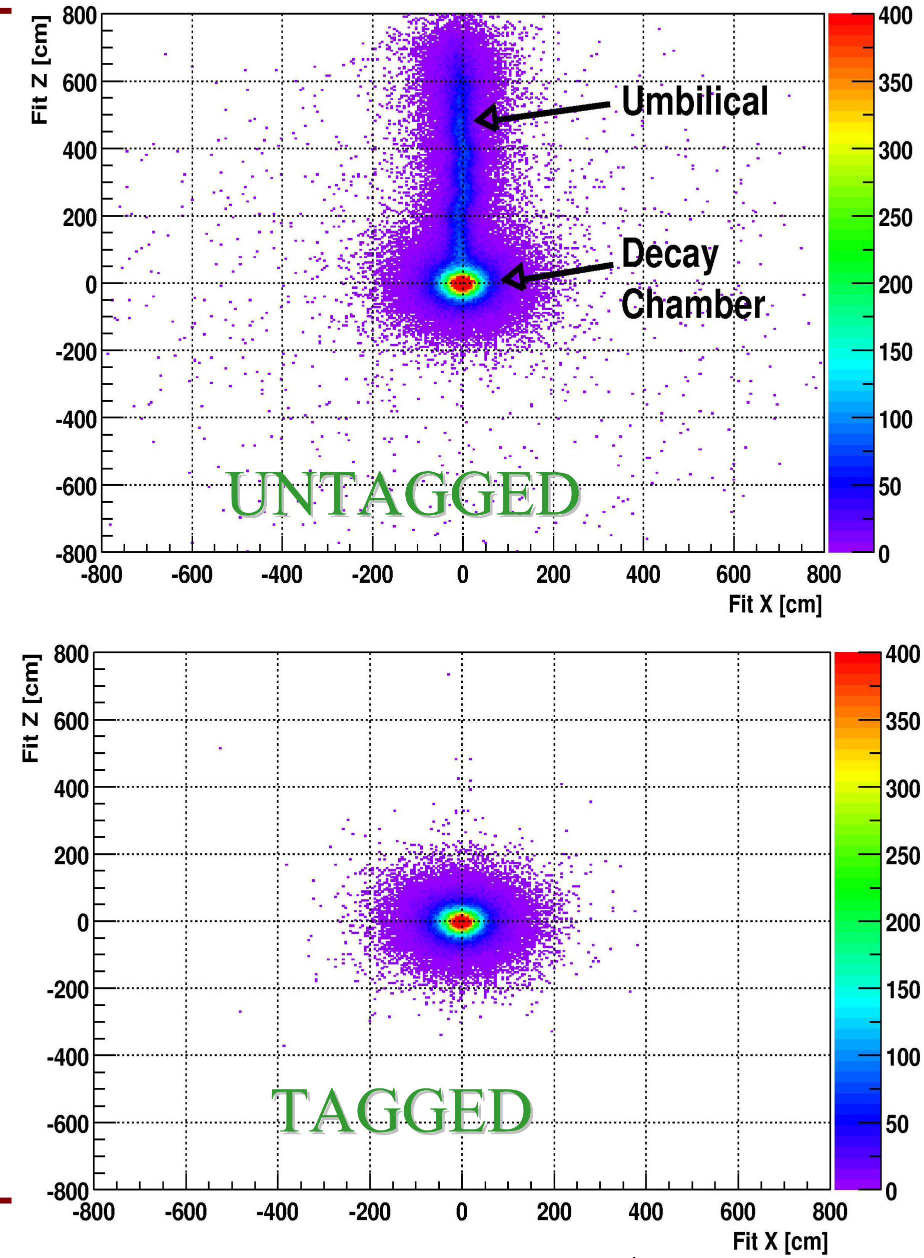


Vertex Reconstruction of ^{16}N Events

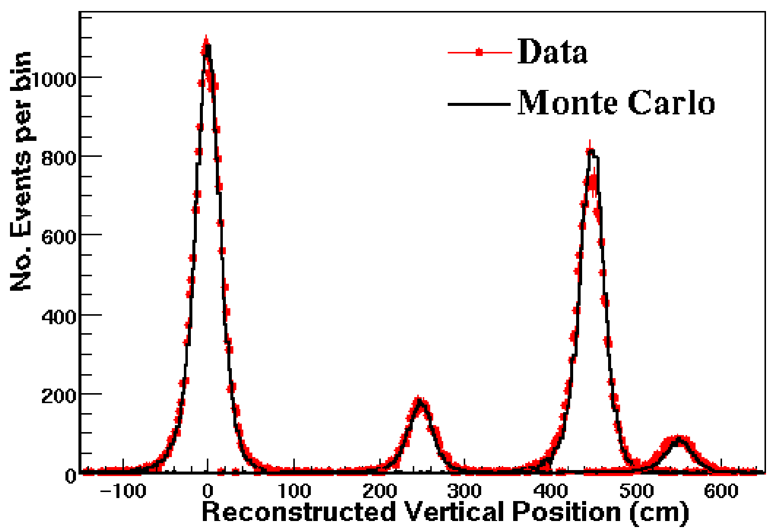
PMT times used to reconstruct event position

Resolution ~15 cm

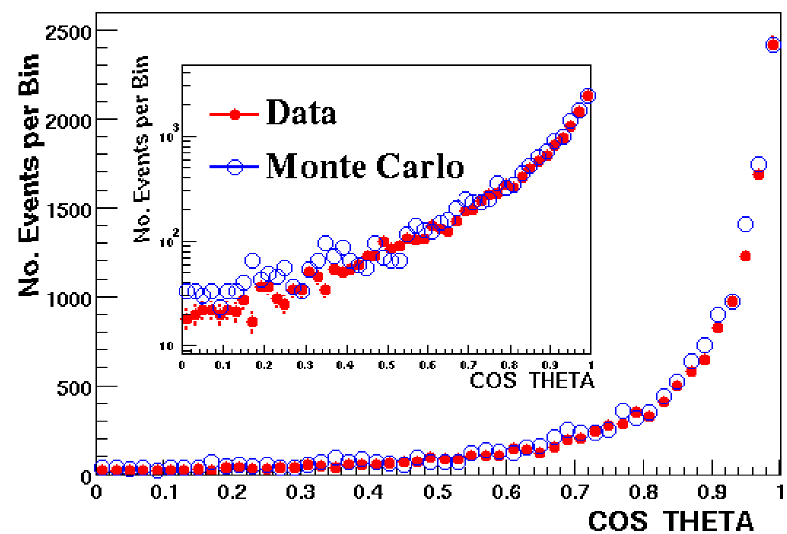




^{8}Li at different positions



^{16}N events far from source



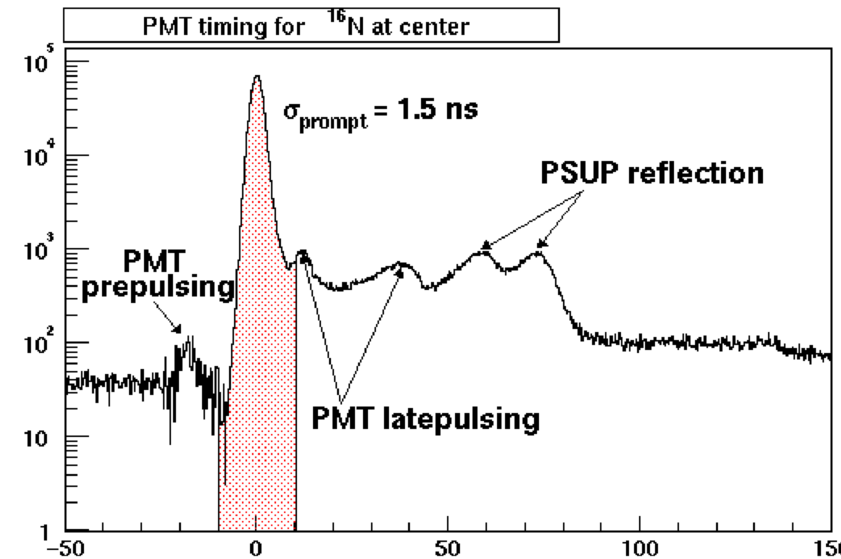
Flux Uncertainties ➡

	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

Energy Calibration

Prompt time cut applied to accept only direct photons

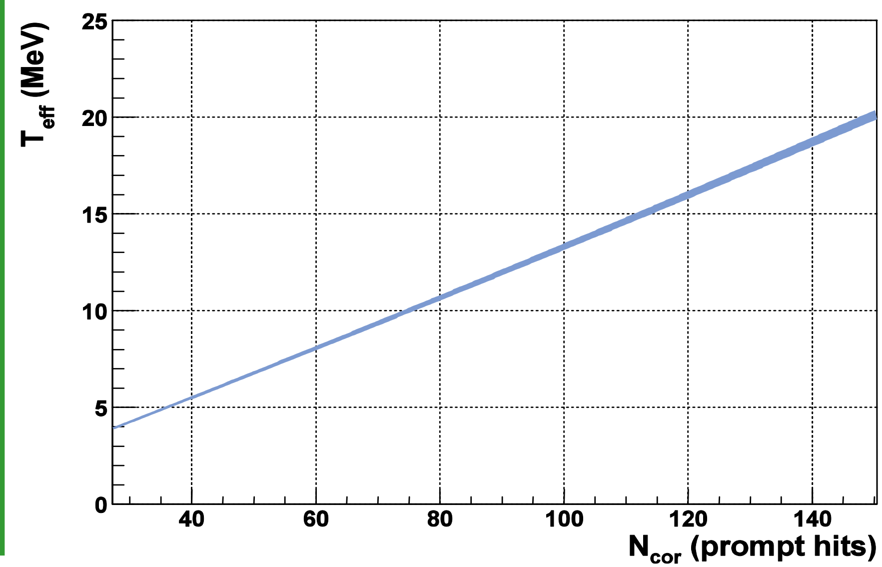
Reduces uncertainty due to scattering



Corrections for detector optics, dead PMTs, and gain applied

No. prompt hits vs. electron energy determined from MC calculations

(SNOMAN ➡ EGS)



Energy Calibration

Calibration

PMT response, optical properties

^{16}N Normalization

Response Uncertainties

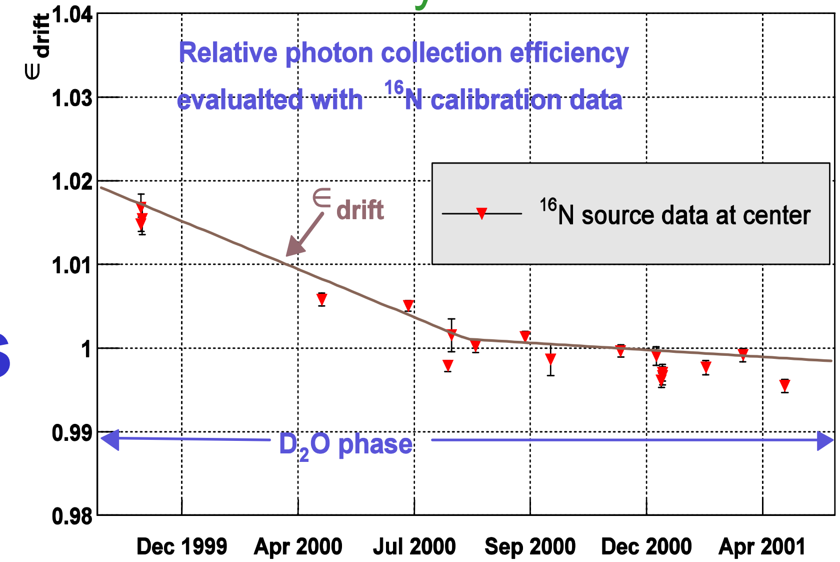
Scale, Resolution, Linearity

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

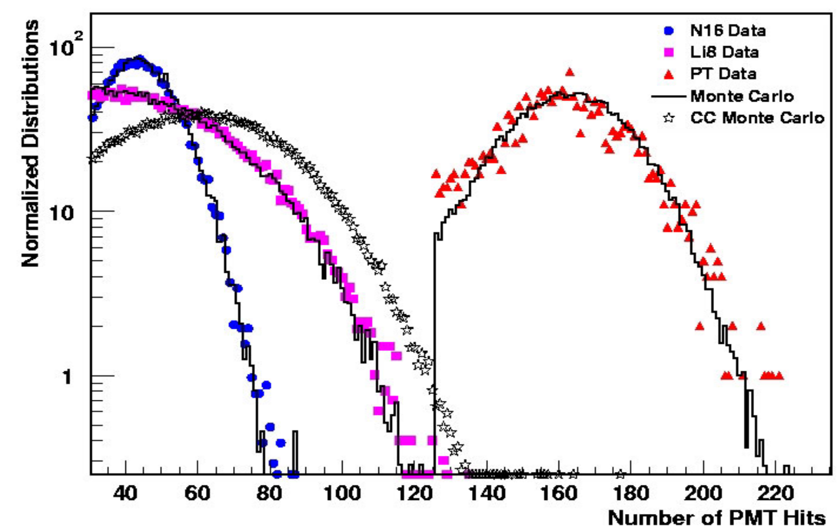
Flux Uncertainties (%)

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

Stability over time



Energy for various sources



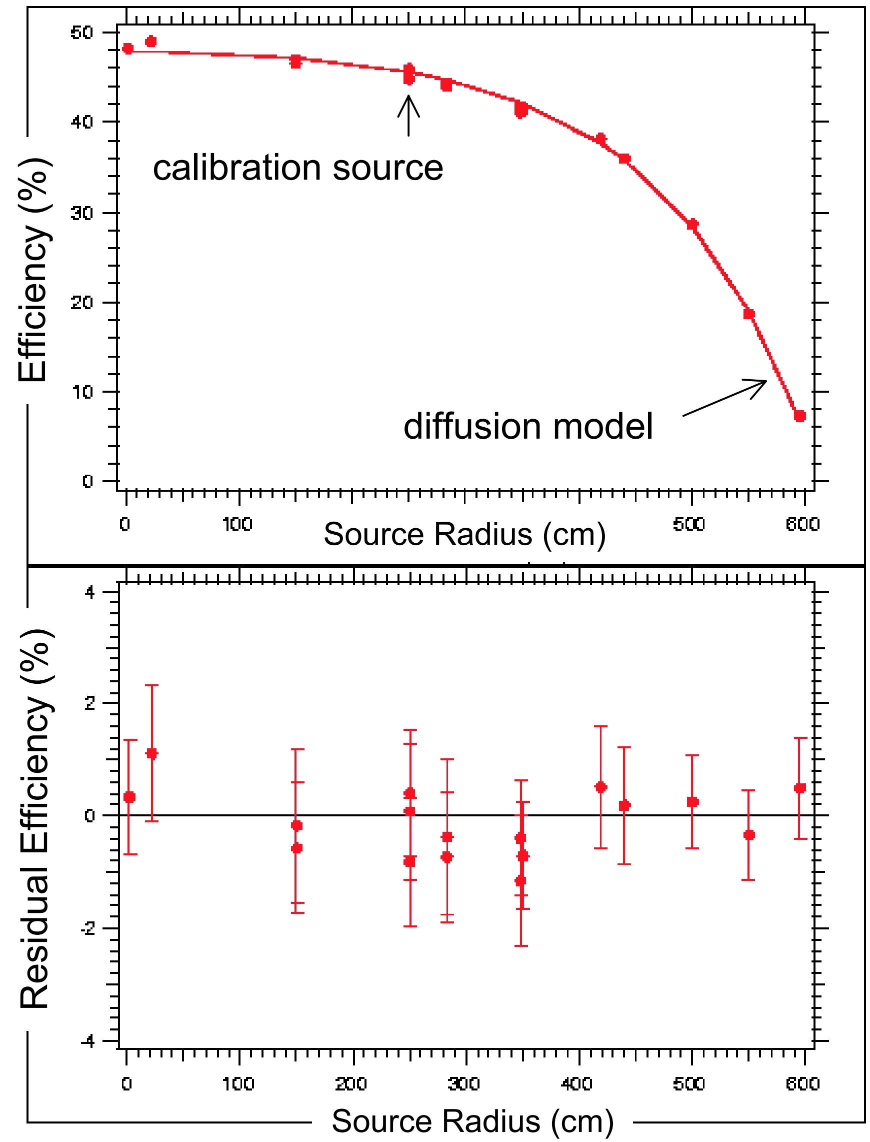
Neutron Capture Efficiency in D_2O

Determination of Capture Efficiency

Critical for understanding NC detection efficiency

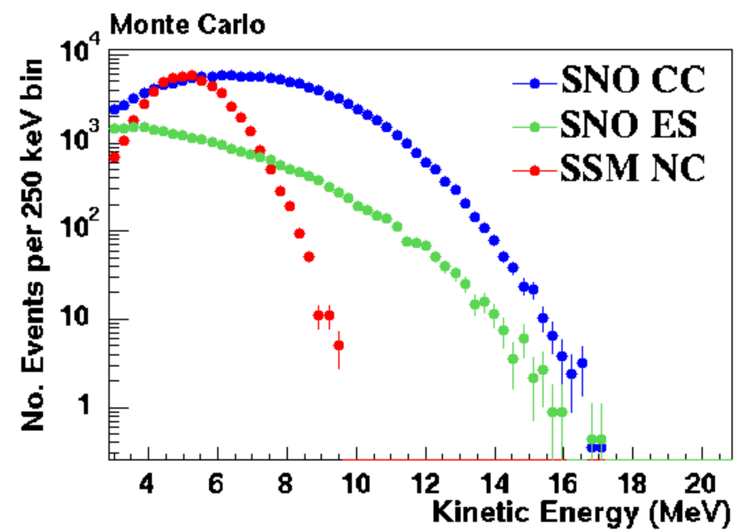
→ Calibration with neutron source
→ Diffusion model calculation

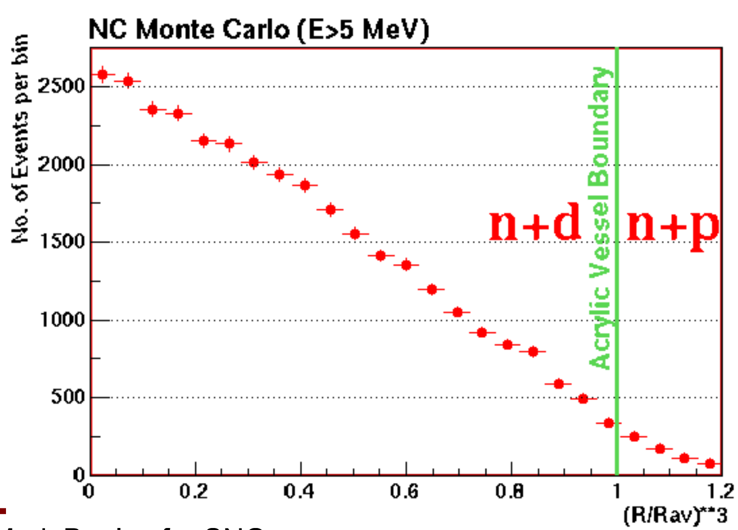
Neutron Capture Efficiency	
Total	29.90 ± 1.10 %
With threshold and fiducial cut	14.38 ± 0.53 %

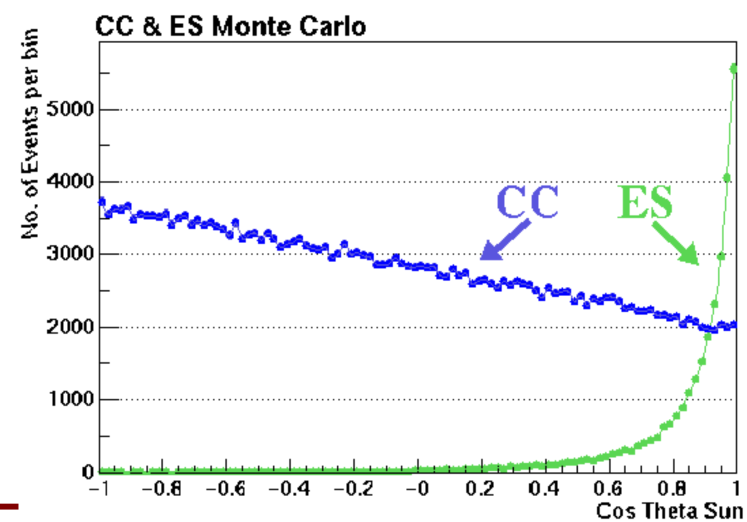


- **Hits and Energy**
- **Direction from Sun**
- **Radial Response**

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







Components in the SNO Dataset

Neutrino Events

Charged-current (CC)
Neutral-current (NC)
Elastic scattering (ES)

Low-Energy Backgrounds

- Internal photodisintegration from U, Th in D_2O
- PMT β-γ
- Backgrounds from PMT support structure and cavity

High Energy Backgrounds

- Backgrounds from PSUP and cavity
- Muon-induced spallation

Instrumental Backgrounds

- PMT flashers
- High voltage breakdown
- Hot cards, etc.

Energy, fiducial volume, and other cuts applied

High Level Data Cuts

I. Reconstruction Figures of Merit

II. In-Time Light Fraction

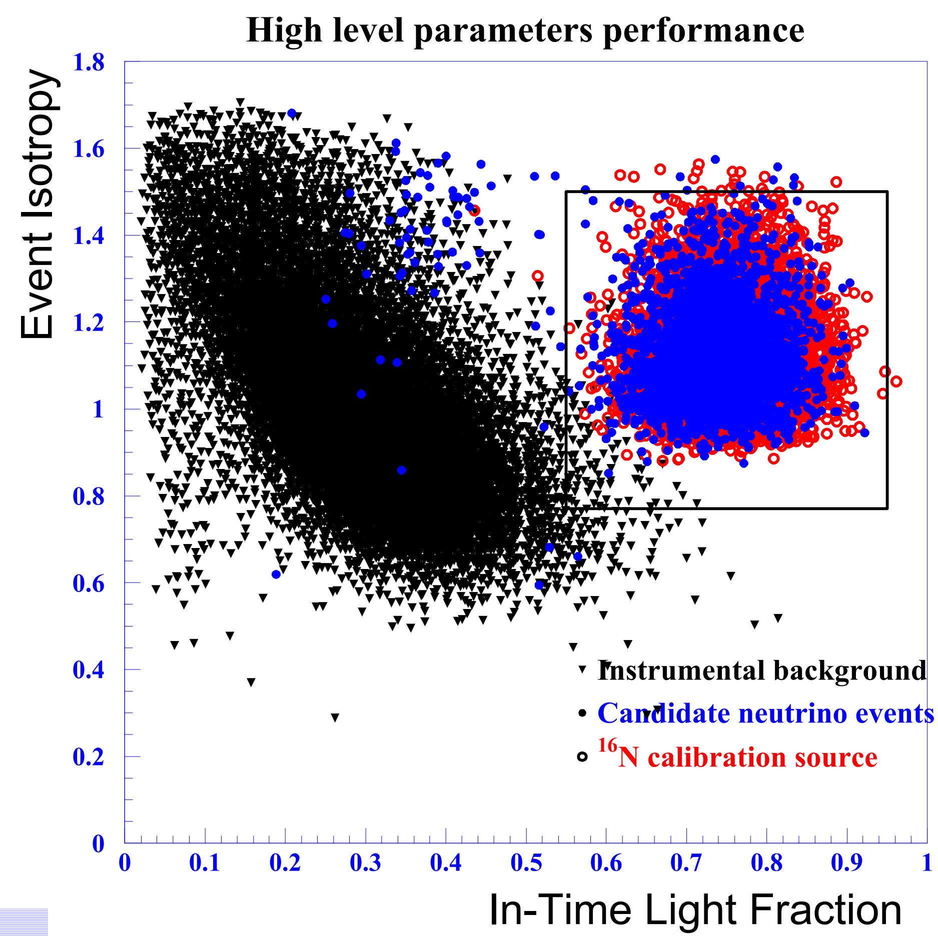
→ uses detailed PMT time distributions

III. Event Isotropy

→ Average angle between hit PMTs

Event Isotropy

- Discriminates between Cerenkov electron and multiple vertices
- Tests hypothesis of single-particle events



Signal loss from triggered ^{16}N, ^{8}Li, and neutron sources:

CC, ES	**1.4** +0.4/-0.2 **%**
Neutrons	**2.3** +0.4/-0.2 **%**

Residual instrumental contamination from bifurcated analysis: **< 0.2%**

Measuring U/Th Content

Ex-situ

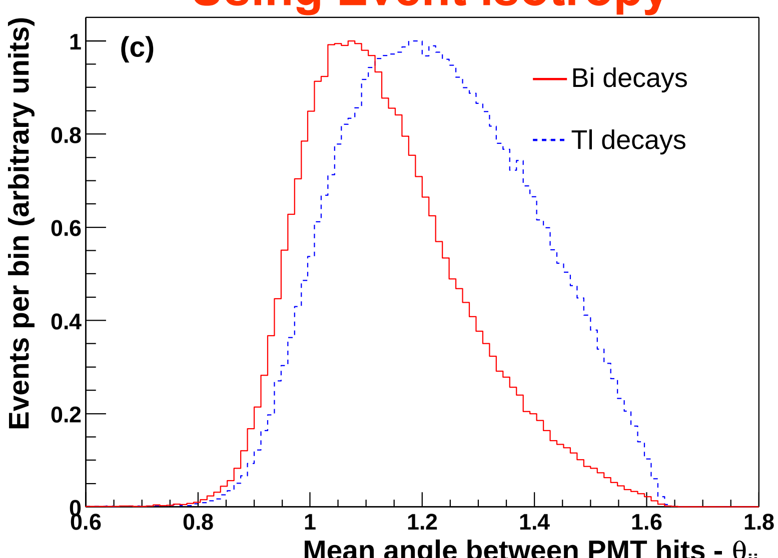
- **Ion exchange (^{224}Ra, ^{226}Ra)**
- **Membrane Degassing (^{222}Rn)**

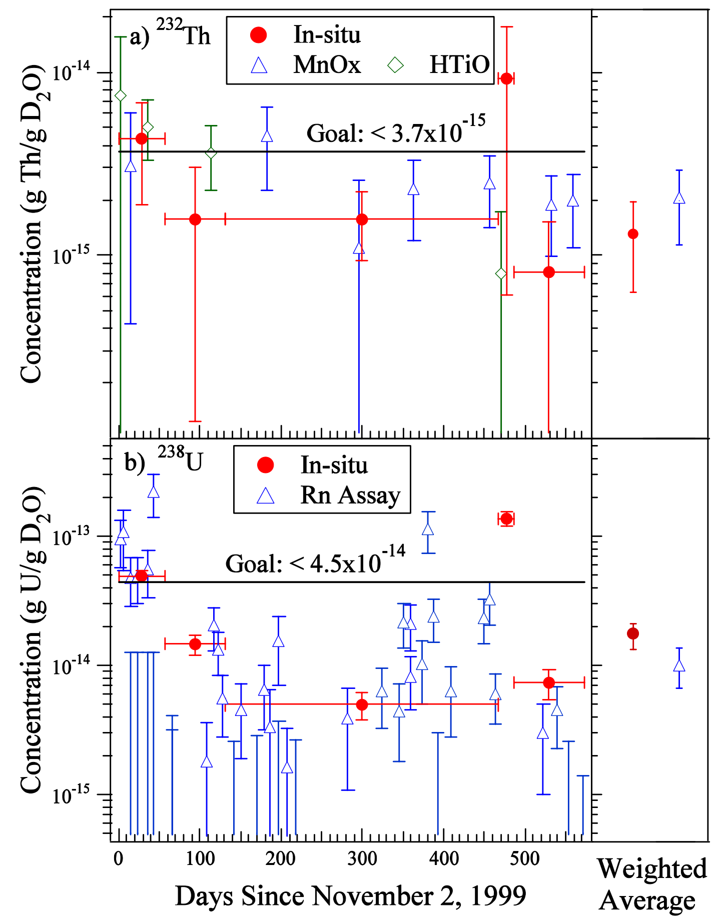
count daughter product decays

In-situ

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

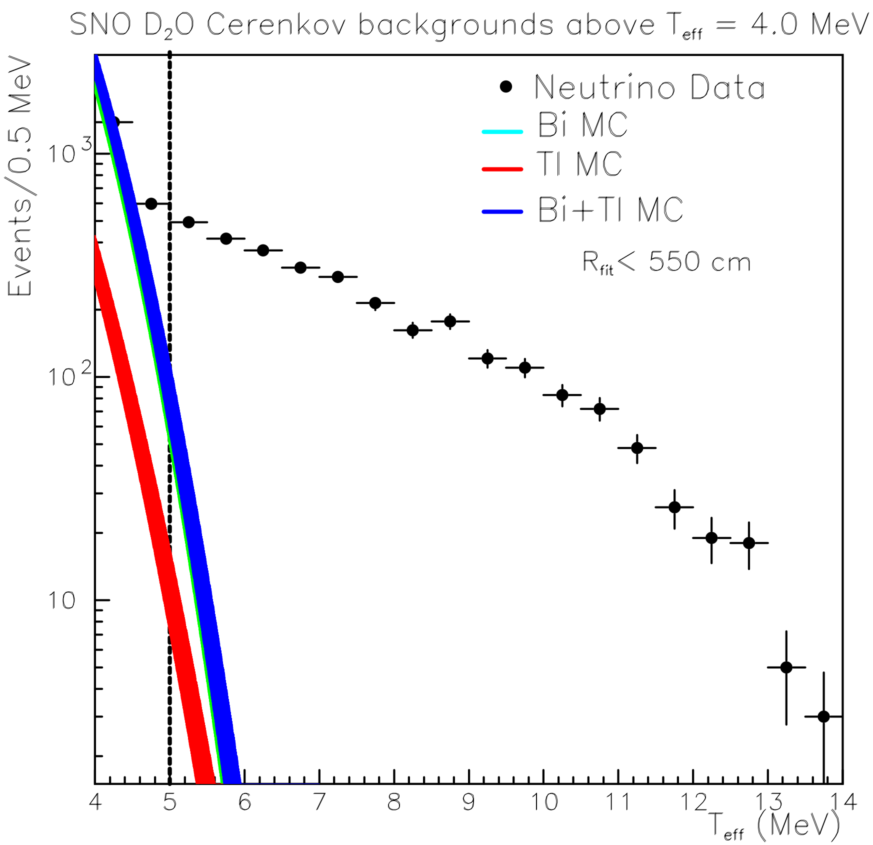
Using Event isotropy

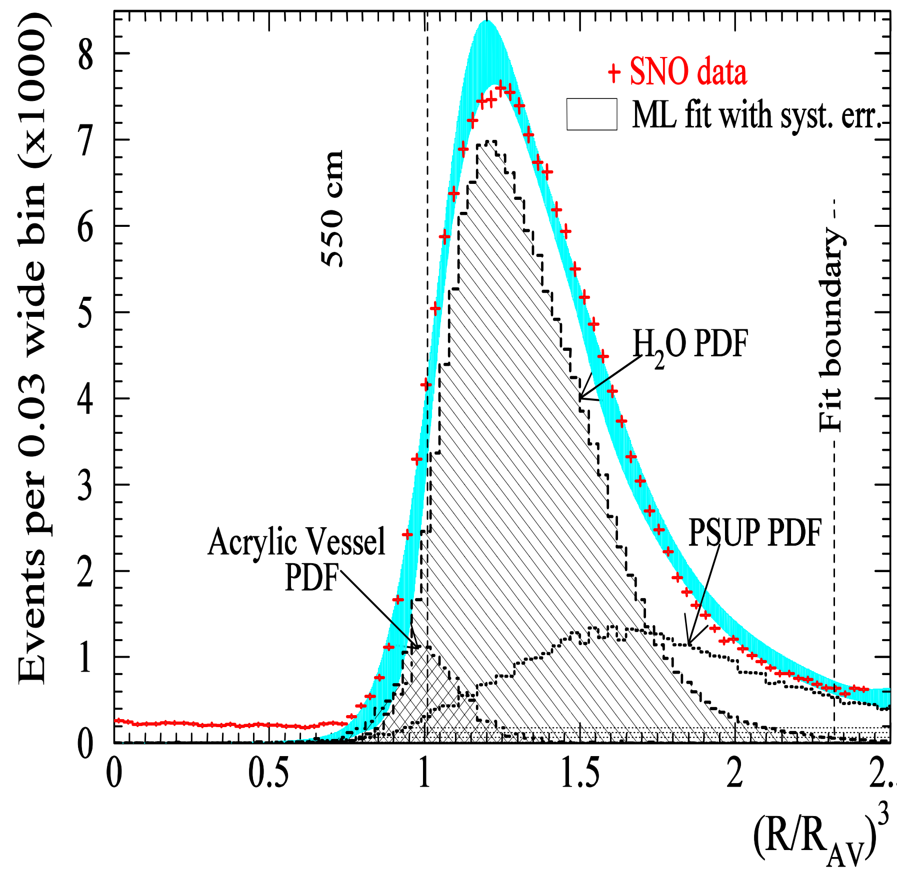




Neutron Events	D_2O	H_2O/AV
	44^{+8}_{-9}	27^{+8}_{-8}

Cherenkov Tails (From Energy Resolution and Event Mislocation)





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

Detector Conditions in the Pure D_2O phase

Data Set:	**Nov 2, 1999 - May 27, 2001**
Neutrino Livetime:	**306.4 live days**

Channel threshold:	~ 0.25 photo-electrons
Multiplicity trigger:	18 PMT hits within 93 ns
Trigger efficiency:	100% efficiency at ~ 3 MeV

Instantaneous Trigger Rate	~ 15-18 Hz
Hardware Threshold	~ 2 MeV

Analysis Threshold	5 MeV kinetic
Fiducial Volume Cut	550 cm
Total Number of Events after cuts	2928
Neutron Background Events	78 +- 12
Cherenkov Background Events:	45 +18,-12

Data Flow & Instrumental Background Cuts

Data Flow

Analysis Step	Events
Total Event Triggers	450,188,649
Neutrino Data Triggers	191,312,560
NHIT ≥30 (Analysis Threshold)	10,088,842
Instrumental Background	7,805,238
High Level Cuts	3,418,439
Fiducial Volume Cut	67,343
Energy Threshold	3440
Muon Followers	2928
Candidate Event Set	**2928**

Instrumental Background Removal

- Charge
- Timing
- PMT hit Geometry
- Event Rate
- PMT Veto Tubes

Cerenkov Nature of Events

- prompt light
- single particle event

Instrumental removal: **Two independent methods**

Signal loss: **0.4±0.3%**within $R_{fit} \leq 550$ cm from ^{16}N, ^{8}Li, and the laser ball

Signal Analysis

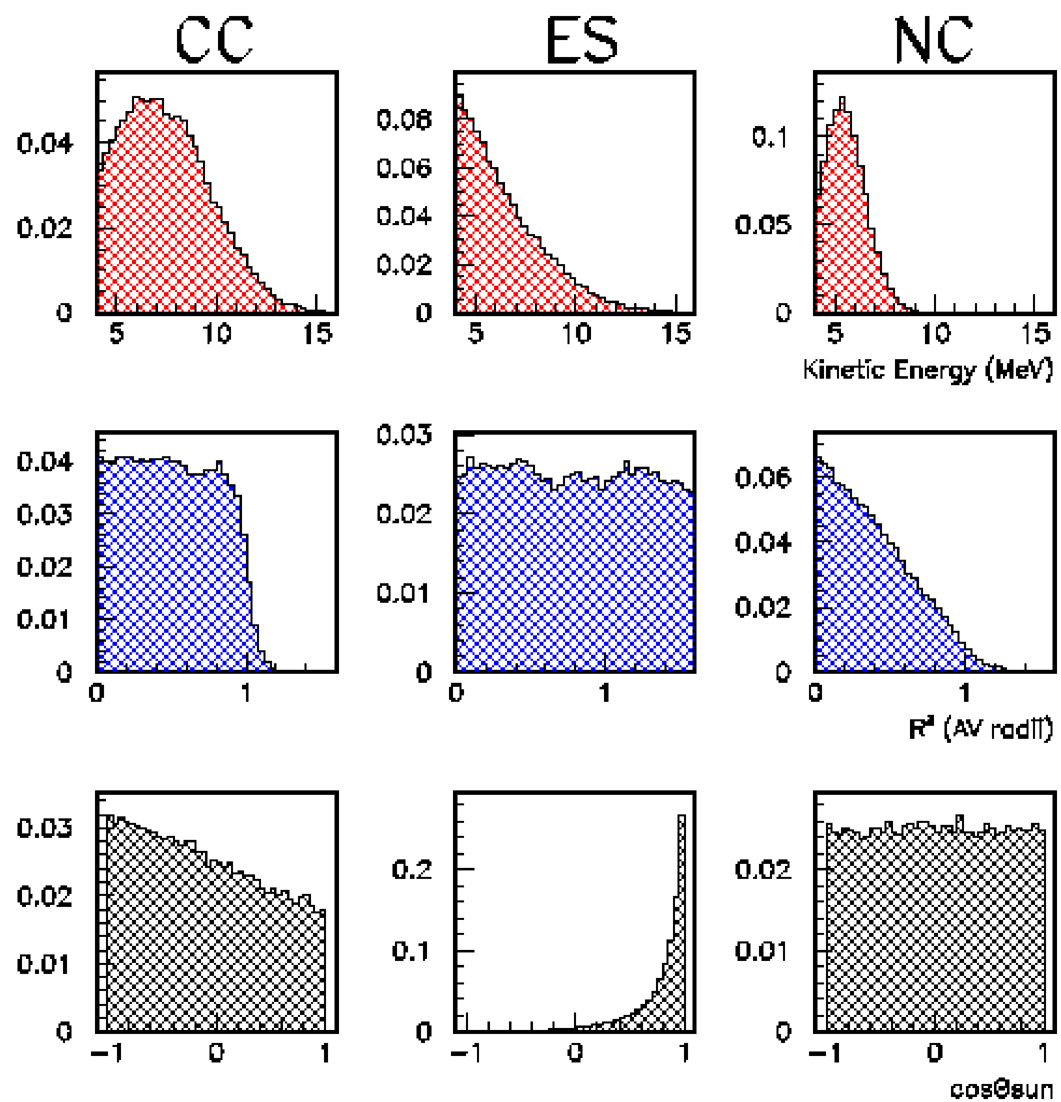
- Once response functions and uncertainties are determined, we can generate neutrino signal PDFs (both through Monte-Carlo calculations and analytically)

$$F_{CC}(r, E, \cos\theta_{sun})$$
$$F_{ES}(r, E, \cos\theta_{sun})$$
$$F_{NC}(r, E, \cos\theta_{sun})$$

→ SNO response in event radius, energy and direction to solar neutrinos through CC, ES, and NC reactions

Signal Analysis

To extract the CC, ES, NC signal SNO performs a Maximum likelihood statistical separation of these signals based on distributions of the SNO observables.



Signal Analysis

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

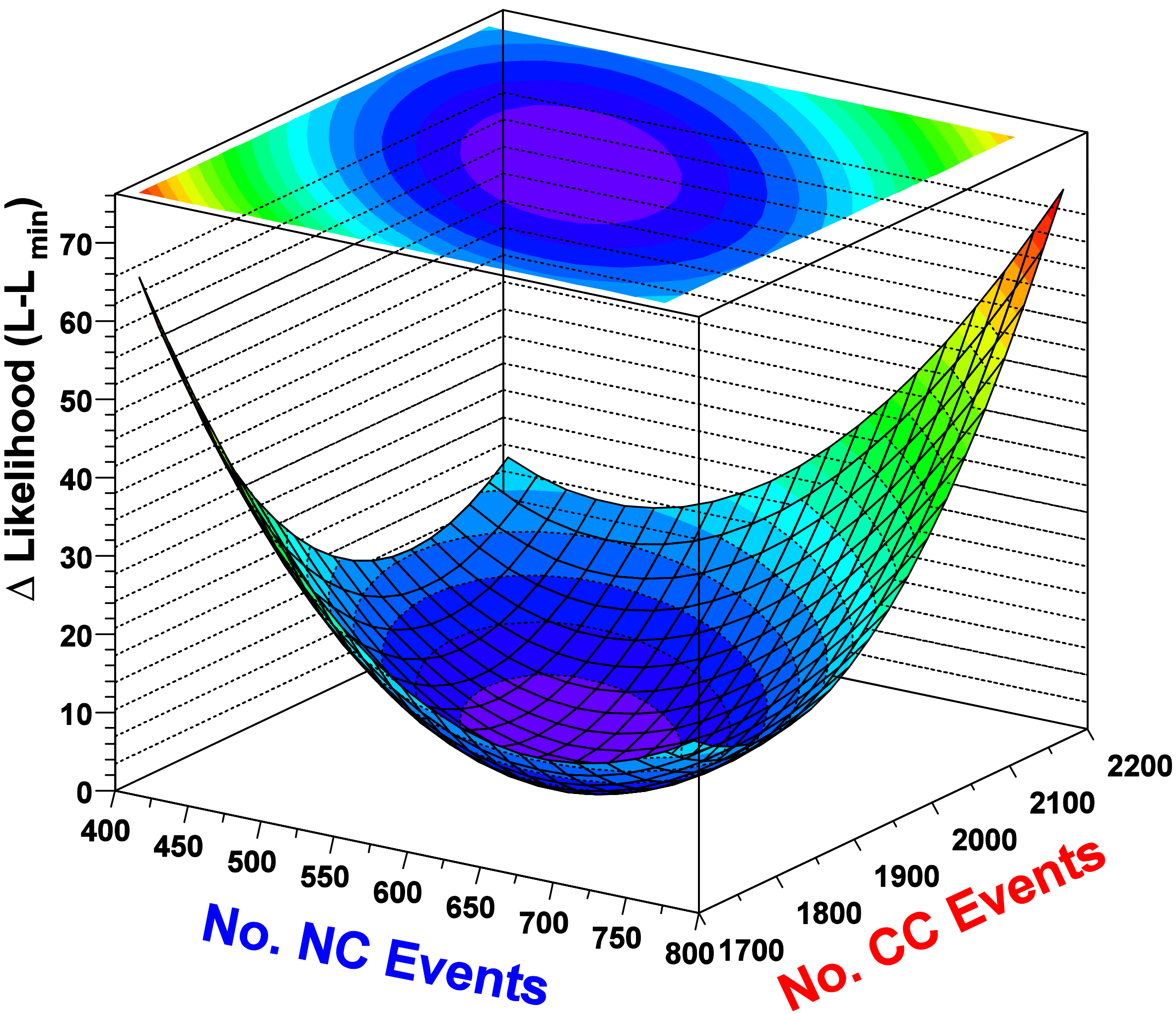
Signals	CC, NC, ES or Φ_e, $\Phi_{\mu\tau}$	Amplitudes Free	Perturb Observables $\vec{x}$, $\vec{u}$, E
Backgrounds	Photodisintegration Cherenkov	Amplitudes Fixed	Shift Amplitudes σ_{bkg}

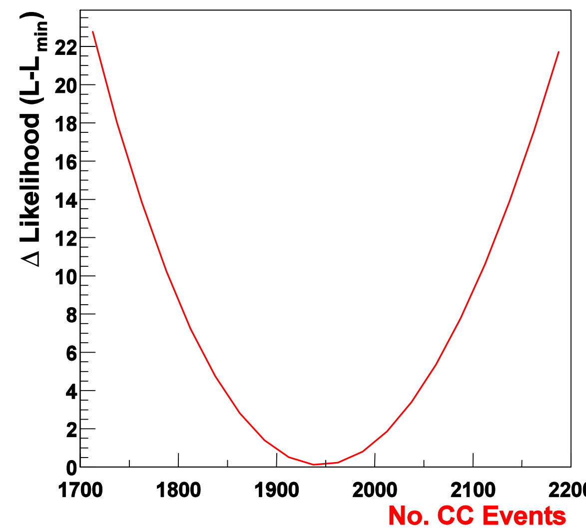
Maximum Likelihood Fit

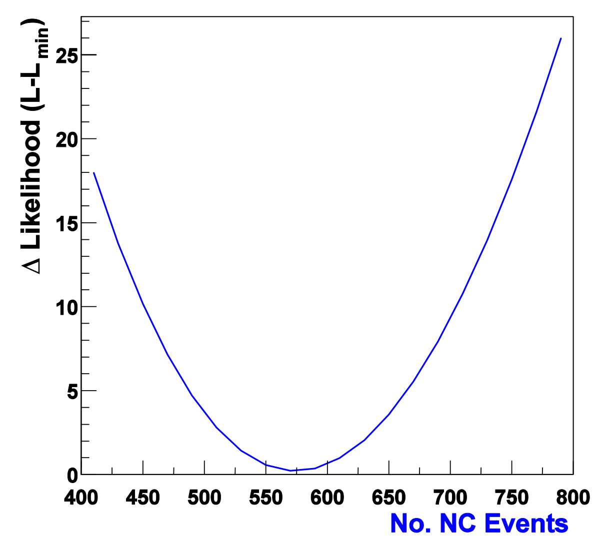
→ # Signal Events | Systematic Error

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

Results of Statistical Signal Separation



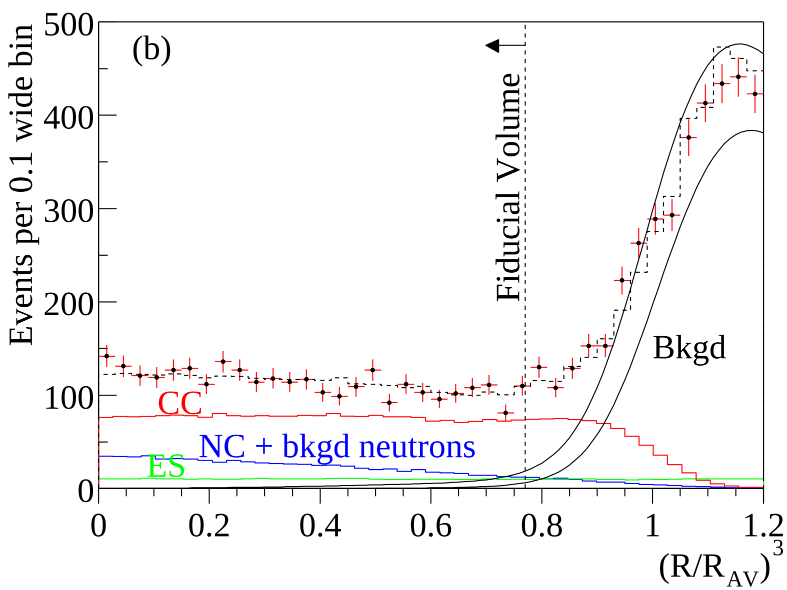


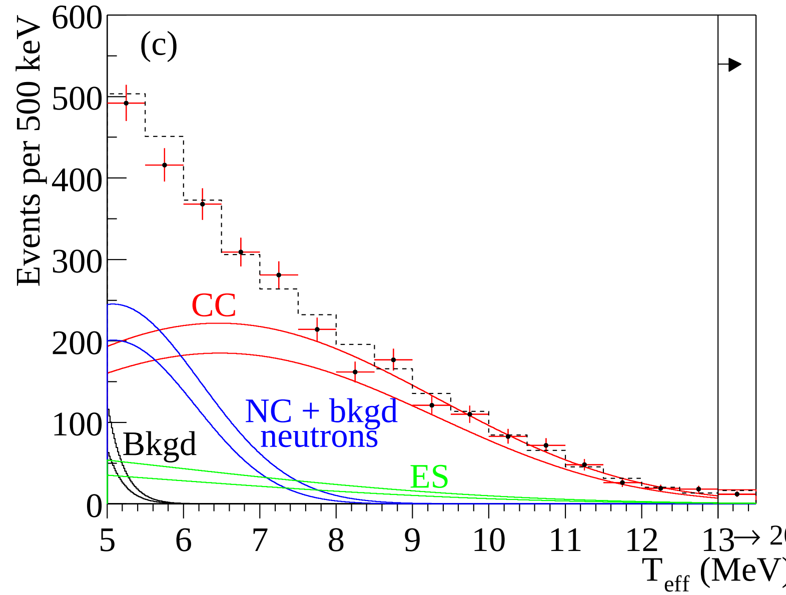


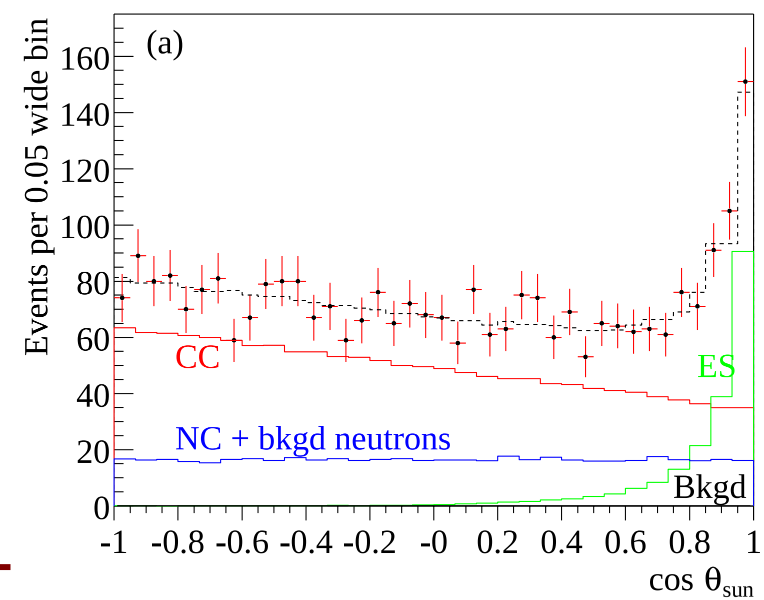
Shape Constrained Signal Extraction Results

#EVENTS

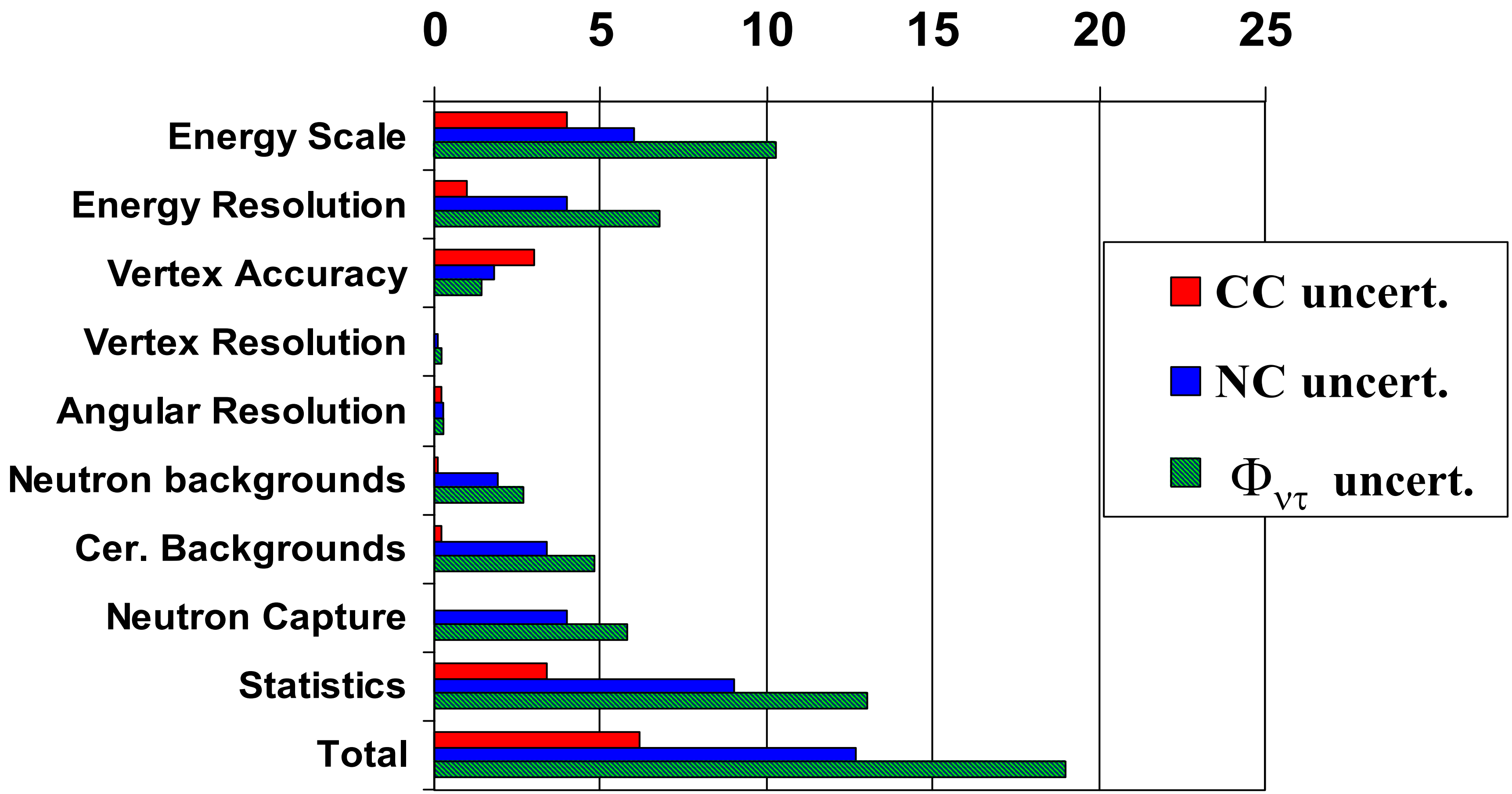
CC	$1967.7^{+61.9}_{+60.9}$
ES	$263.6^{+26.4}_{+25.6}$
NC	$576.5^{+49.5}_{+48.9}$







Uncertainties on ν fluxes



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

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

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

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

$E_{Theshold} > 5$ MeV

Low threshold results agrees with first publication (6.75 MeV threshold).

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

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

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

$\Phi\mu\tau > 0$!

But only ν_e's from the sun,

→ ν flavor has changed.

5.3 σ effect

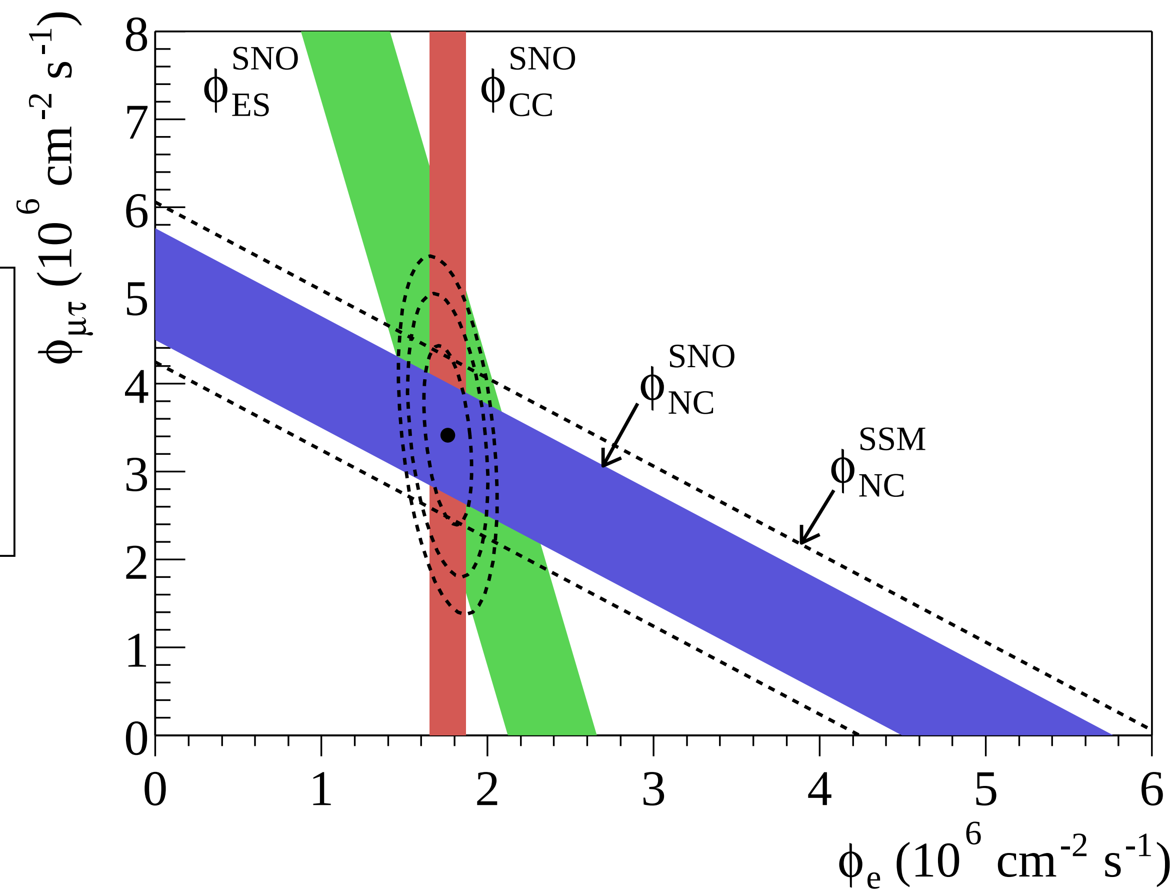
Flavor Content of the Solar ^{8}B Neutrino Flux

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

Standard Solar Model predictions for total ^{8}B flux in excellent agreement!

$$\Phi^{8B}_{SSM} = 5.05 \,^{+1.01}_{-0.81}$$

$$\Phi^{NC}_{SNO} = 5.09 \,^{+0.44}_{-0.43}\,^{+0.46}_{-0.43}$$



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

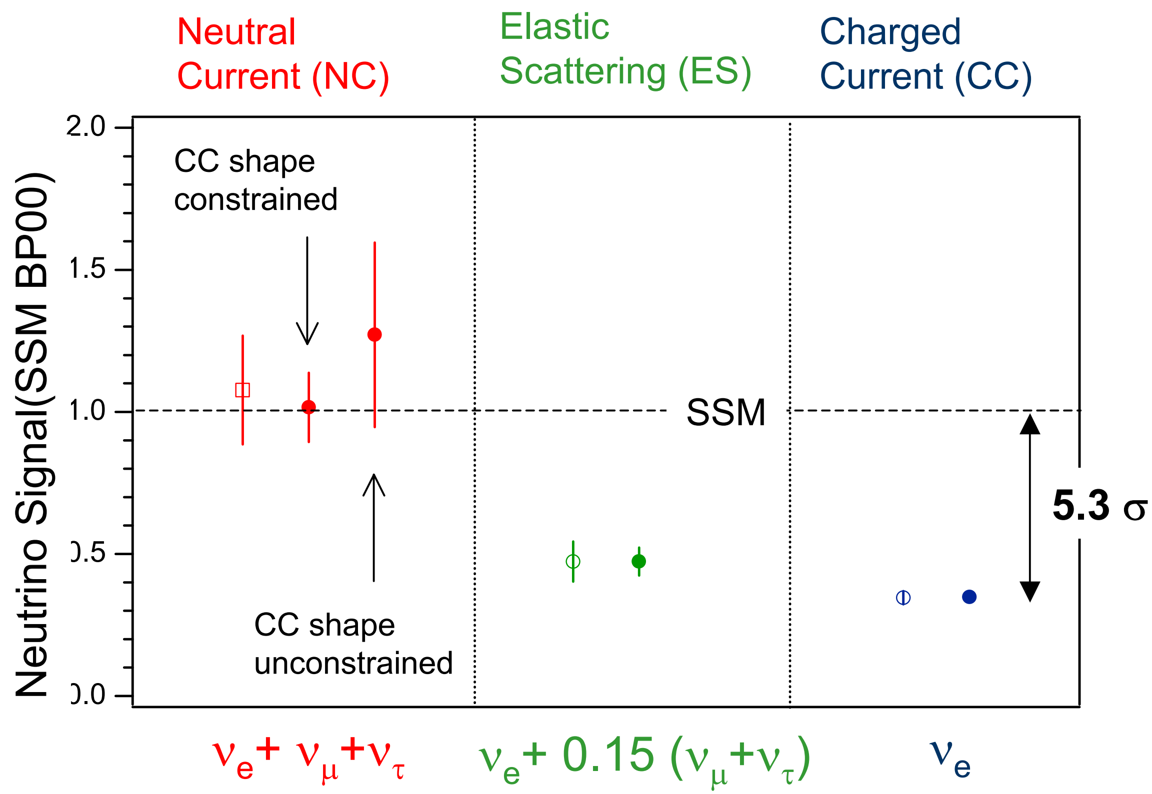
Signal extraction in R^3, $\cos\theta_{Sun}$

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

^{8}B Solar Neutrino Flux Measurements at SNO

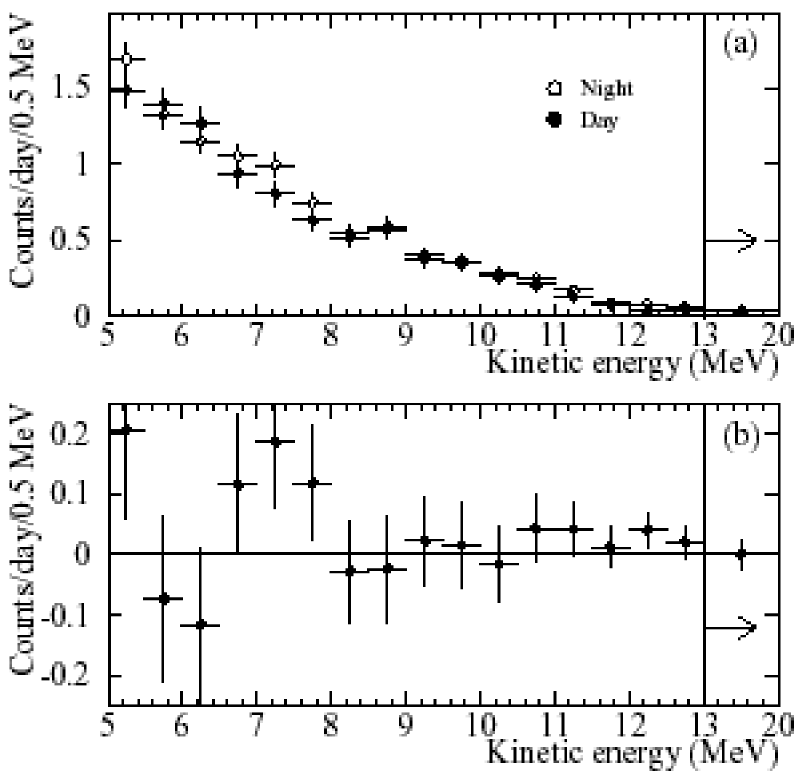
Summary of Results

- □ ^{8}B from $CC_{SNO}+ES_{SK}$ (2001)
- ○ ES_{SNO} (2001)
- ○ CC_{SNO} (2001)
- ● NC_{SNO} (2002)
- ● ES_{SNO} (2002)
- ● CC_{SNO} (2002)



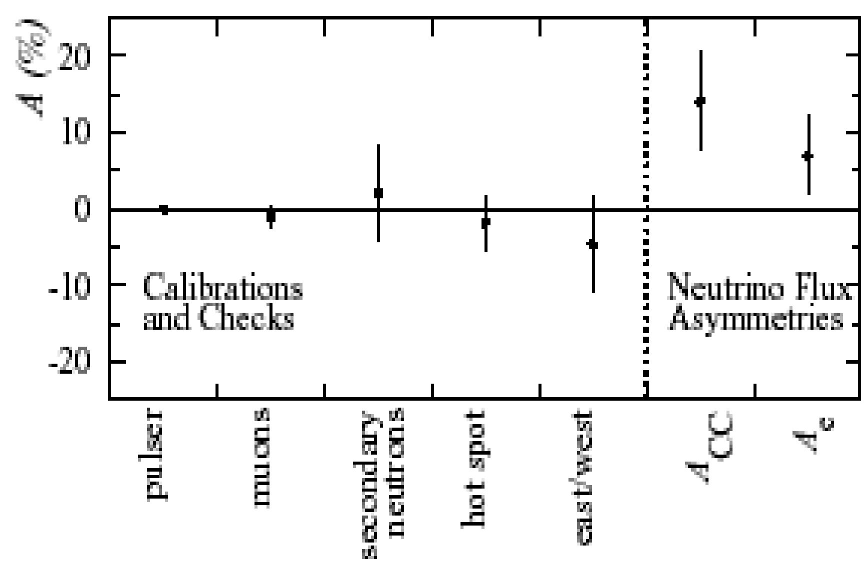
→ Null hypothesis (no flavor change) ruled out at 5.3 σ level

Certain MSW oscillation solutions predict ν's can change flavor while passing through the earth



Define Asymmetry

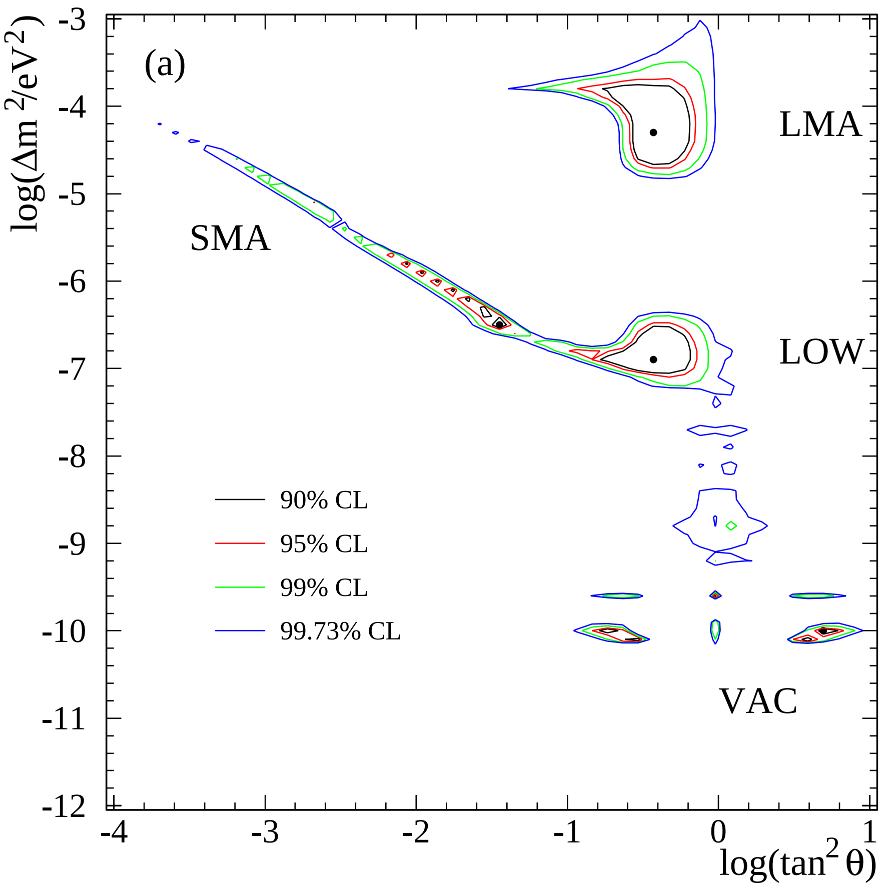
$$A_x = 2^*\frac{(\Phi_{N,X} - \Phi_{D,X})}{(\Phi_{N,X} + \Phi_{D,X})}$$



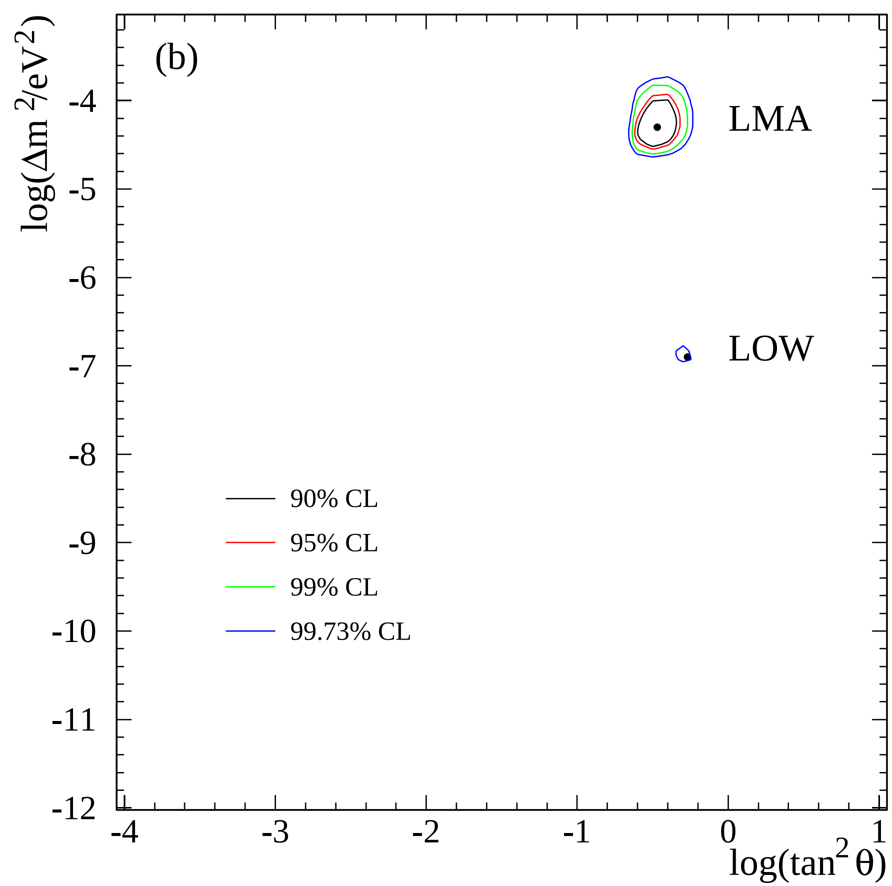
Inputs to Global Solar ν Analysis

- 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

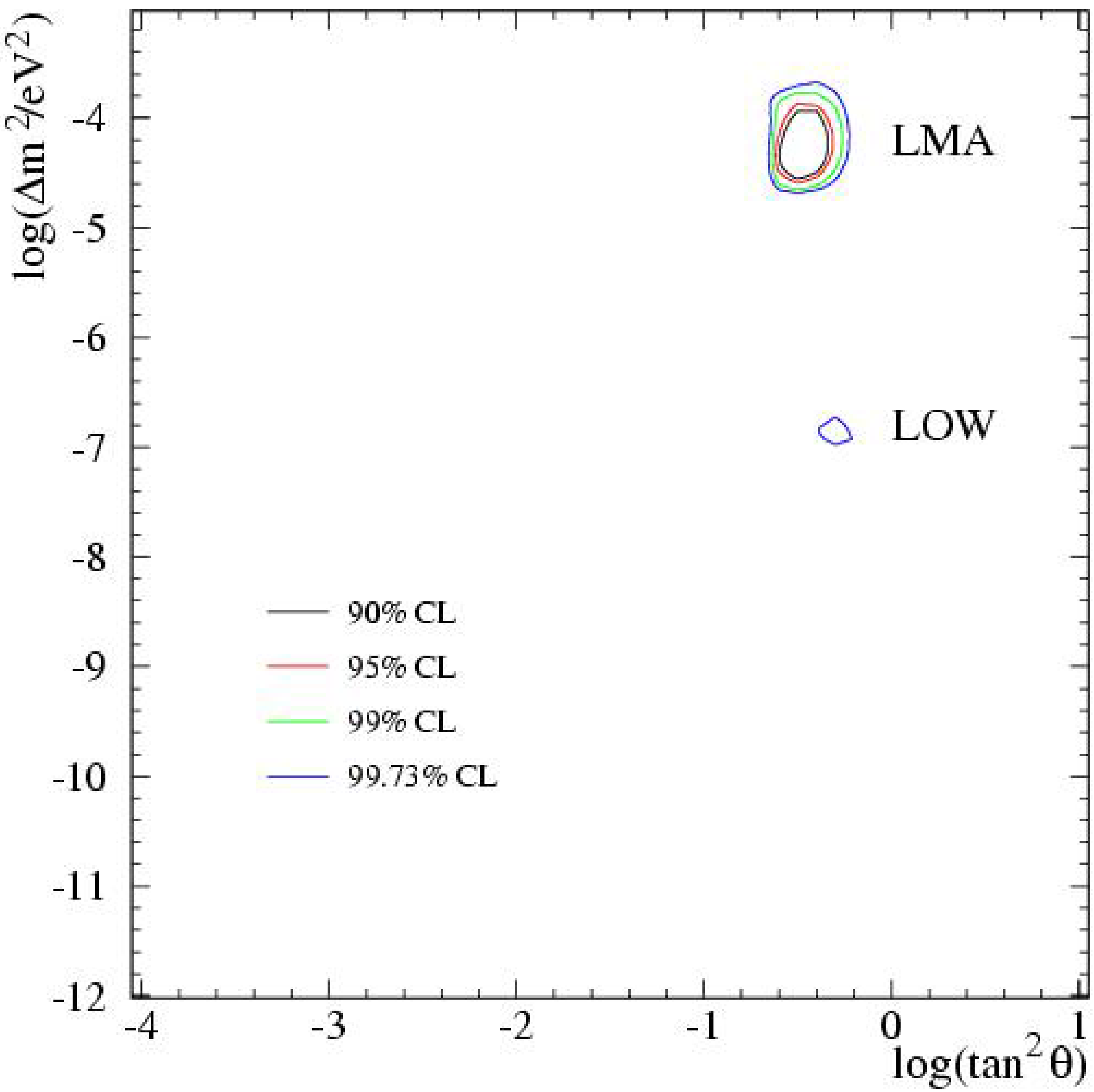
SNO Day and Night Energy Spectra Alone



Combining All Experimental and Solar Model information



Global Fit with total SNO spectrum



without separate day and night spectra

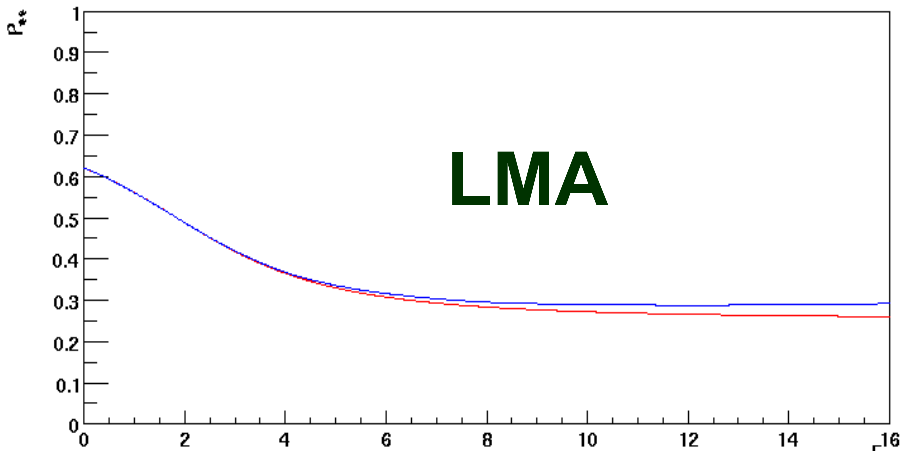
most of the MSW model constraints comes from SNO CC/NC!

Global Analysis Fit Results

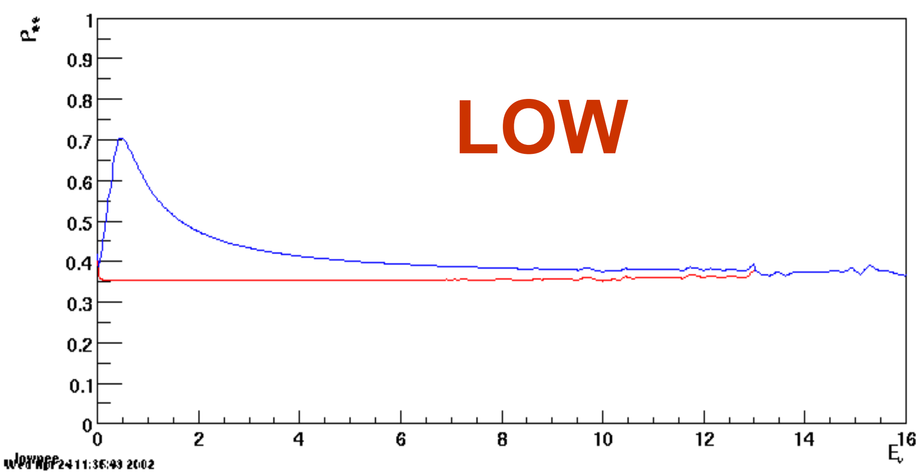
region	χ^2/dof	ϕ_B/SSM	A_e	Δm^2 (eV^2)	$\tan^2\theta$	CL
LMA	57.0/72	1.16	6.4%	5.0×10^{-5}	0.34	---
LOW	67.7/72	0.98	5.9%	1.3×10^{-7}	0.55	99.5%

- SNO CC/NC measurement directly constrains the survival probability at high energy
- Forces LOW solution to confront the 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

The Salt Phase

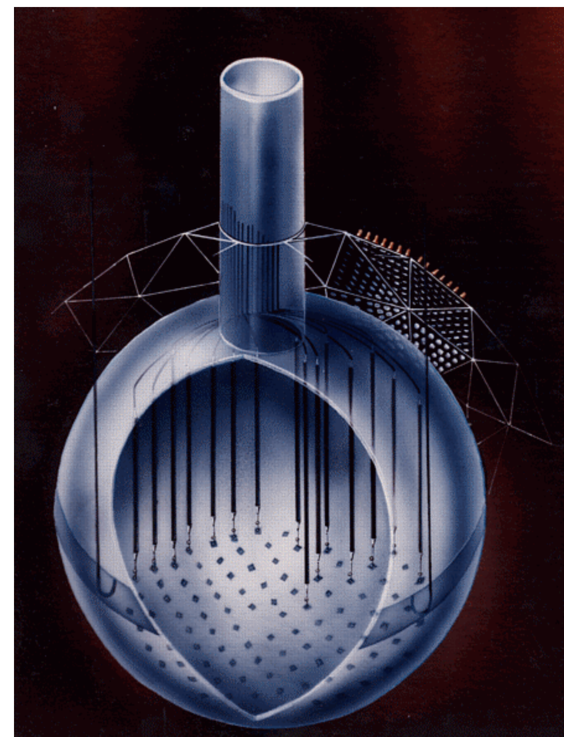
$n + {}^{35}Cl \rightarrow {}^{36}Cl + \Sigma\gamma \ldots \rightarrow e^-$ ($E_{\Sigma\gamma}$ = 8.6 MeV)

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

Neutral Current Detectors

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

- Event by event separation



Conclusions

Nucl-ex/0204008, Nucl-ex/0204009

- **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

- **Interpretation**
    - SNO Data is consistent with MSW oscillation interpretation
    - combined with global solar neutrino data favors LMA solution

- **Measurement, with NaCl underway since June 2001**