Results from the Sudbury Neutrino Observatory

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For the SNO Collaboration

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Outline

- Neutrino Physics introduction
- Overview of SNO physics
- The SNO Detector
  - Neutrino Detection and Analysis
  - The 3 Phases of SNO
- Results
- Summary and Outlook

Particle Physics: Neutrino mixing

Flavor | Mass

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

SK, K2K, MINOS
$\theta_{23} \approx 45^o$
$\Delta m^2_{23} \sim 2.7\times10^{-3}$ eV^2

CHOOZ
$\theta_{13} < 12^o$

δ is unknown

Solar, KamLand
$\theta_{12} \approx 32^o$
$\Delta m^2_{12} \sim 8\times10^{-5}$ eV^2

Mixing	Quarks	Leptons
1-2 θ_{12}	13^o	32^o
2-3 θ_{23}	2.3^o	45^o
1-3 θ_{13}	$\sim 0.5^o$	$<12^o$

Physics Program at the Sudbury Neutrino Observatory

1. Precision Measurements of solar ν flux
    a) Constraints on θ_{12}, Δm^2_{12} (and θ_{13}, $\phi_{sterile}$)
    b) Test of Standard Solar Model
        i) Total neutrino flux
        ii) hep neutrino flux
2. Search for oscillation mechanism (MSW)
    a) Distortion of neutrino energy spectrum
    b) Day-night flux asymmetries
3. Other Neutrino Physics
    a) Search for neutrinos from relic SNe
    b) Periodicities of neutrino signals
    c) Atmospheric neutrinos and muons
    d) Exotic/new physics

SNO's Primary Source of Neutrinos

The Sun:

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

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

${}^2H + p \rightarrow {}^3He + \gamma$

85%

15%

${}^3He + {}^3He \rightarrow {}^4He + 2p$

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

${}^7Be + p \rightarrow {}^8B + \gamma$

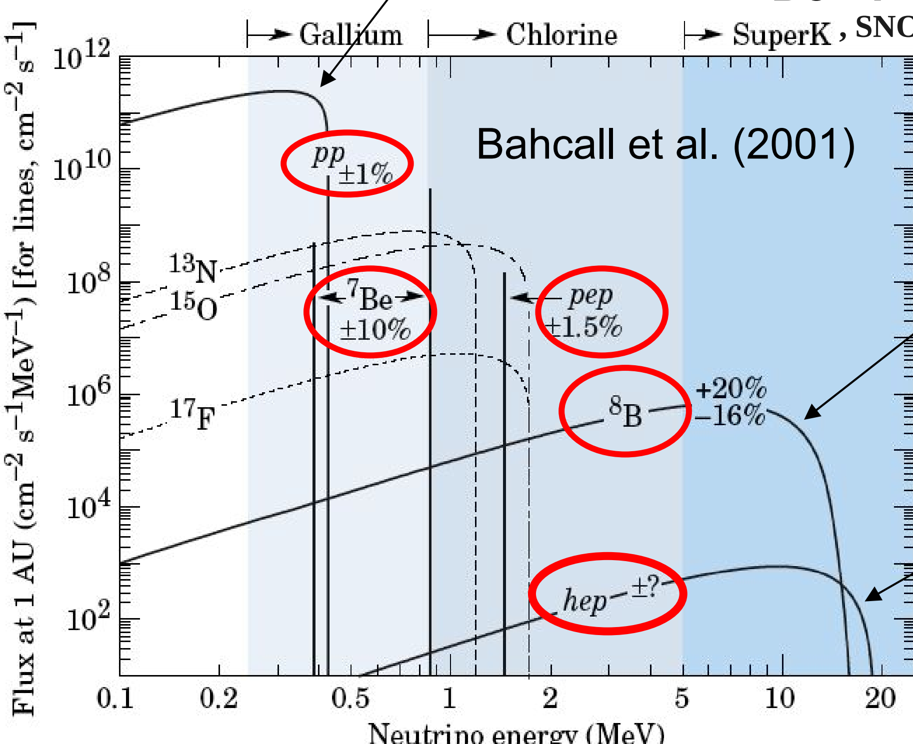
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

${}^8Be^* \rightarrow {}^4He + {}^4He$

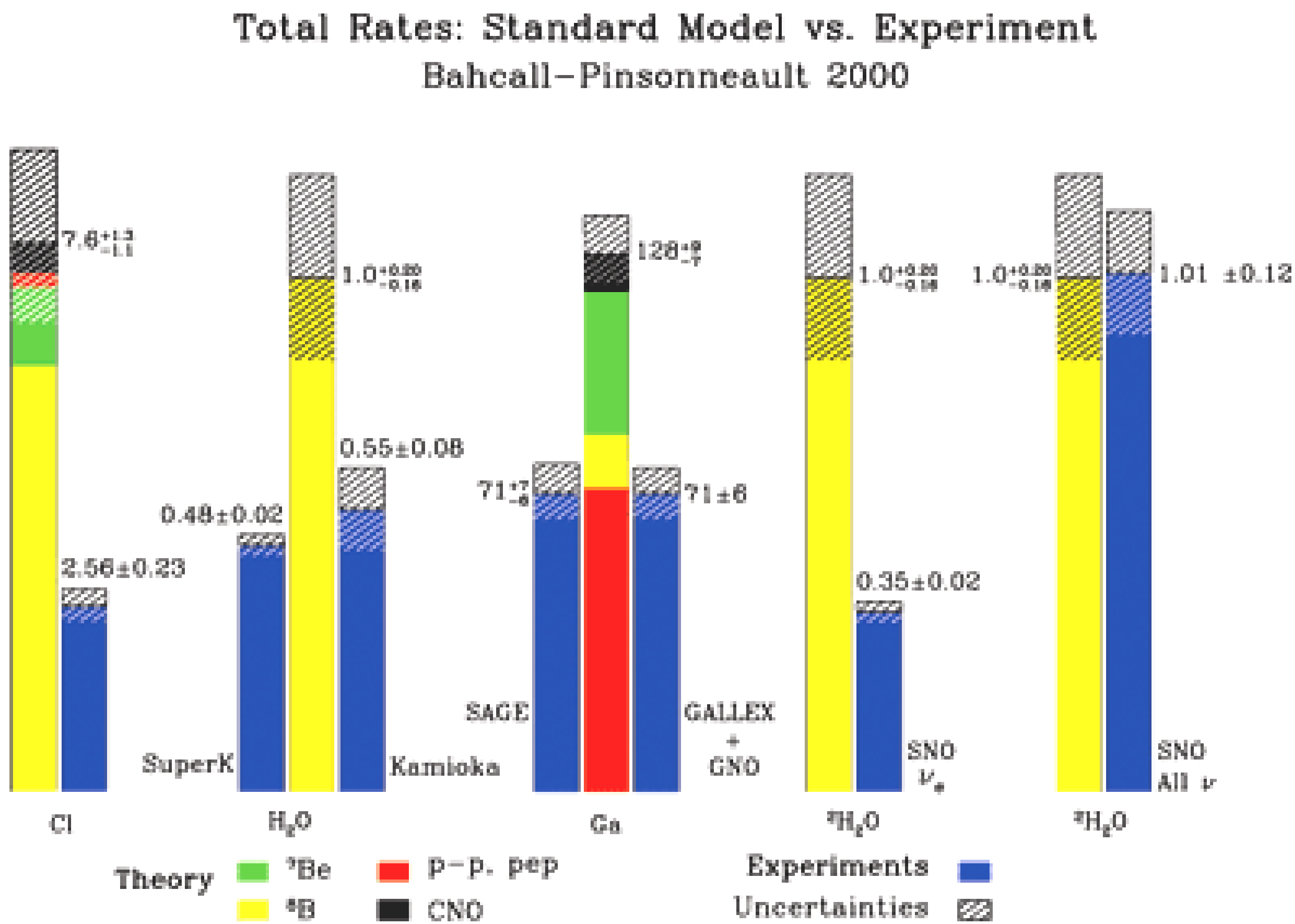
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

${}^7Li + p \rightarrow {}^4He + {}^4He$

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

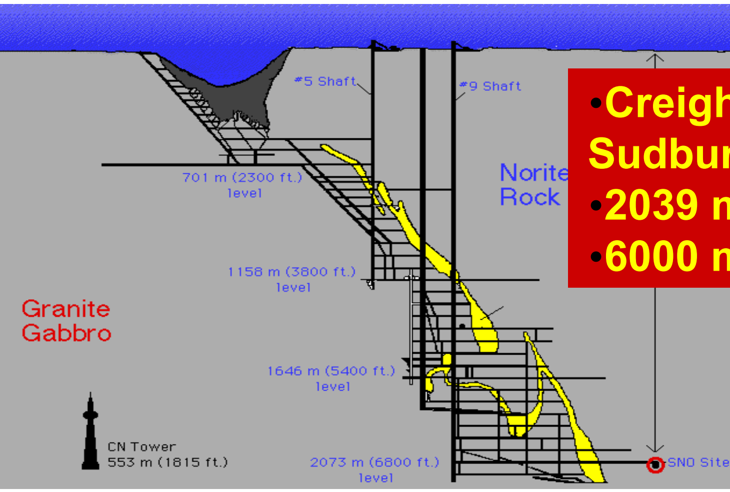


History: Solar Neutrino Problem

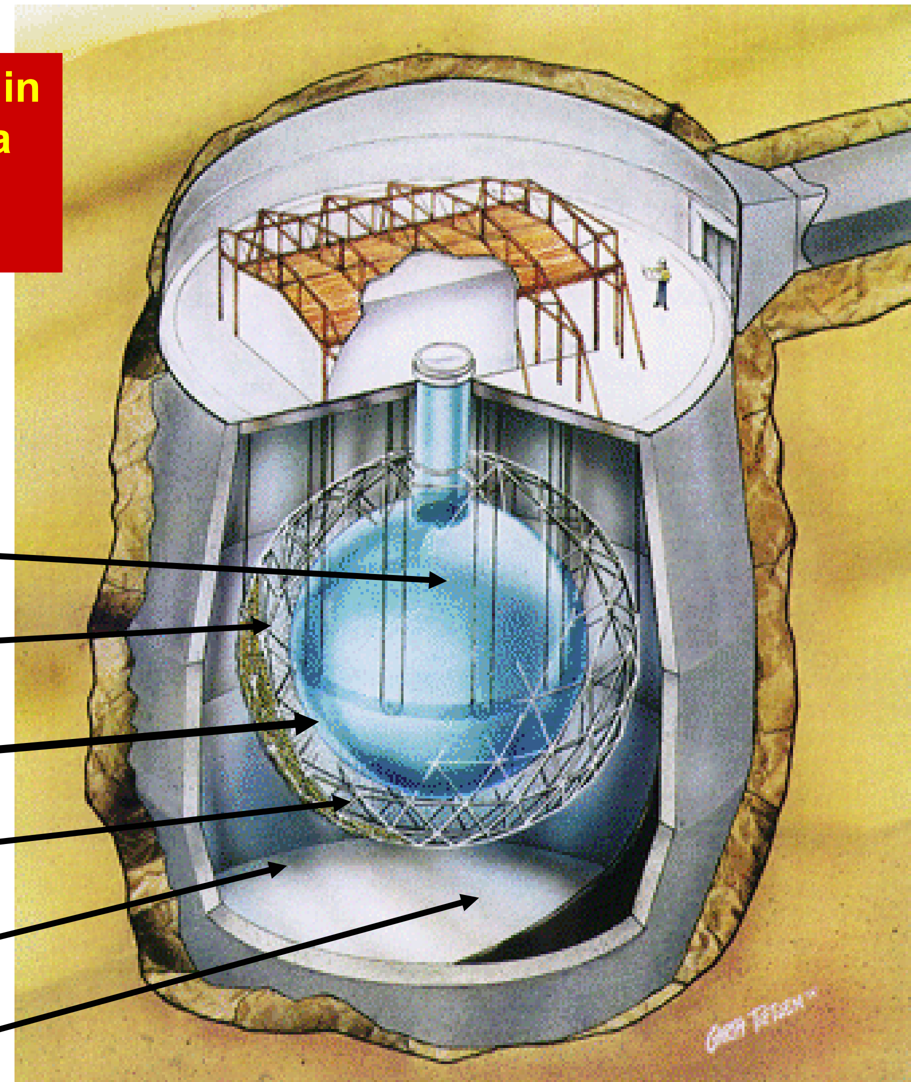


The SNO Detector

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



- Creighton mine in Sudbury, Canada
- 2039 m depth
- 6000 mwe



Heavy Water : 1000 ton

Support structure for 9500 PMT

Acrylic Vessel: 12 m diameter

Internal H_2O shielding: 1700 ton

External H_2O shielding: 5300 ton

Urylon liner: Radon sealing

Neutrino 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(q)
ν_e only $E_{thresh} = 1.4$ MeV

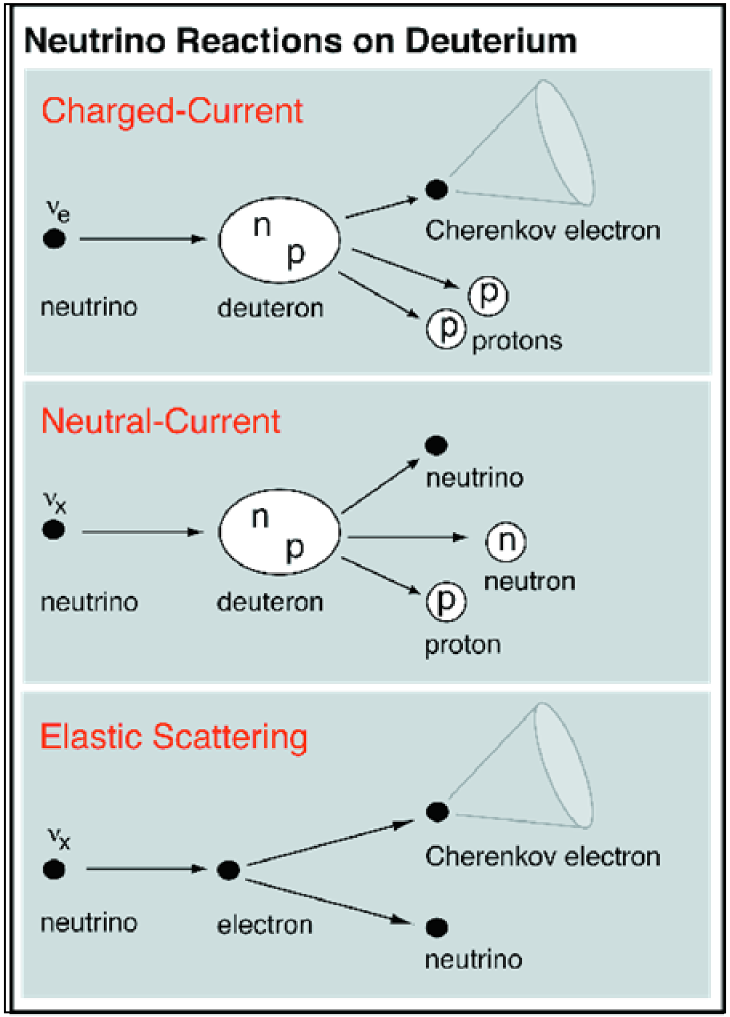
NC $\nu_x + d \rightarrow \nu_x + p + n$

Equally sensitive to ν_e, ν_μ, ν_τ
Measure total ^8B ν flux from the sun
$E_{thresh} = 2.2$ MeV

SNO uses 3 different techniques to detect neutrons

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

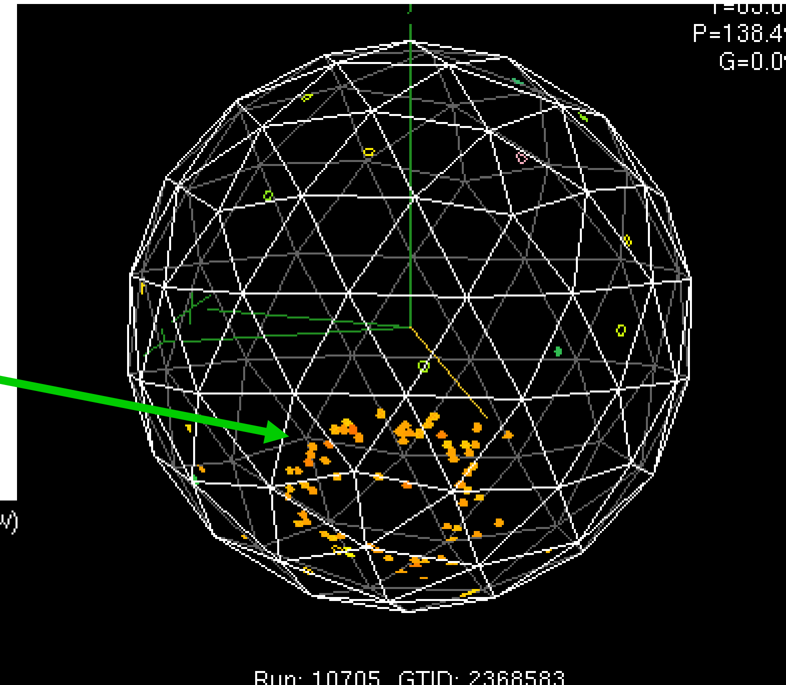
Strong directional sensitivity
Mainly sensitive to ν_e, some sensitivity to ν_μ and ν_τ
Low Statistics

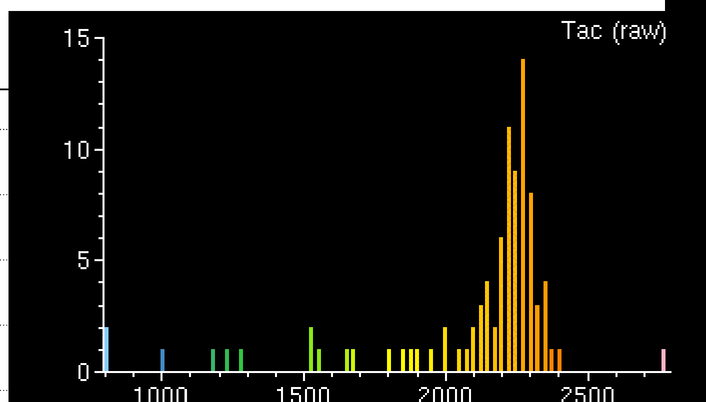


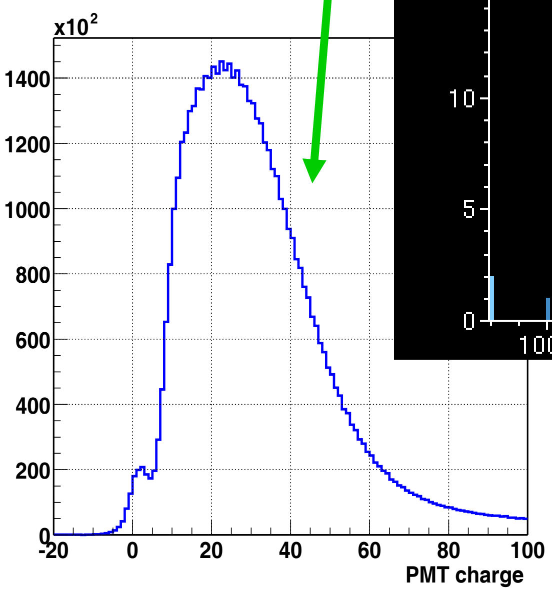
SNO observables

PMT Measurements

- position
- time
- charge





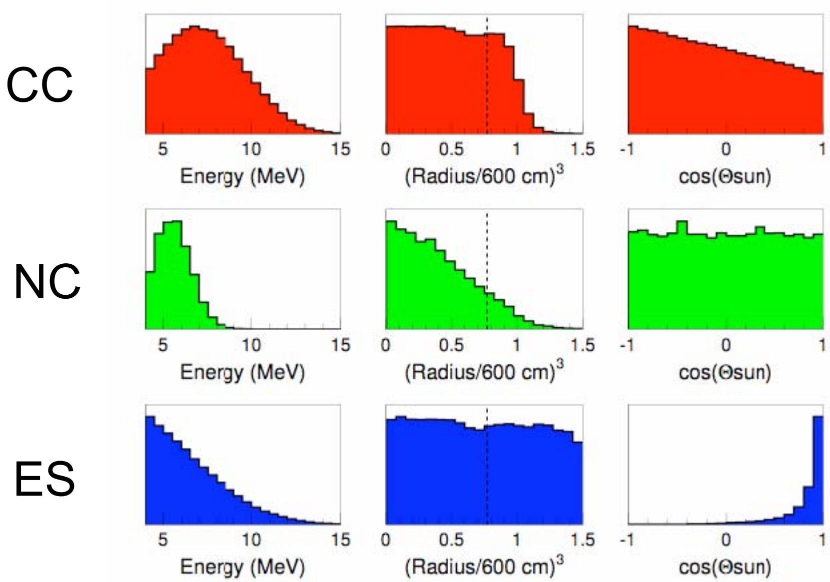


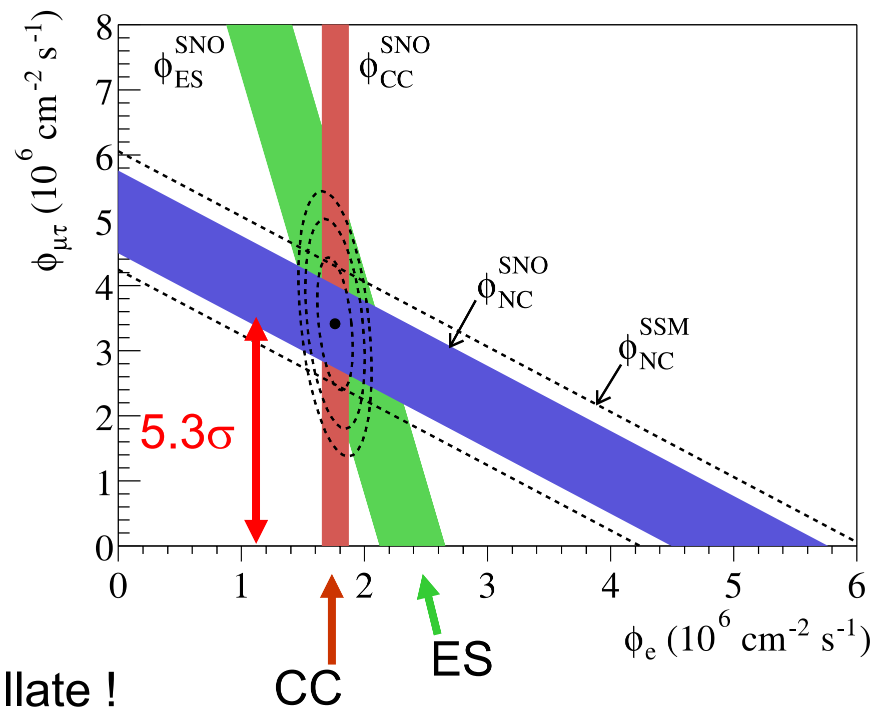
Reconstructed event

- vertex
- direction
- energy
- isotropy

SNO Signal Distributions

SNO Collaboration, PRL 87,071301 (2001) ; PRL 89, 011301 (2002)





Evidence for flavor change → neutrinos oscillate !

2001: $\Phi^{SK}{}_{ES}(\nu_x) - \Phi^{SNO}{}_{CC}(\nu_e) = 0.57 \pm 0.17 \times 10^6 cm^{-2}s^{-1}$ (3.3σ)

2002: $\Phi_{\mu\tau} = 3.41 \pm 0.45$ (stat.) $^{+0.48}_{-0.45}$ (syst.) (5.3σ)

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

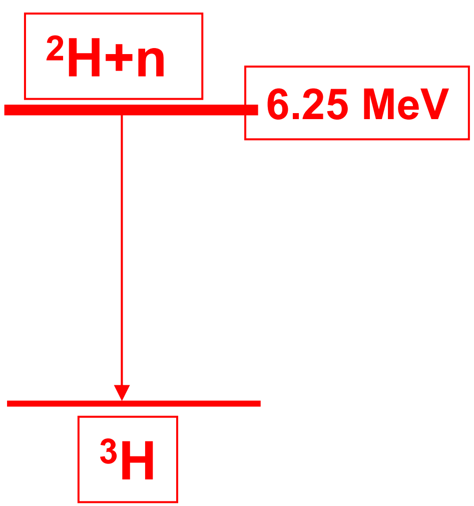
Confirmation of solar model neutrino flux

Three neutron detection techniques

Phase I (D_2O)

Nov. 99 - May 01

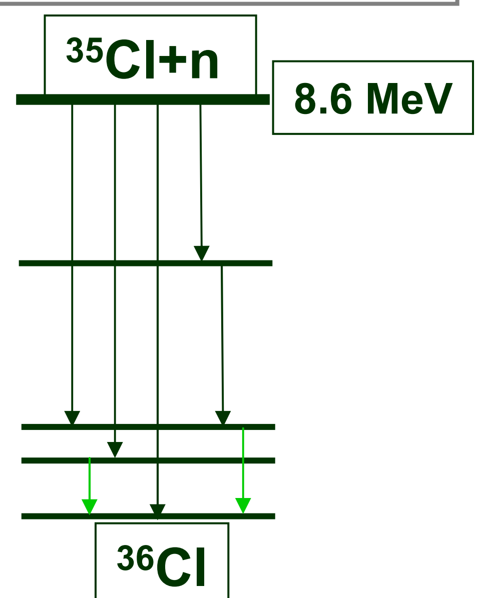
n captures on
$^2H(n, \gamma)^3H$
Effc. ~14.4%
NC and CC separation by energy, radial, and directional distributions



Phase II (salt)

July 01 - Sep. 03

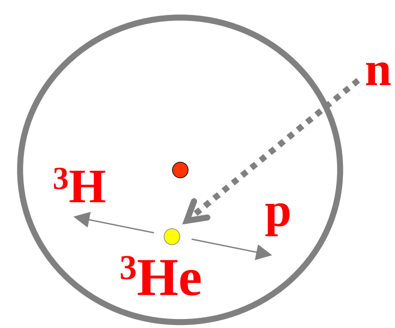
2 t NaCl. n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
Effc. ~40%
NC and CC separation as in D_2O phase <u>and</u> by event isotropy



Phase III (^3He)

Nov. 04 - Nov. 06

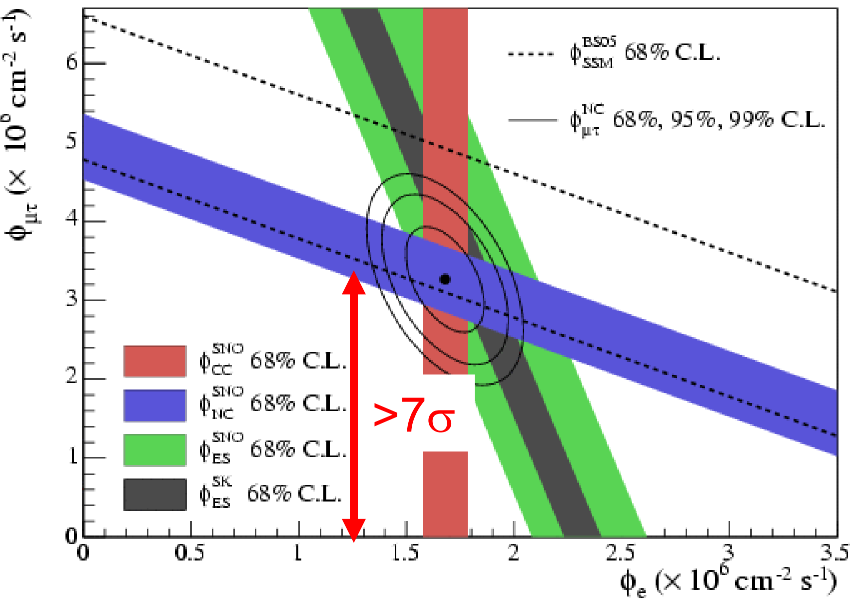
40 proportional counters
$^3He(n, p)^3H$
Effc. ~ 30% capture
Measure NC rate with entirely different detection system.

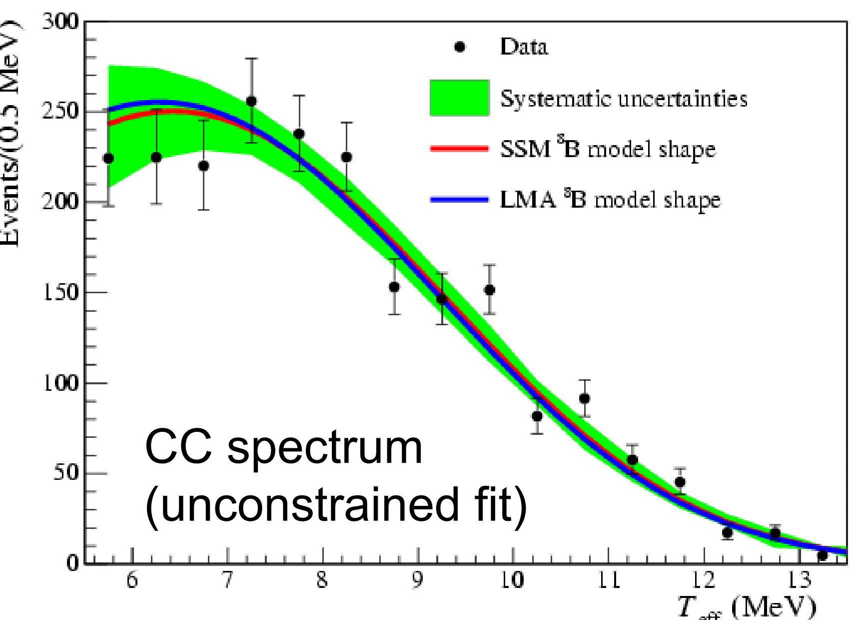


$$n + {}^3He \rightarrow p + {}^3H$$

SNO Salt Phase Results

SNO Collaboration, PRC **72**, 055502 (2005)





solar model calculations:

Φ_{NC} = 5.82 ± 1.3 (Bahcall et al),

Φ_{NC} = 5.31 ± 0.6 (Turck-Chieze et al)

in units of 10^6 cm^{-2} s^{-1}

$$\Phi_{CC} = 1.68\ ^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

$$\Phi_{NC} = 4.94\ ^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

$$\Phi_{ES} = 2.35\ ^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

in units of 10^6 cm^{-2} s^{-1}

$$\frac{\Phi_{CC}}{\Phi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}$$

Precision measurement of θ_{12}

Importance of Spectral Analyses

Neutrino mixing parameters

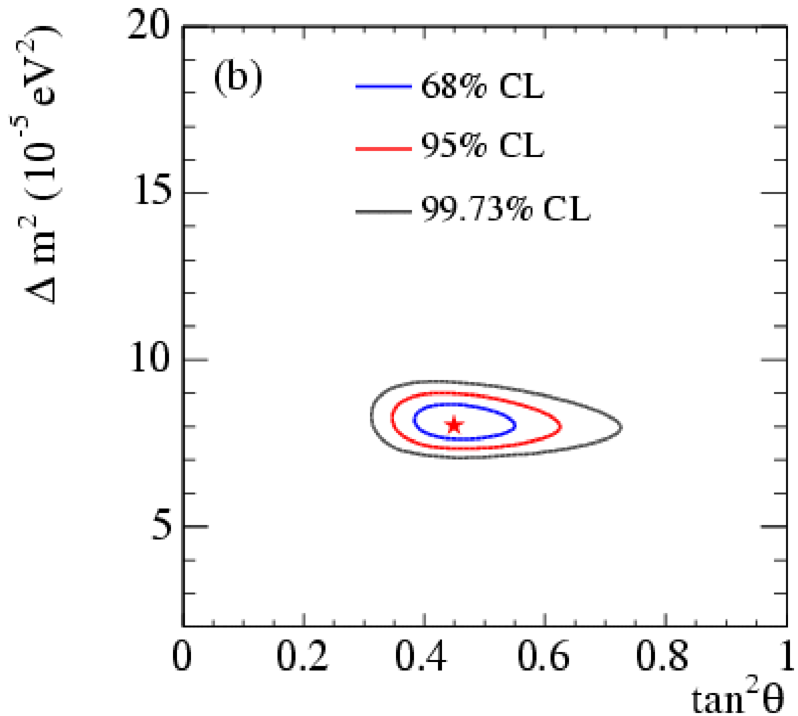
(solar experiments and KamLAND + CPT invariance)

→ LMA-I is favored: $(\Delta m^2_{12}, \theta_{12}) = (8.0\times10^{-5}eV^2, 33.9)$

→ Mass hierarchy $m_2 > m_1$

→ weak constraints on θ_{13}

→ For 2 flavor analysis:
null hypothesis of no MSW effect is rejected at ~ 5σ



But need to directly confirm MSW:

1) Day – Night flux asymmetry due to regeneration of ν_e in interior of Earth

$$A_{DN} = \frac{(\text{Night} - \text{Day})}{(\text{Night} + \text{Day})/2}$$

$A_{DN}(\text{salt} + D_2O) = 0.037 \pm 0.040$ (assumes $A^{NC}=0$)
analysis is statistically limited

$$\Delta m^2 = 8.0^{+0.6}_{-0.4} \times 10^{-5} eV^2$$

$$\theta = 33.9^{+2.4}_{-2.2} \text{ deg}$$

2) Spectral distortion at low E

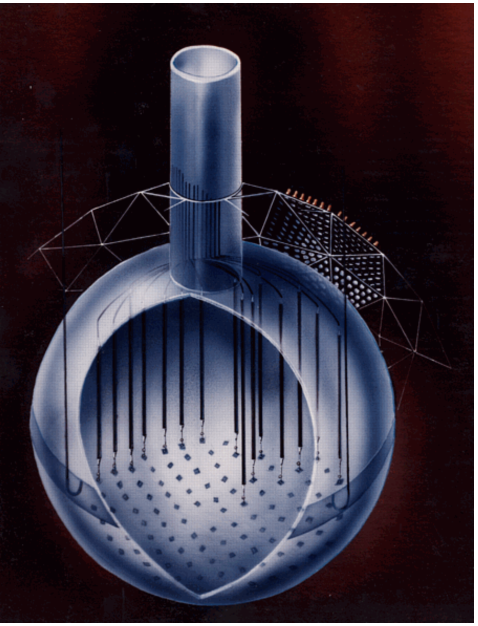
→ low E threshold analysis (in progress)

Prospects of low threshold analysis:

- new optics → use early and late light
- PMT angular response → better precision
- improvements to event fitter → better energy resolution

→ Good prospects to lower threshold to ~4 MeV

SNO Phase III : NCD



Neutral-Current Detectors (NCD):
An array of 36 ^3He and 4 ^4He proportional counters
~440 m total active length

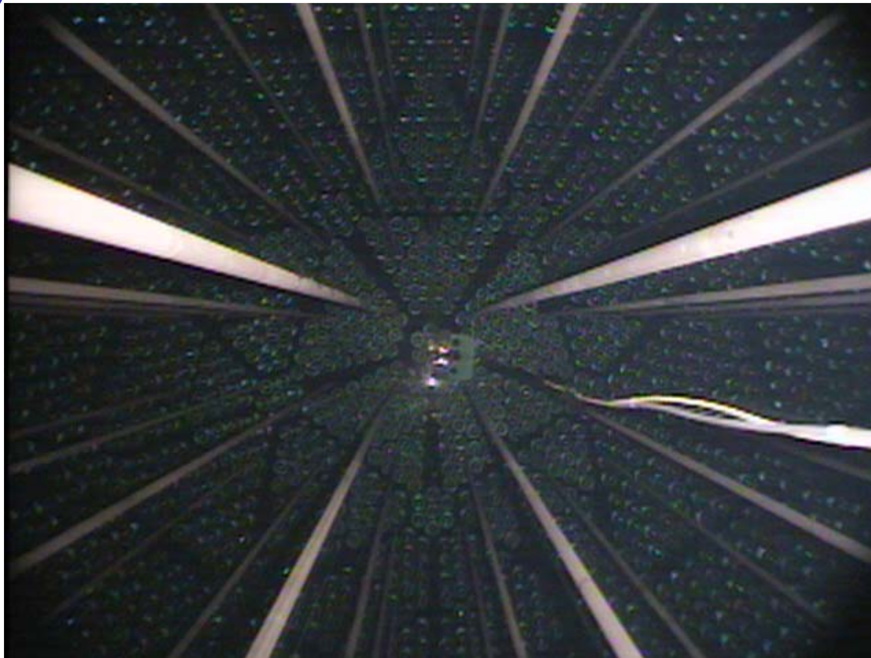
Motivation:
1) Independent NC measurement
   NC: NCD array; **CC** : PMT array
1) Improve statistical precision by breaking the CC and NC correlation ($\rho \approx -0.5$)

→ reduce systematic uncertainties
→ Lower analysis energy threshold

CC and NC Flux Uncertainties:

	Salt phase		NCD phase	
	$\Delta\Phi_{CC}/\Phi_{CC}$	$\Delta\Phi_{NC}/\Phi_{NC}$	$\Delta\Phi_{CC}/\Phi_{CC}$	$\Delta\Phi_{NC}/\Phi_{NC}$
sys	4.9	7.3	3.3	5.2
stat	3.7	4.2	2.2	3.8
total	6.1	8.4	4.0	6.4

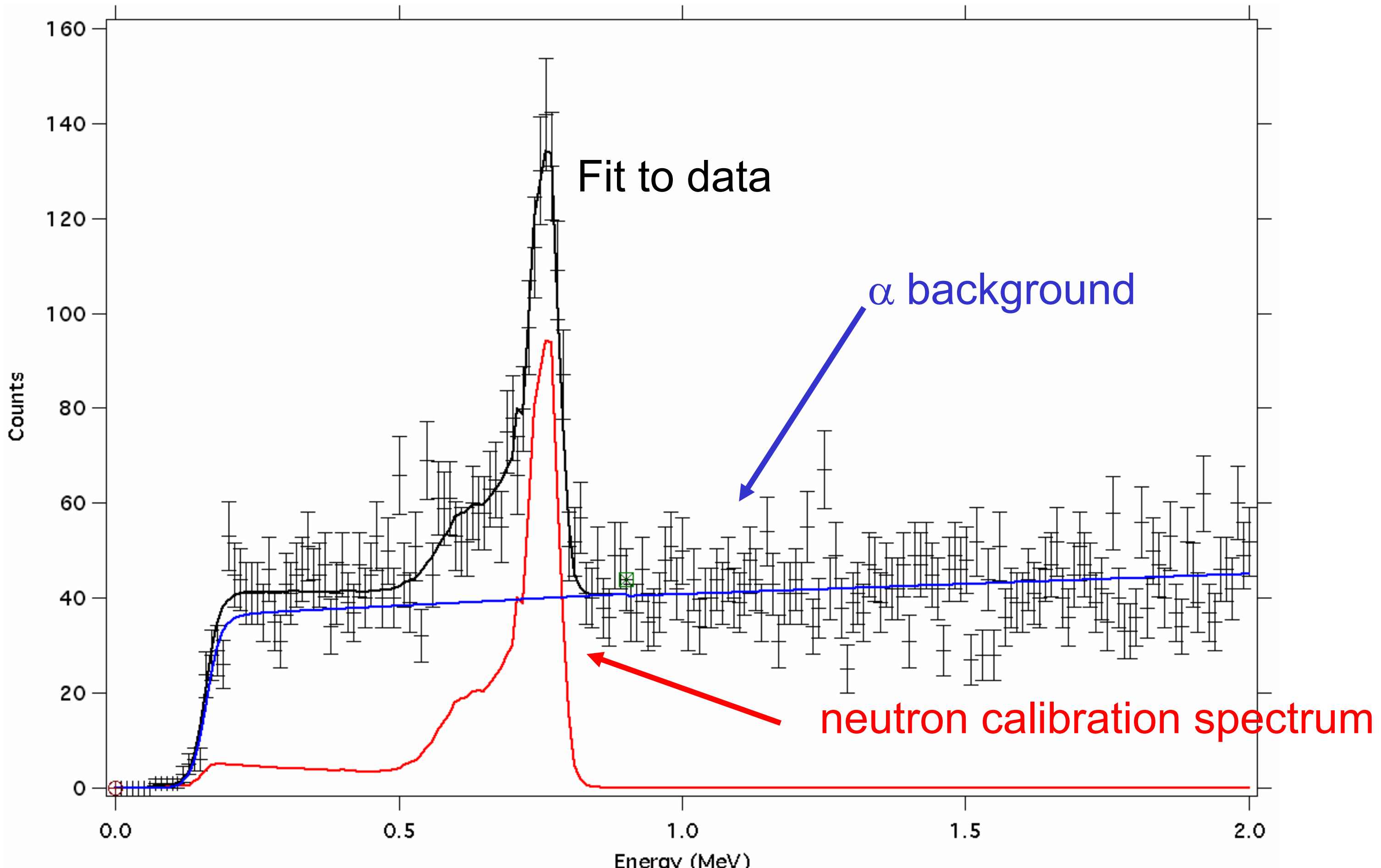
projected



SNO NCD Signals

$$n + {}^{3}He \rightarrow p + {}^{3}H \quad (q=768\ keV)$$

Pulse shape analysis to discriminate neutrons and alphas underway
String-by-string and ring-by-ring symmetry

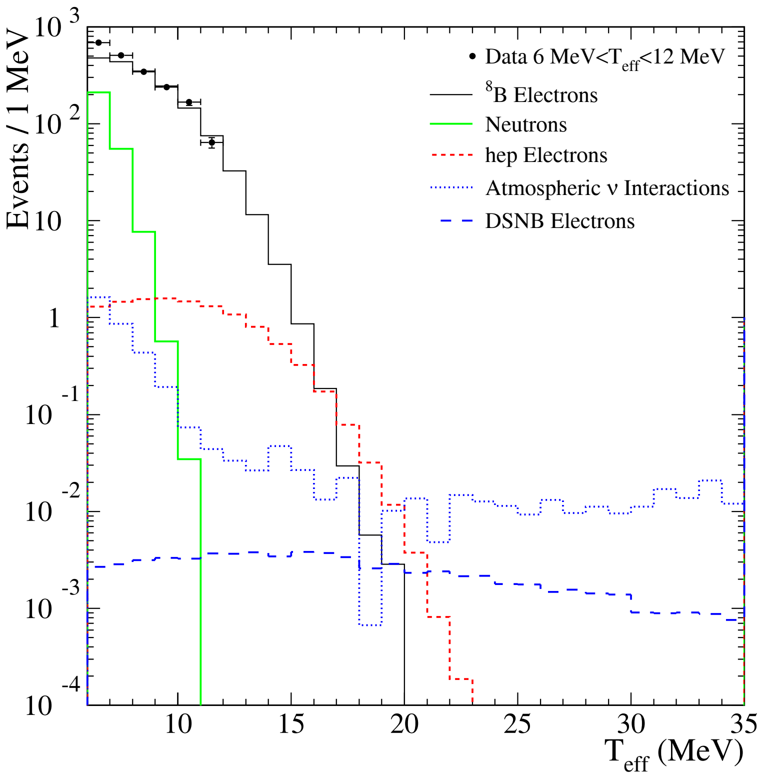


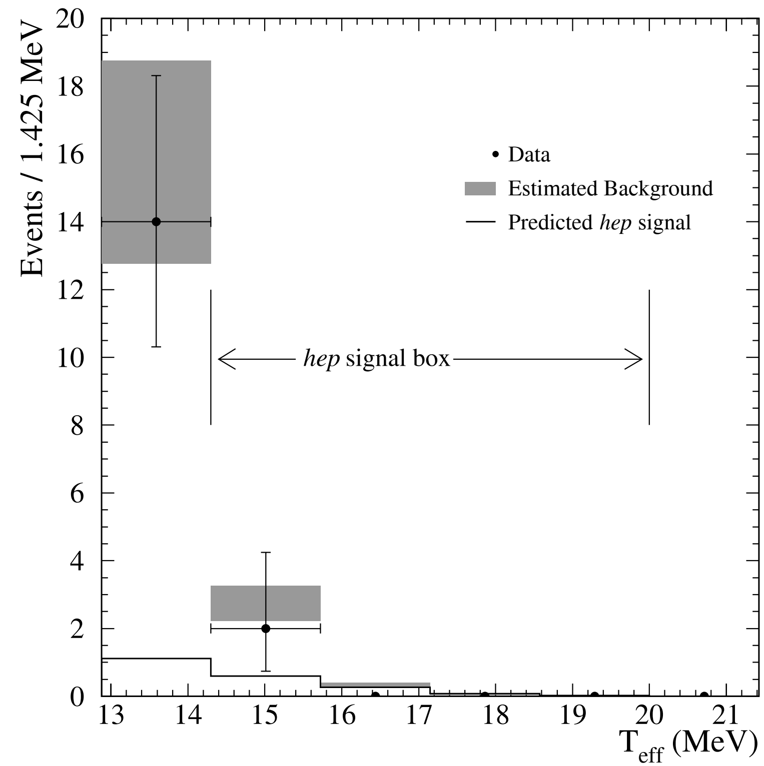
Other Analyses

- Search for hep neutrinos and neutrinos from relic SNe
- Periodicities of neutrino signals
- Atmospheric neutrinos and muons

Search for hep and DSNB neutrinos

SNO Collaboration, *ApJ **653** (2006) 1545*



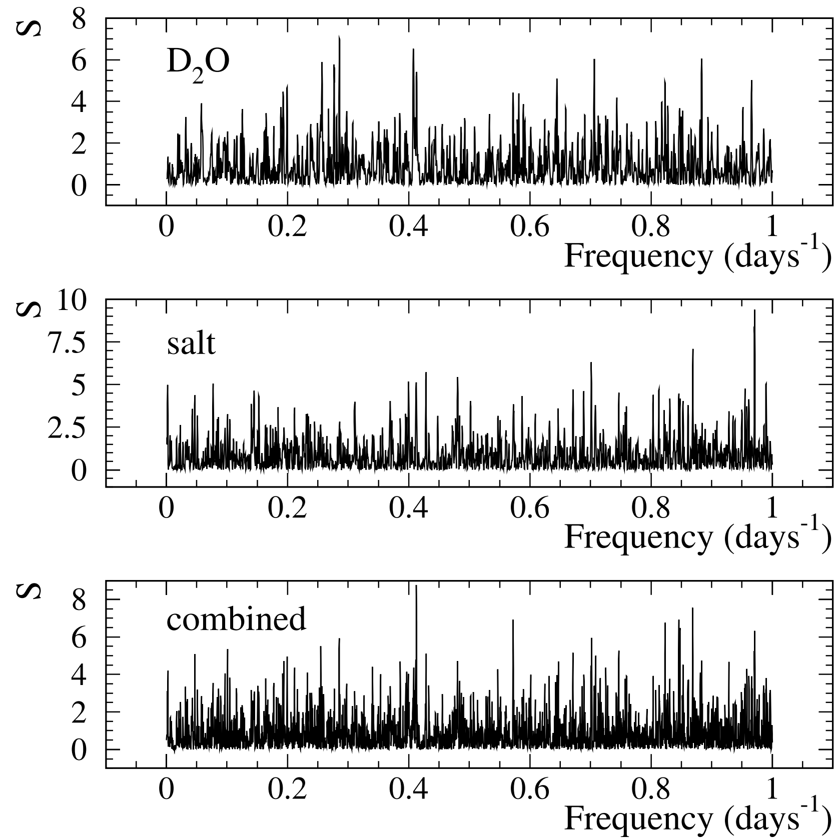


- ***hep* neutrino flux:** D2O data set: 14.3 MeV <T_{eff} < 20 MeV
  observe 2 events, expect 3.1±0.6 background events (predominantly from ^{8}B)
  → new limit: $\Phi < 2.3\times10^4$ cm^{-2}s^{-1} (90 % CL) [SSM: $7.97 \pm 1.24 \times 10^3$ cm^{-2}s^{-1}]

- **diffuse Supernovae background:** 21 MeV < T_{eff} < 35 MeV
  observe no events → new limit for ν_e: $\Phi < 70$ cm^{-2}s^{-1} (90% C.L.)

Periodicity Search in ^8B Neutrino Flux

SNO Collaboration, Phys. Rev. D 72, 052010 (2005)



Unbinned max. likelihood

- Method compares fit for sinusoidal variation with expectation for zero amplitude.
- Monte Carlo sensitivity estimate:

  35% probability of a larger likelihood ratio (S) with zero sinusoidal amplitude than the maximum S observed in the fits.

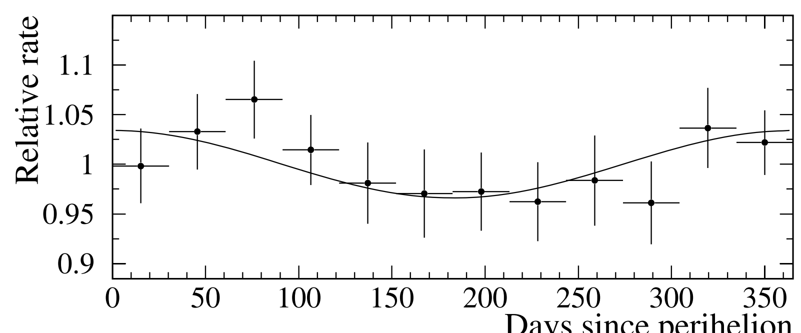
Conclusion: No observed sinusoidal variation at periods from 1 day to 10 years.

Amplitude sensitivity of 8-10% at 99% C.L..

Orbital Eccentricity:

observed: $\varepsilon = 0.0143 \pm 0.0086$

actual: $\varepsilon = 0.0167$

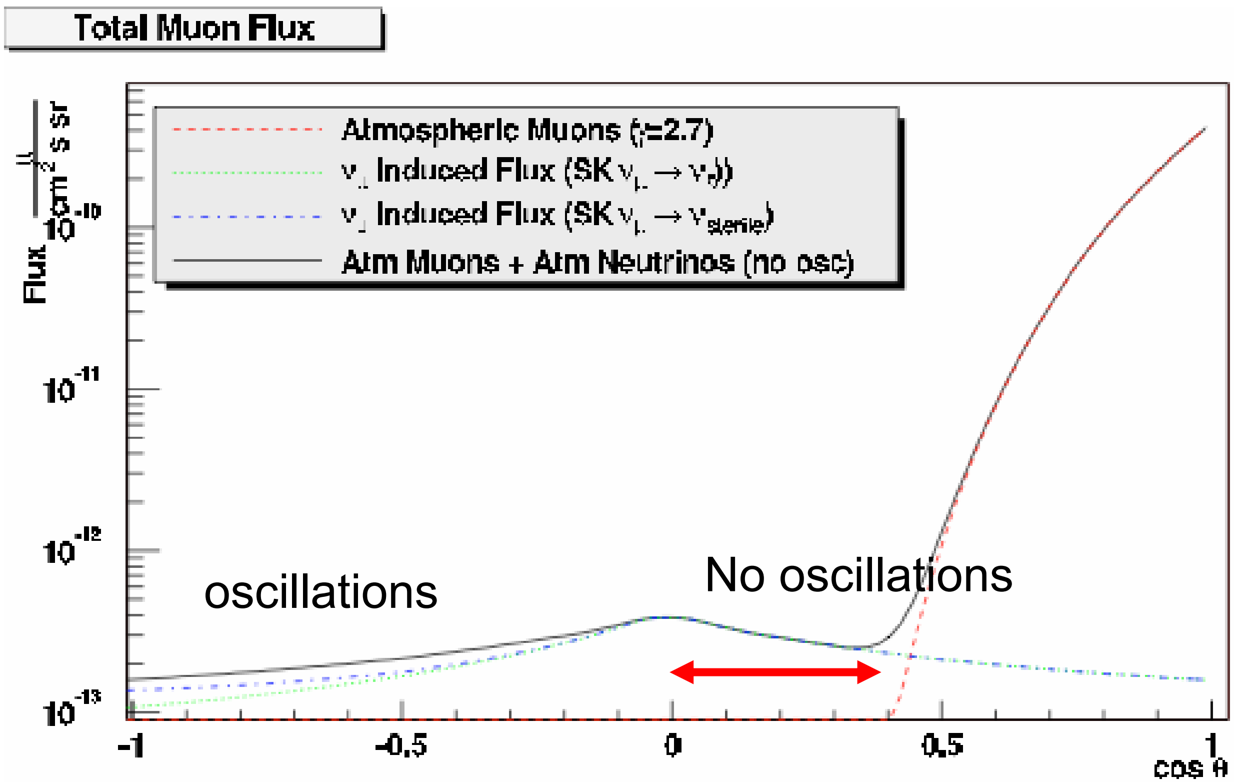


Atmospheric Neutrinos

- SNO is of modest size → not competitive data sample of contained events
  → zenith angle distribution of muons (up vs down)

- For zenith angles θ<66° (cosθ > 0.4), muons from cosmic rays

- For 0 < cosθ < 0.4 can observe un-oscillated atmospheric neutrino flux through muons generated in neutrino interactions in the rock



Can obtain normalization of Atmospheric neutrino flux

Summary and Outlook

- Presented Flux and Spectrum Results from SNO solar neutrino analyses

→ Era of precision measurements of neutrino mixing parameters has started

→ Next step is to test for direct indications of MSW as the mechanism underlying neutrino oscillations
  - Day-night effect
  - Spectral distortions at low E_{thresh}

- Search for solar hep neutrinos and DSNB neutrinos in the SNO data set
- NO indication of periodicities in SNO solar ^{8}B data found (other than that due to orbital eccentricity)

→ Prospects of current NCD phase analysis and low energy threshold analysis are promising to address open questions of oscillation mechanism