Recent Results from the Sudbury Neutrino Observatory

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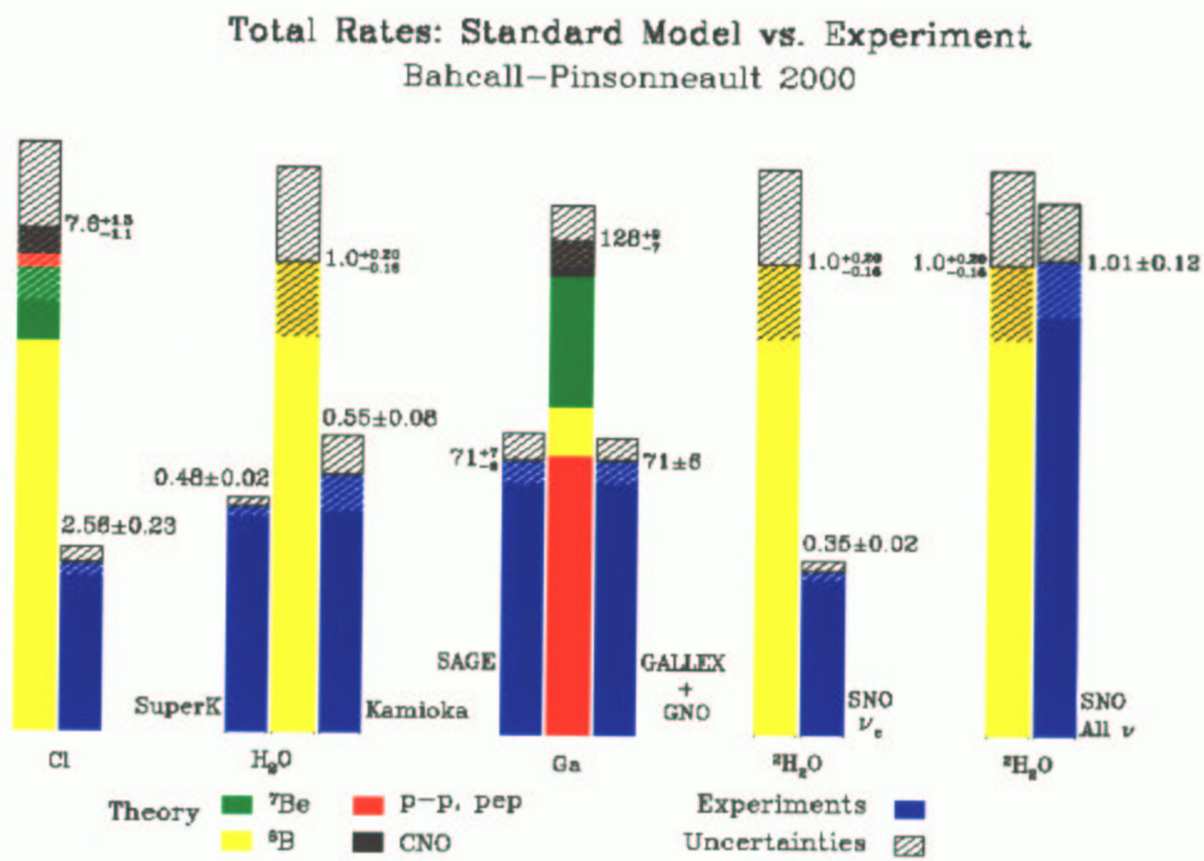
for the SNO Collaboration

Neutrinos and Implications for Physics Beyond the Standard Model.
Stony Brook Oct. 11-13, 2002.

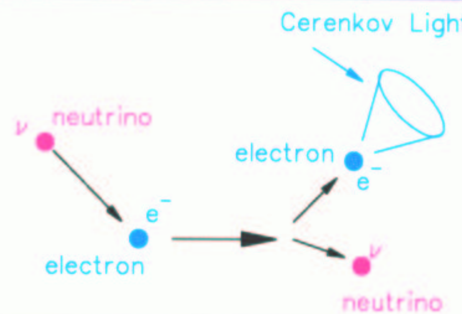
The Solar Neutrino Problem: April 2002



Neutrino Signals In Heavy Water

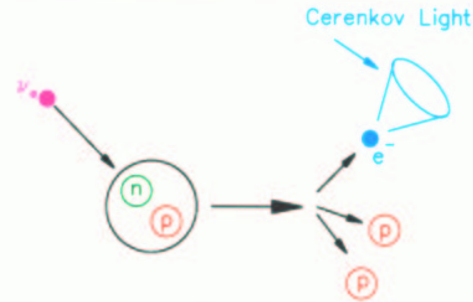
ES: Elastic Scattering

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



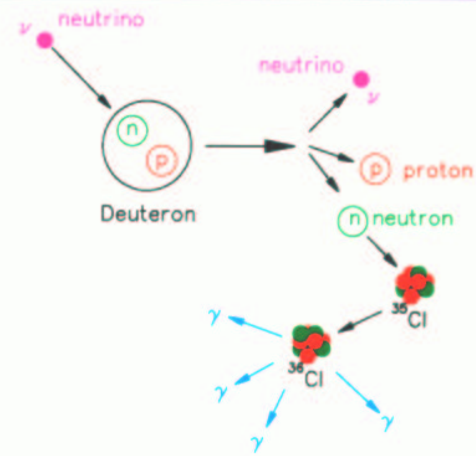
CC: Charged Current

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



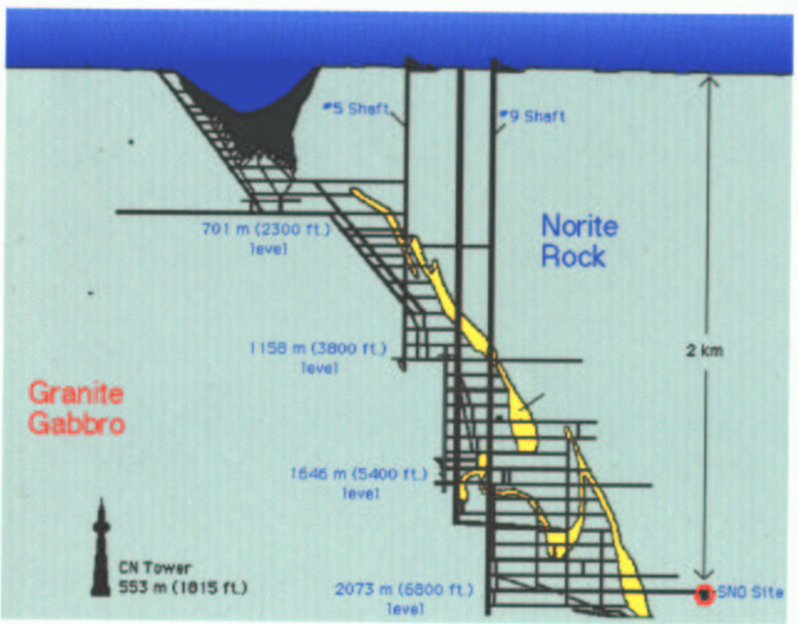
NC: Neutral Current

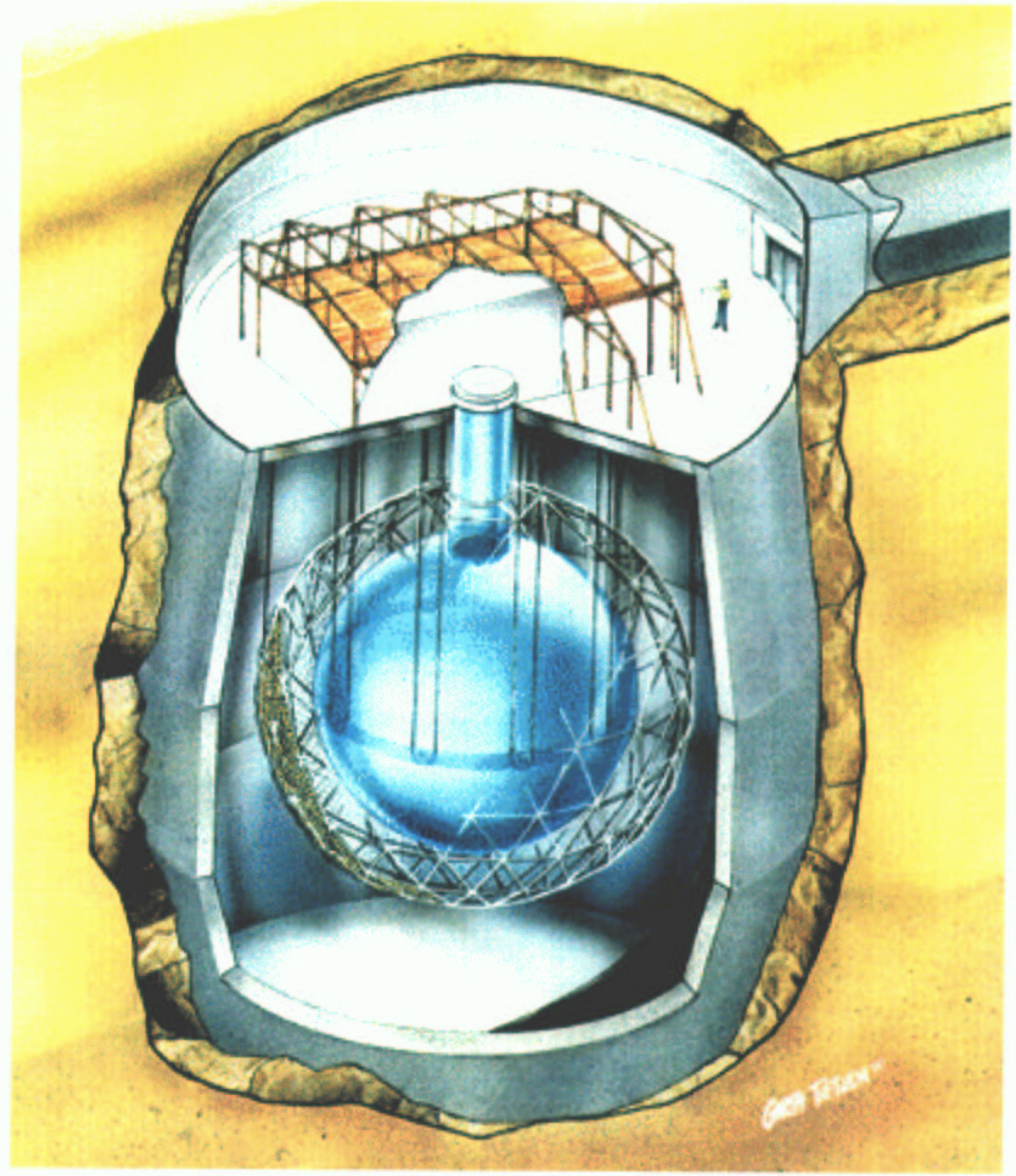
$$\nu_x + d \rightarrow p + n + \nu_x$$



Sudbury Neutrino Observatory

- 6010m water equivalent overburden.
- 1000 Tonnes D_2O.
- 9438, 20cm PMTs with reflectors
  $\Rightarrow$ 60% coverage.
- 7000 tonnes ultrapure light water shielding.





Three Experiments in One

Three ways detect to detect the Neutral Current interactions...

The Three Phases	Neutron Detection Method	
1) Pure D_2O ⇒ Good CC sensitivity	Capture on deuteron $n + d \to t + \gamma \ldots \to e^-$ $(E_\gamma = 6.3 MeV)$	**Done**
2) Added Salt in D_2O ⇒ Enhanced NC sensitivity	Capture on Cl $n +^{35} Cl \to^{36} Cl + \Sigma\gamma \ldots \to e^-$ $(E_{\Sigma\gamma} = 8.6 MeV)$	**Taking Data**
3) NCD (Neutron Counters) ⇒ ^{3}He proportional counters in the D_2O	Capture on ^{3}He $n +^3 He \to p + t$ Event by event separation of CC and NC events.	**Future**

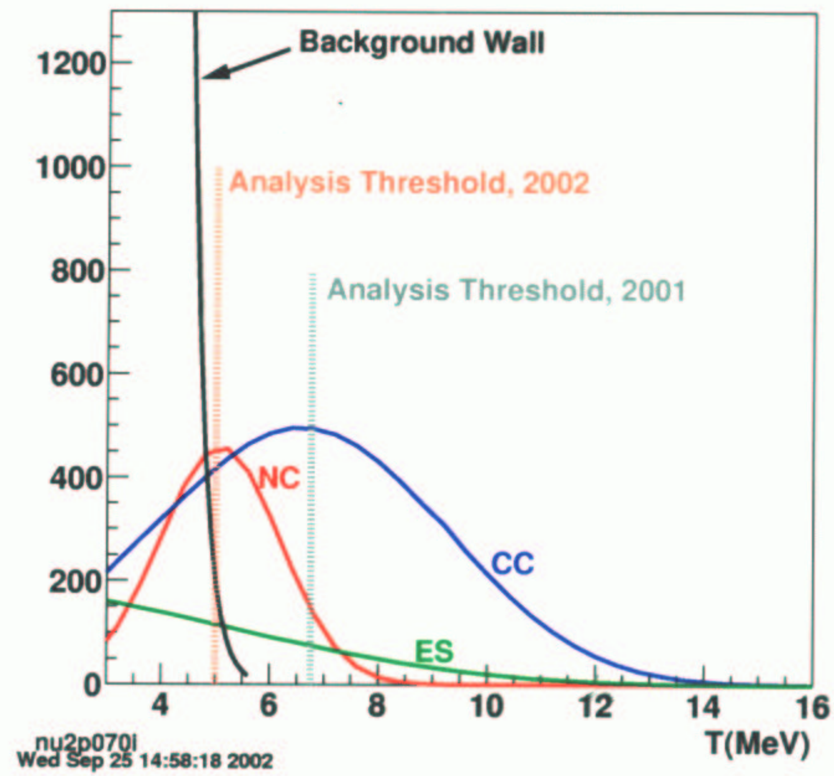
Phase 1: Pure D_2O

- Data taking period: Nov 1999 to June 2001
- 306 live days of data.
- June 2001:
  High threshold (6.75 MeV) analysis
  CC Flux measurement

  Phys. Rev. Lett. **87** (2001) 071301 `nucl-ex/0106015`
- April 2002:
  Low threshold (5 MeV) analysis
  NC Flux and Day-Night measurement

  Phys. Rev. Lett. **89** (2002) 011301 `nucl-ex/0204008`

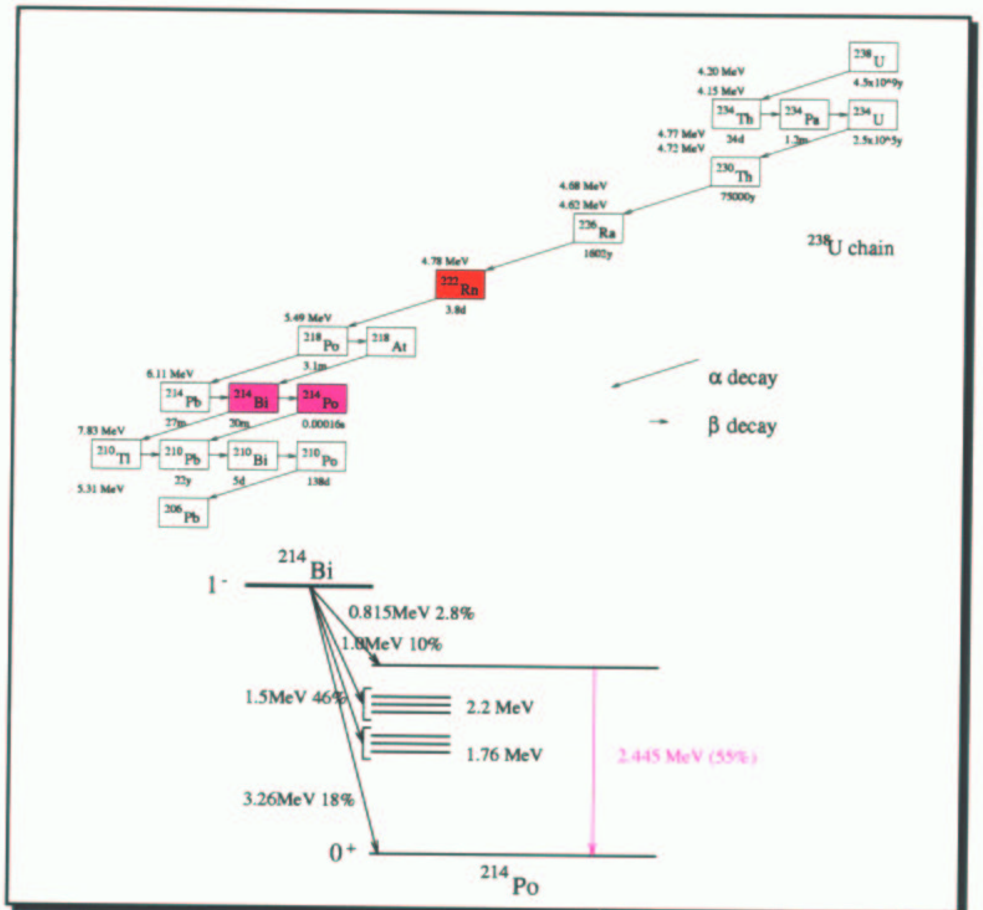
  Phys. Rev. Lett. **89** (2002) 011302 `nucl-ex/0204009`
- Only sensitive to ^8B and HEP solar neutrinos.

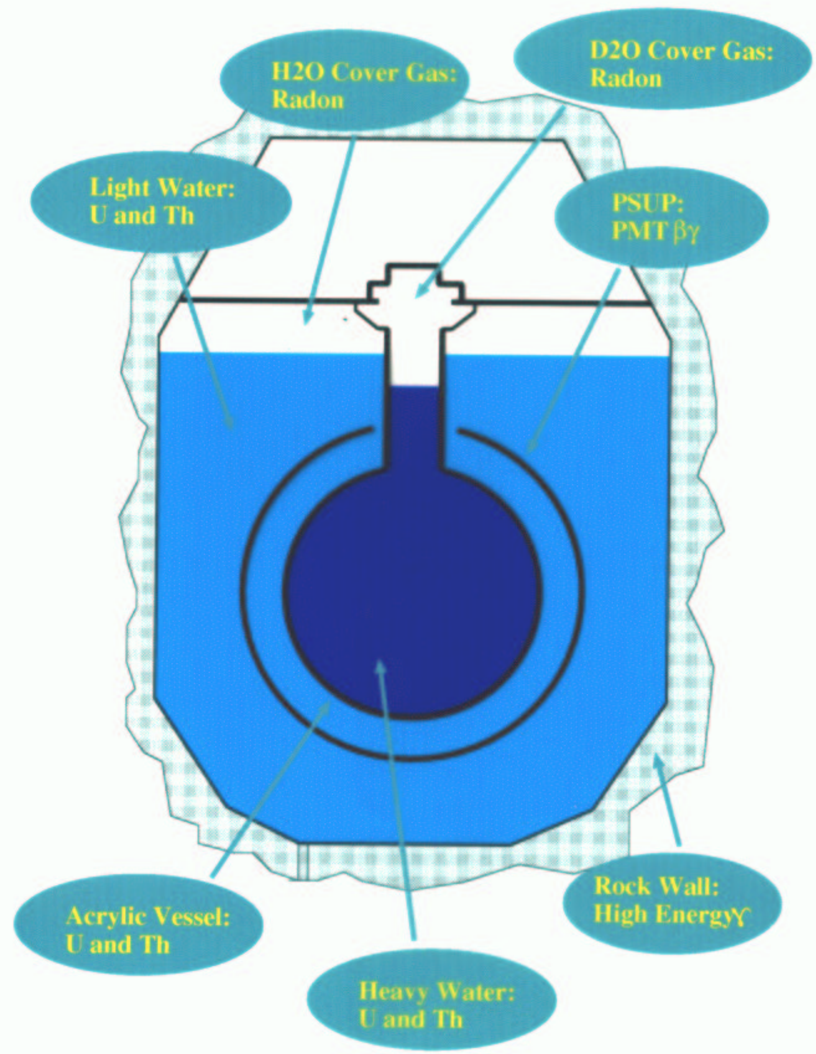


Radioactive Backgrounds

- Čerenkov Light from U and Th.
- ^{214}Bi and ^{208}Tl cause $\gamma d \rightarrow pn$

  ⇒ NC Background



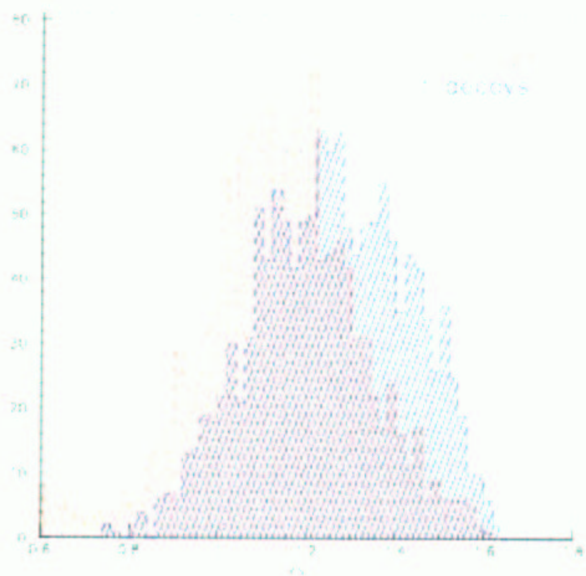


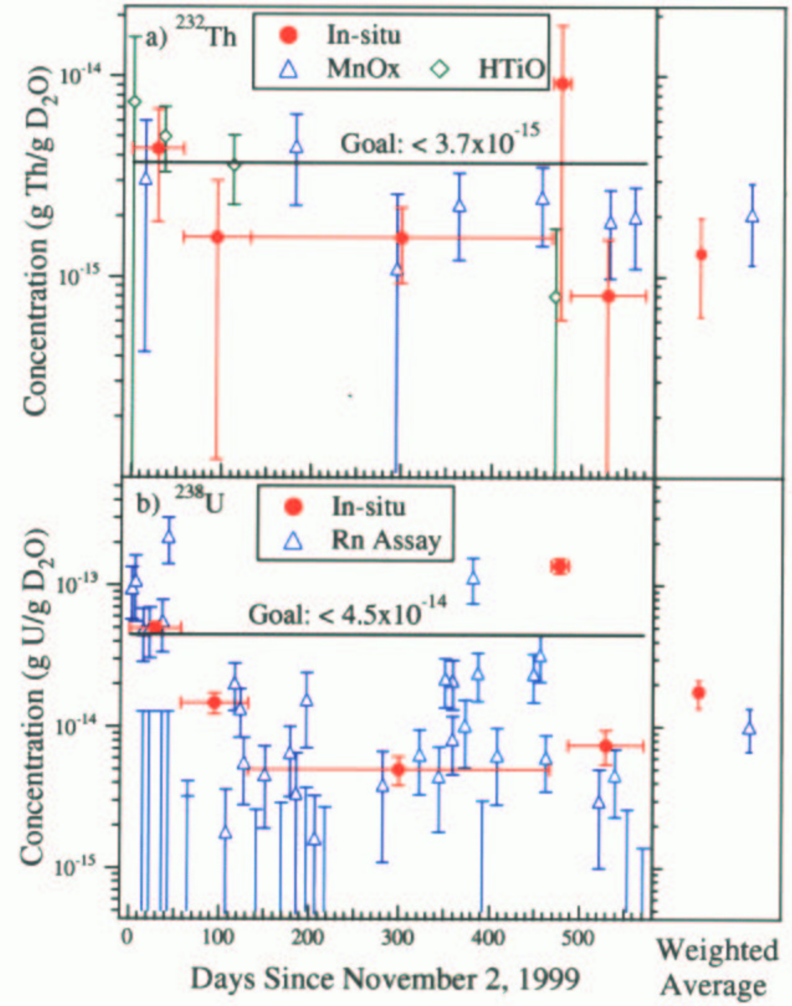
Ex-situ Measurements

- Ion exchange (^{224}Ra, ^{226}Ra)
- Membrane degassing (^{222}Rn)
- Count daughter product decays.

In-situ Measurements

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





78 ± 12 neutrons $\Rightarrow$ 12% SSM

Calibrations

Electronics

Timing and Charge calibration and stability ⇒ Electronic pulsars

Optical

Media attenuation, reflections, scattering, ⇒ Pulsed laser: 0.6ns
PMT angular response (337,365,386,420,500,620 nm)

Position and Direction

D_2O vs H_2O vs PSUP events; Radial profiles; ⇒ ^{16}N 6.13 MeV γ, ^{8}Li ~14 MeV β
Fiducial volume; Direction relative to Sun

Energy

CC energy spectrum, NC/CC discrimination ⇒ ^{16}N γ, pT 19.8 MeV γ, ^{8}Li

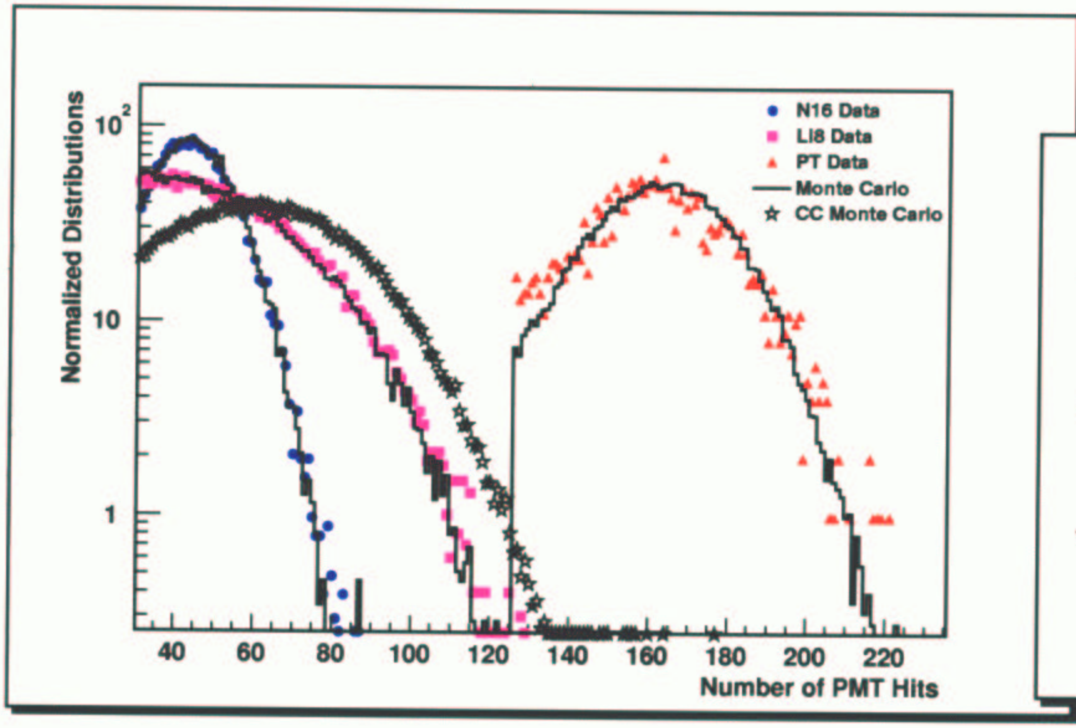
Neutron

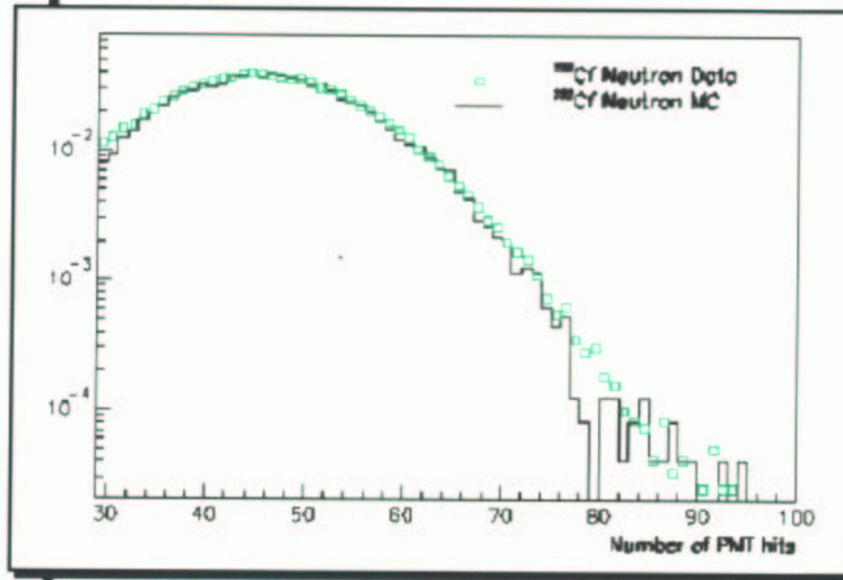
NC/CC discrimination; Capture efficiency ⇒ ^{252}Cf fission neutrons

Low Energy Backgrounds

Radial profile, Event identification ⇒ Th and U chain sources

Energy Calibration



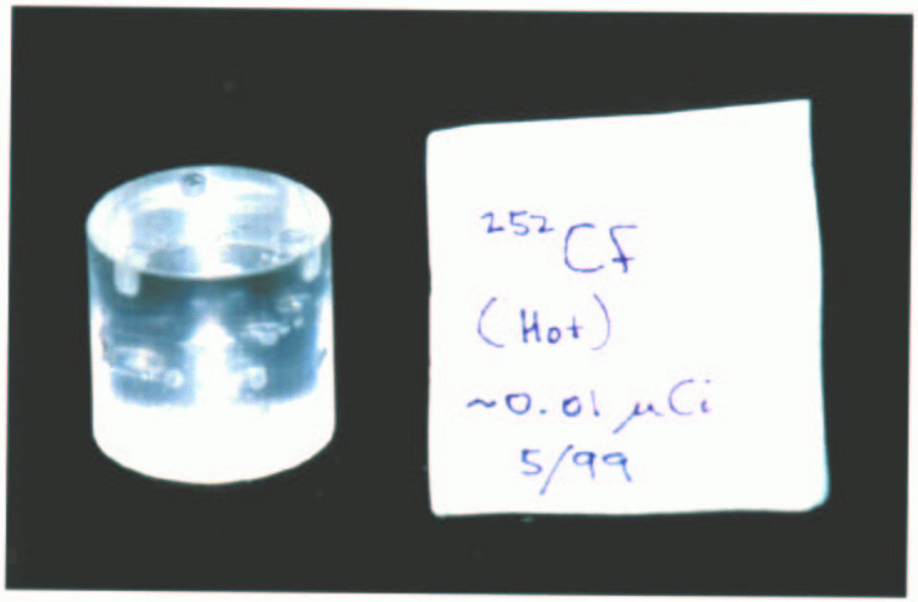


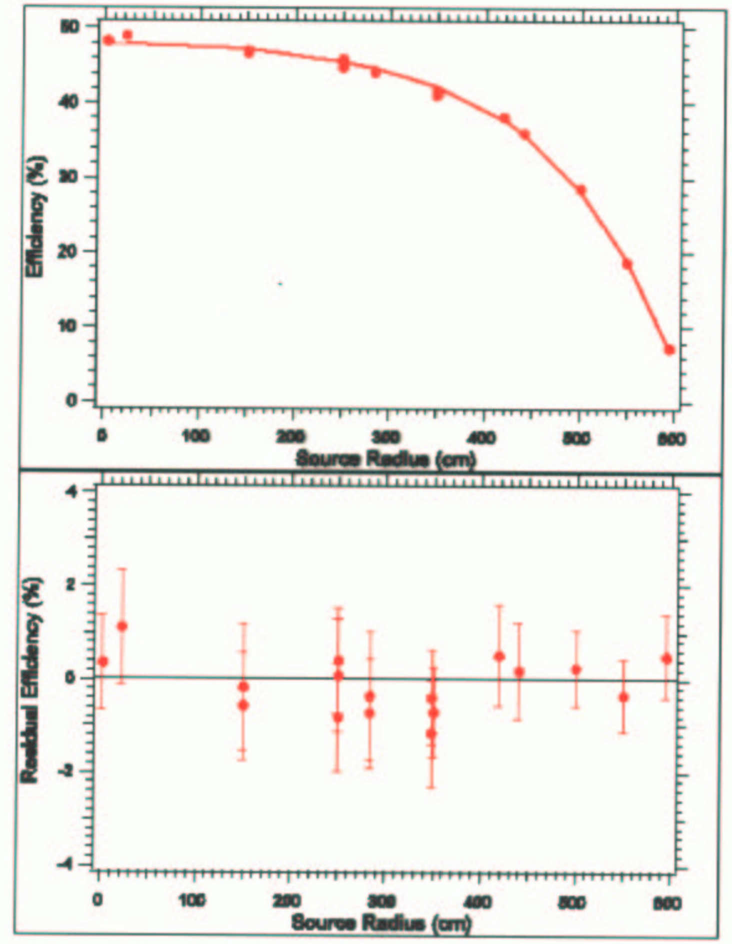
^{16}N	$\Rightarrow$	6.13 MeV γs
$p + t \rightarrow {}^4He + \gamma$	$\Rightarrow$	19.8 MeV γs
$n + d \rightarrow t + \gamma$	$\Rightarrow$	6.25 MeV γs
^{8}Li	$\Rightarrow$	β spectrum, endpoint $\approx$ 14 MeV

Energy Scale Uncertainty: 1.2 %

Neutron Capture Efficiency

Neutron capture efficiency measured using ^{252}Cf fission sources.

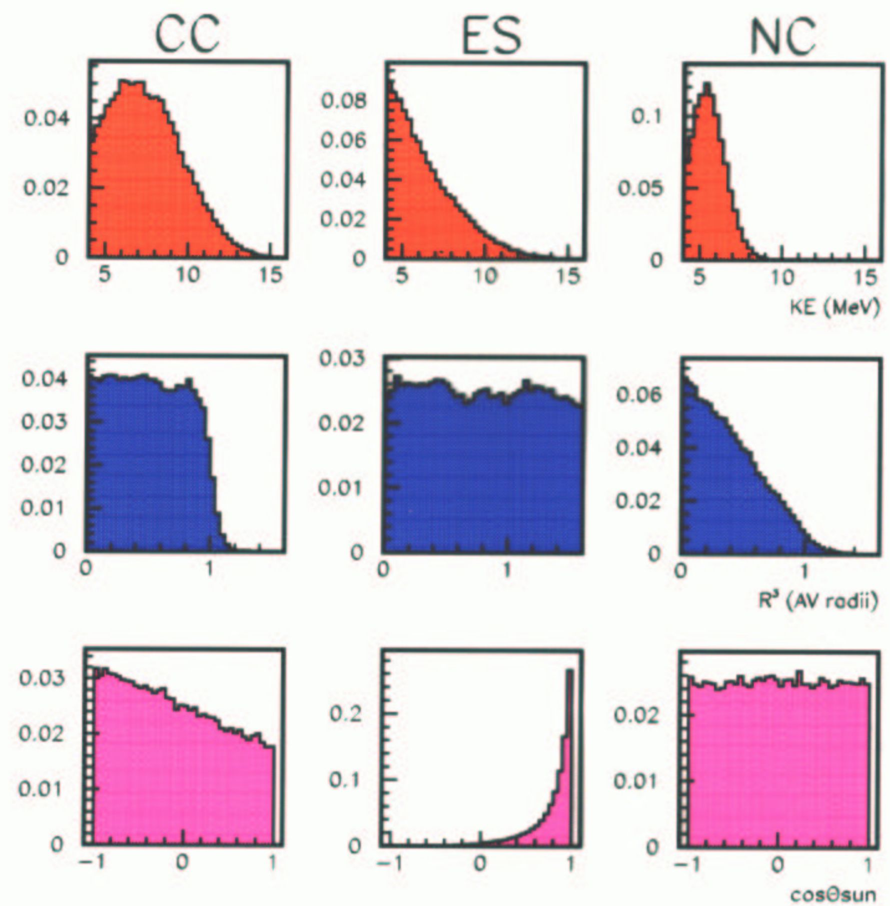




29.9±1.1% capture efficiency for a uniform neutron source in the D_2O.

Signal Extraction

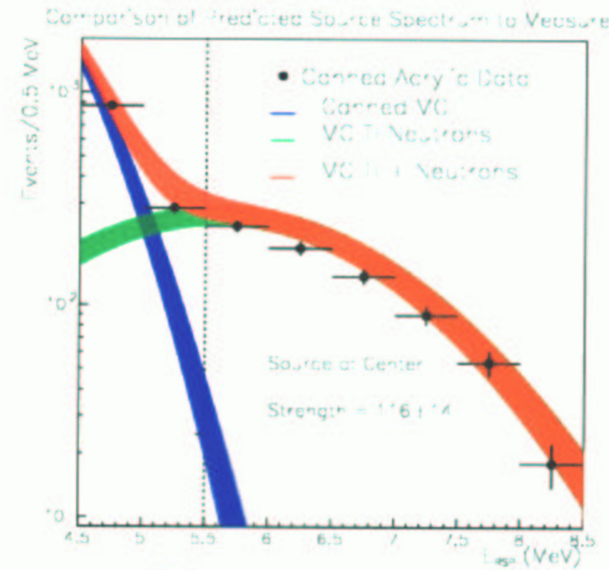
- Apply cuts
  - Cuts to remove instrumental backgrounds
  - Radial cut at $R \leq 5.5m$.
  - Energy Threshold, $T \geq 5MeV$
  - 2928 events left
- Derive Probability Density Functions for Neutrino Signal (CC, ES and Neutrons):
  - The energy spectrum, T_e
    $\Rightarrow$ Assume no spectral distortion.
  - The volume weighted radial distribution, $(R/R_{AV})^3$
  - The direction wrt to the sun, $\cos\theta_{sun}$

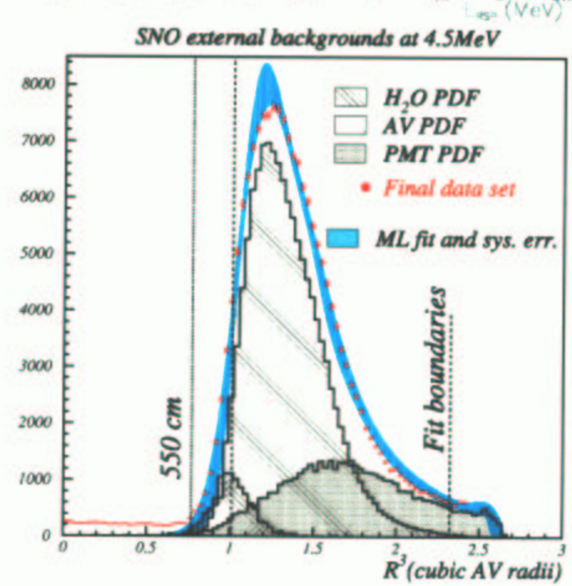


Background PDFs

Energy spectrum and radial profile determined using Uranium and Thorium Chain sources + Monte Carlo.

Source	Events
D_2O photodisintegration	44^{+8}_{-9}
H_2O + AV photodisintegration	27^{+8}_{-8}
Atmospheric ν's and sub-Cherenkov threshold μ's	4 ± 1
Fission	$\ll 1$
$^2H(\alpha,\alpha)pn$	2 ± 0.4
$^{17}O(\alpha,n)$	$\ll 1$
Terrestrial and reactor $\bar{\nu}$'s	1^{+3}_{-1}
External neutrons	$\ll 1$
Total neutron background	78 ± 12
D_2O Cherenkov	20^{+13}_{-6}
H_2O Cherenkov	3^{+4}_{-3}
AV Cherenkov	6^{+3}_{-6}
PMT Cherenkov	16^{+11}_{-8}
Total Cherenkov background	45^{+18}_{-12}



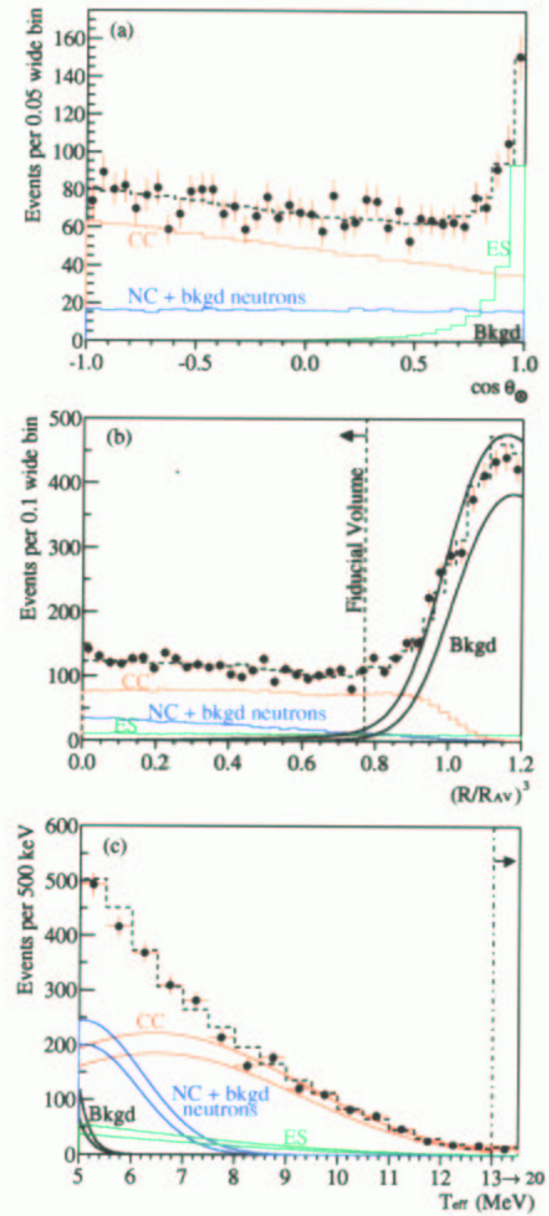


Signal Extraction

Maximum likelihood fit:

- Fixed contributions from Čerenkov and neutron backgrounds.
- Fit fractional contributions from CC, ES and NC.
- Fit is *not* constrained by either SSM or oscillation hypothesis.

$$\mathrm{CC} = 1967.7^{+61.9}_{-60.9} \text{ events}$$
$$\mathrm{ES} = 263.6^{+26.4}_{-25.6} \text{ events}$$
$$\mathrm{NC} = 576.5^{+49.5}_{-48.9} \text{ events}$$



Testing the No Oscillation Hypothesis

If there is no flavor conversion, then each of the CC, ES and NC yields can be used to infer the total ^{8}B solar neutrino flux.

$$\Phi_{CC}^{SNO} = 1.76^{+0.06}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}\ (\text{syst.})$$
$$\Phi_{ES}^{SNO} = 2.39^{+0.24}_{-0.23}(\text{stat.})^{+0.12}_{-0.12}\ (\text{syst.})$$
$$\Phi_{NC}^{SNO} = 5.09^{+0.44}_{-0.43}(\text{stat.})^{+0.46}_{-0.43}\ (\text{syst.})$$

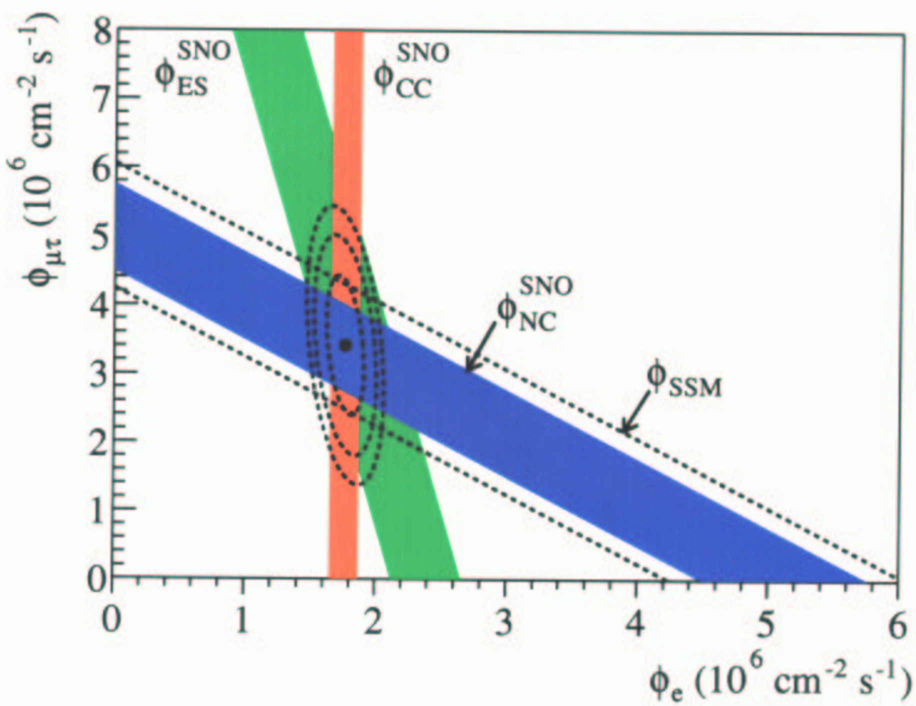
$\Rightarrow$

Alternatively, the total flux can be expressed as the sum of an electron neutrino flux and a muon or tau neutrino flux, $\Phi = \Phi_e + \Phi_{\mu\tau}$.

$$\Phi_e = 1.76^{+0.05}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}\ (\text{syst.})$$
$$\Phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}(\text{stat.})^{+0.48}_{-0.45}\ (\text{syst.})$$

- **Non-electron neutrino flux is 5.3σ from zero.**
  $\Rightarrow$ *FLAVOR CONVERSION OF SOLAR NEUTRINOS*
- **Excludes pure (2 flavor) electron $\leftrightarrow$ sterile neutrino oscillations.**

Comparison With SSM



- Excellent agreement with the SSM ^{8}B Flux prediction.
- However, the extracted flux is sensitive to the CC spectral shape.

	Φ_{B8} $(\times 10^6 cm^{-2} s^{-1})$
SSM	$5.05^{+1.01}_{-0.81}$
SNO Constrained (SSM ^{8}B Shape)	$5.09^{+0.44}_{-0.43}$(stat.)$^{+0.46}_{-0.43}$(syst.)
SNO Unconstrained	$6.42^{+1.57}_{-1.57}$(stat.)$^{+0.55}_{-0.58}$(syst.)

Day-Night Asymmetry

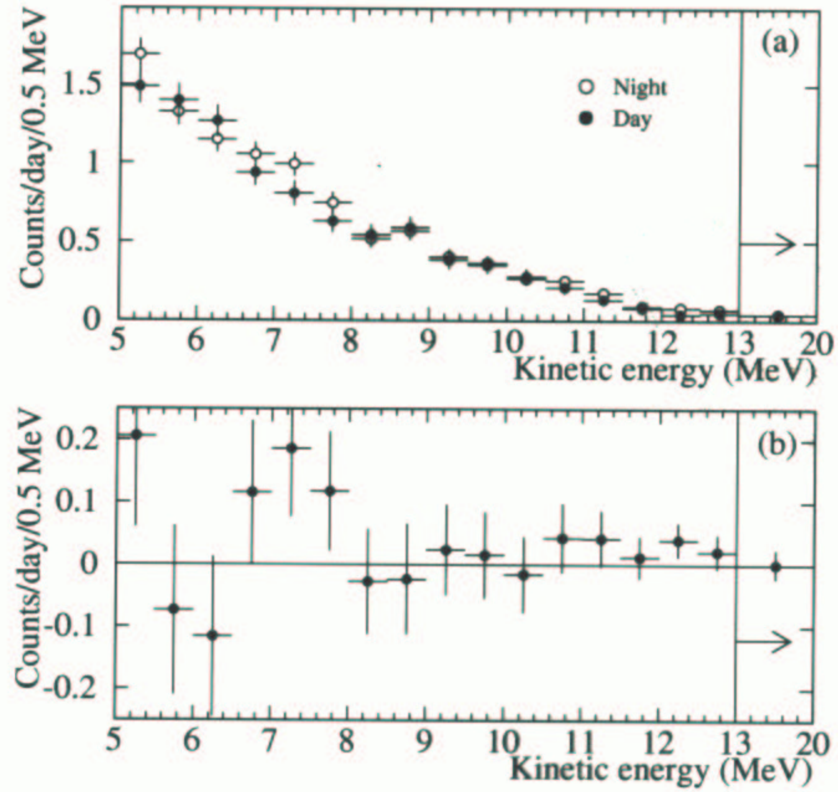
- Asymmetry between the night and day neutrino rates,

$$A = 2 \times \frac{R_{\rm Night} - R_{\rm Day}}{R_{\rm Night} + R_{\rm Day}}$$

- Can measure asymmetries in both the CC and NC fluxes.
- Look for Matter Regeneration

$$A_{CC} \neq 0 \quad \Rightarrow \quad \nu_e \leftrightarrow \nu_x$$

$$A_{NC} \neq 0 \quad \Rightarrow \quad \nu_{active} \leftrightarrow \nu_{sterile} \ ?$$



A_e versus A_{total}

Extraction in Φ_{CC}, Φ_{NC}, Φ_{ES}

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

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

Extraction in Φ_e, Φ_{total}

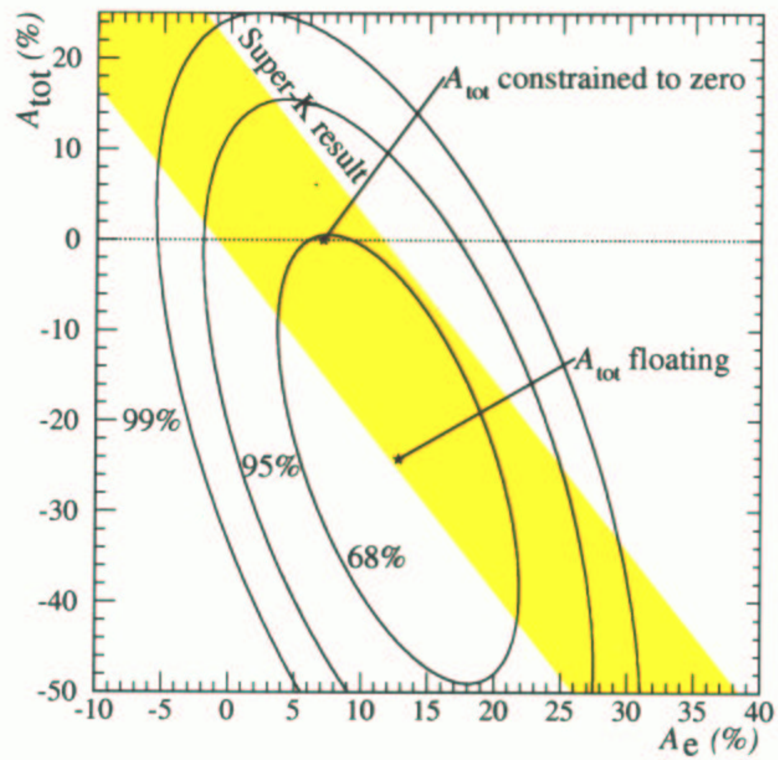
$A_e = 12.8 \pm 6.2^{+1.5}_{-1.4}\%$

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

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

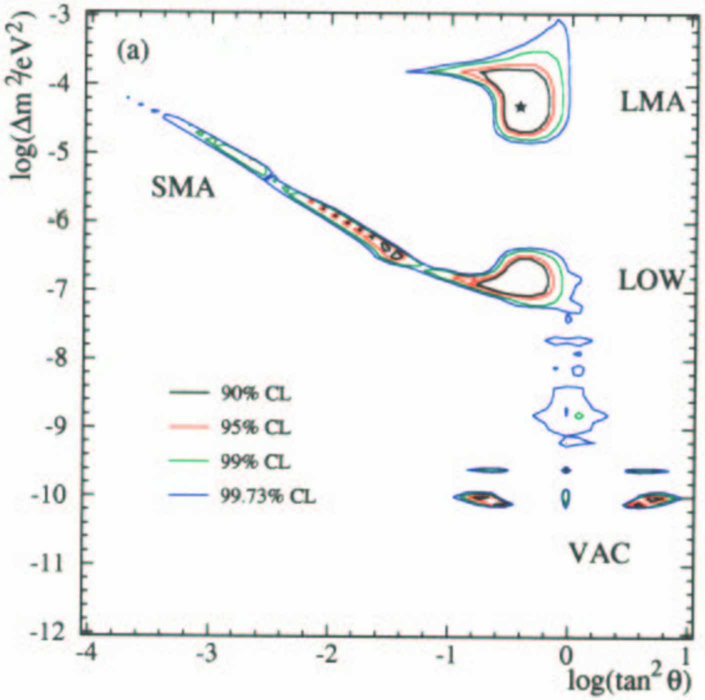
$A_e = 7.0 \pm 4.9^{+1.3}_{-1.2}\%$

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

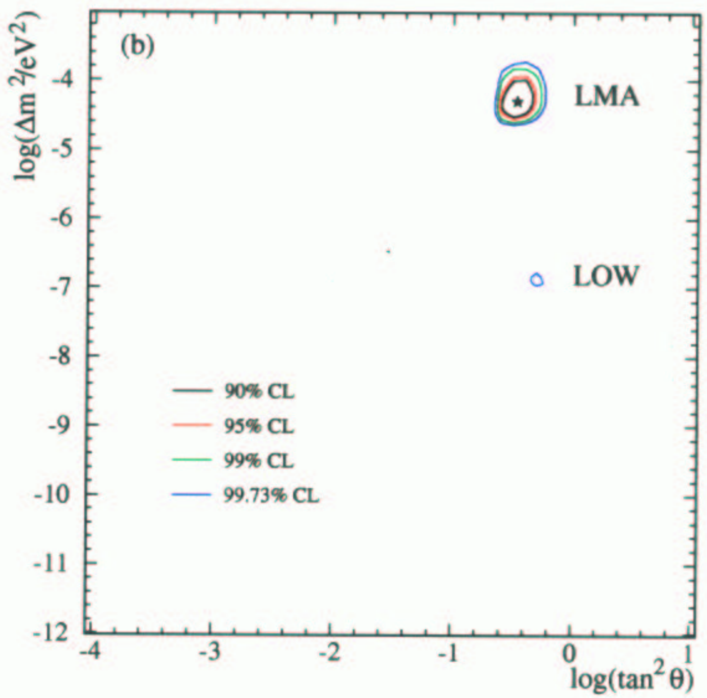


Constraints on Mixing Parameters

SNO Day and Night Energy Spectra Alone



Combining All Experimental and Solar Model Information



Region	χ^2_{min}/dof	ϕ_B	$A_e(\%)$	Δm^2	$\tan^2\theta$	c.l.(%)
LMA	57.0/72	5.86	6.4	5.0×10^{-5}	0.34	—
LOW	67.7/72	4.95	5.9	1.3×10^{-7}	0.55	99.5

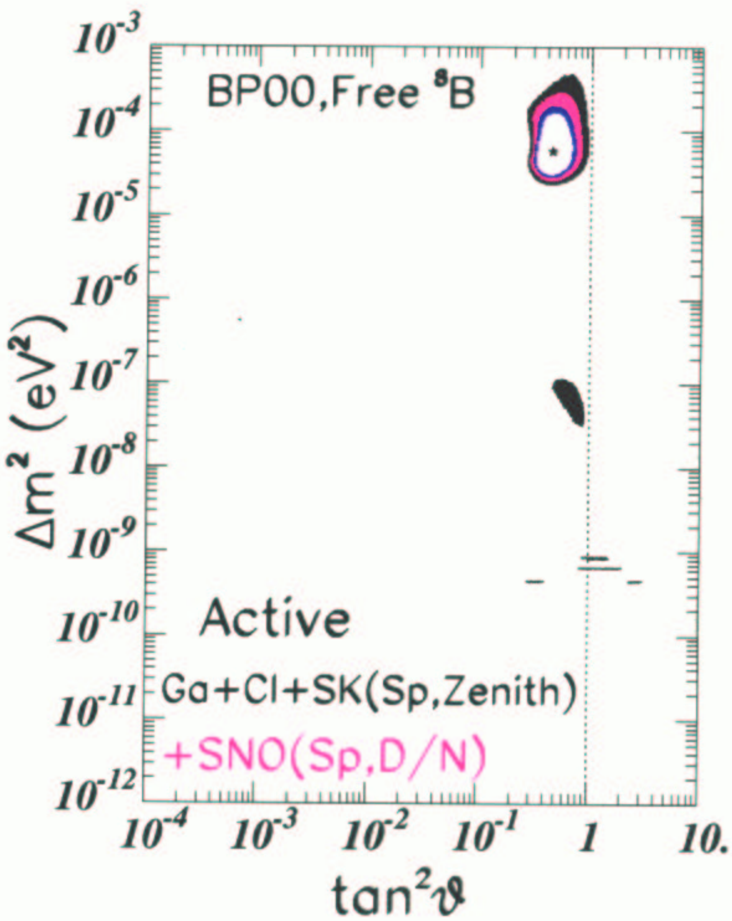
What About Vacuum?

- Different groups

  e.g. Bahcall, Gonzalez-Garcia, Pena-Garay hep-ph/0204314
  Fogli, Lisi, Marrone, Montanino, Palazzo hep-ph/0206162

  have found a vacuum solution at the 3σ level as well.

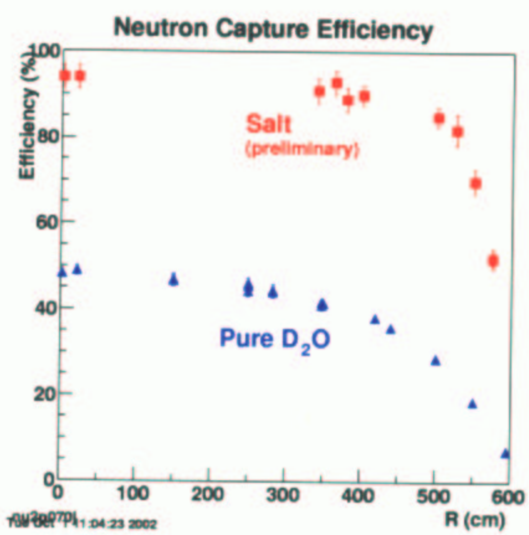
- Possible differences:
  - ^8B spectrum uncertainty.
  - Correlations between Ga and Cl cross section uncertainties
  - More exact treatment of SNO spectral uncertainties.

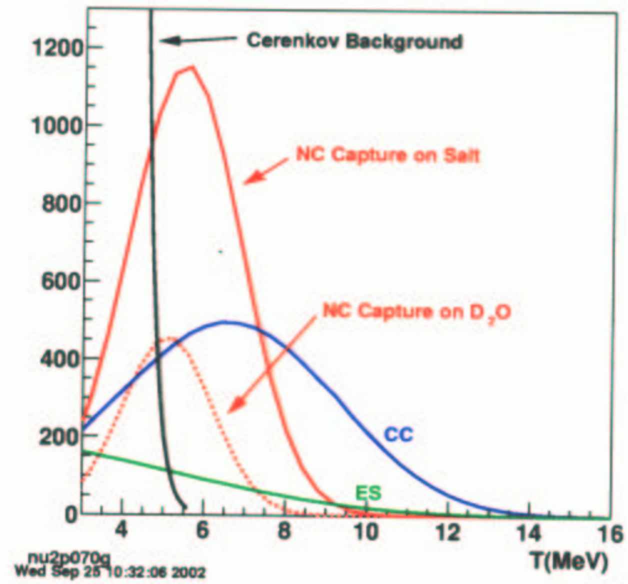


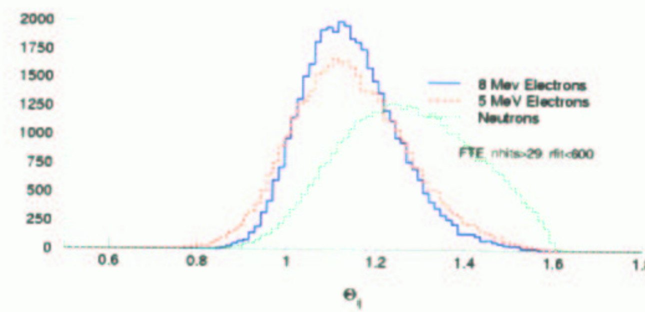
Bahcall *et. al.* hep-ph/0204314

Phase 2: Salt

- Added 2 tonnes of NaCl to the D_2O in May 2001.
- Capture on Cl
  $n +^{35} Cl \rightarrow^{36} Cl + \Sigma\gamma \ldots \rightarrow e^-$
  $(E_{\Sigma\gamma} = 8.6 MeV)$
- Increases capture efficiency from 27% to ~ 82%







Phase 3: Neutral Current Detectors

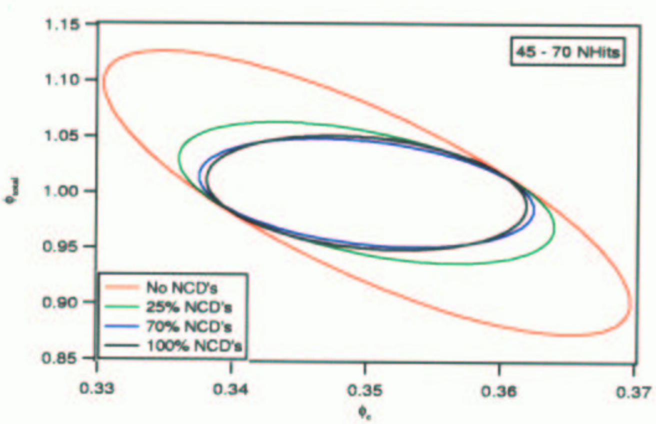
- Install ultra pure material ^{3}He proportional counters,

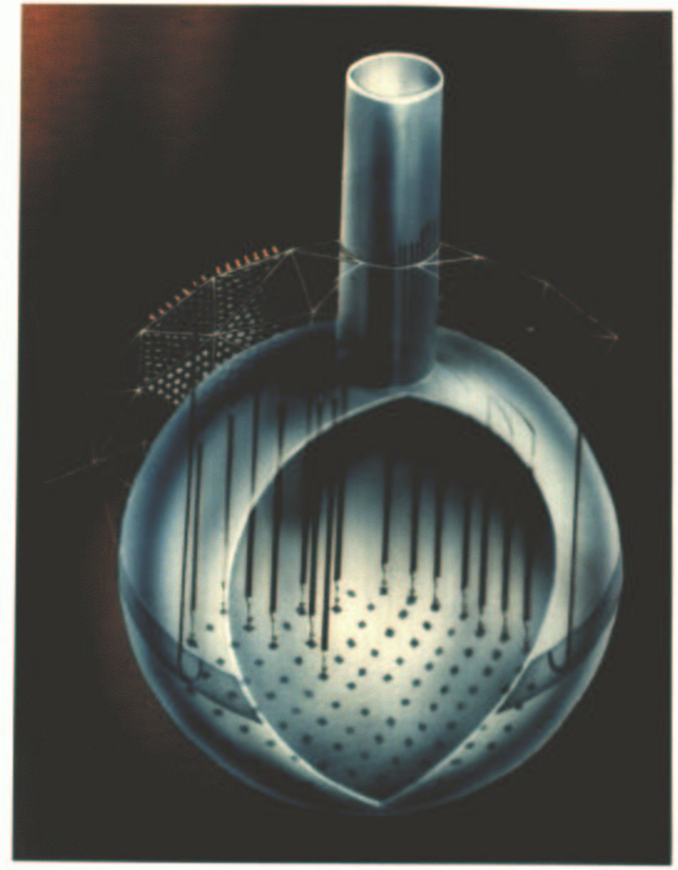
  $^3He + n \rightarrow p + ^3H + 764keV$

- Capture efficiency (full string)

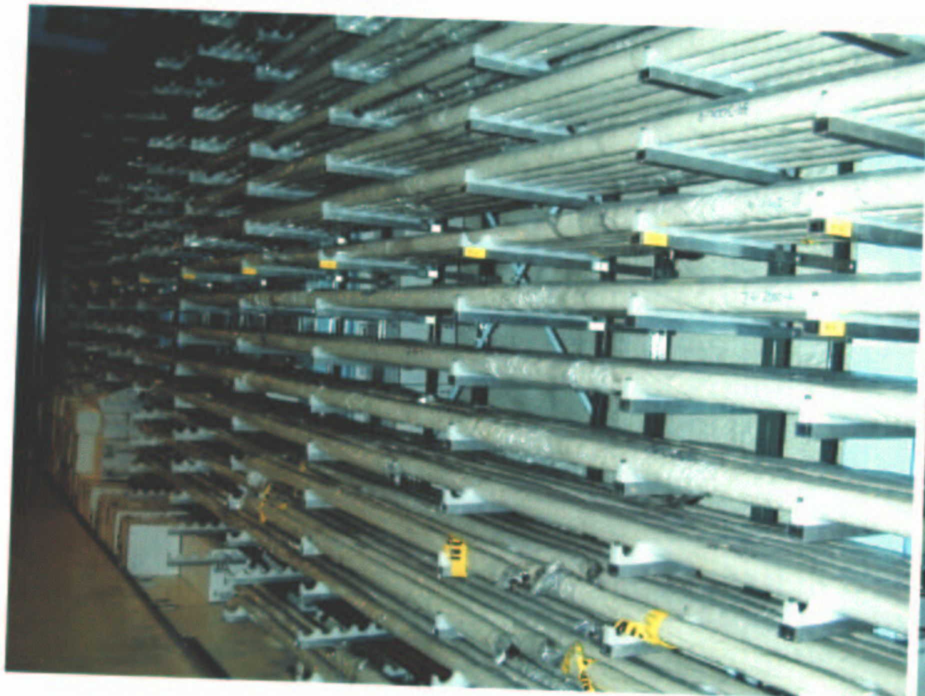
  NCD(capture): ~46%

  D_2O: ~12%





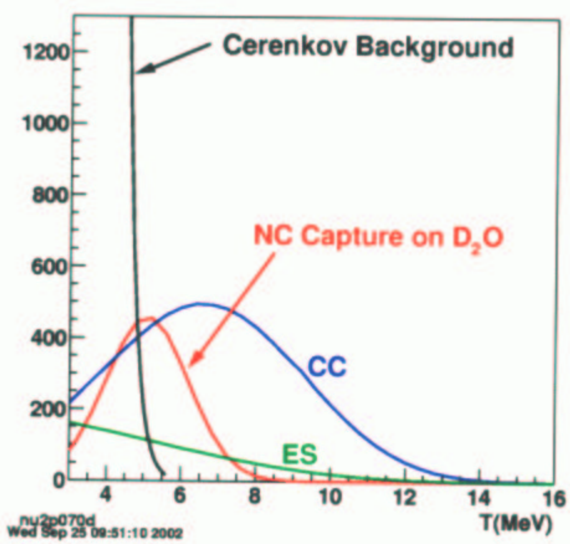
Total string length: 770m



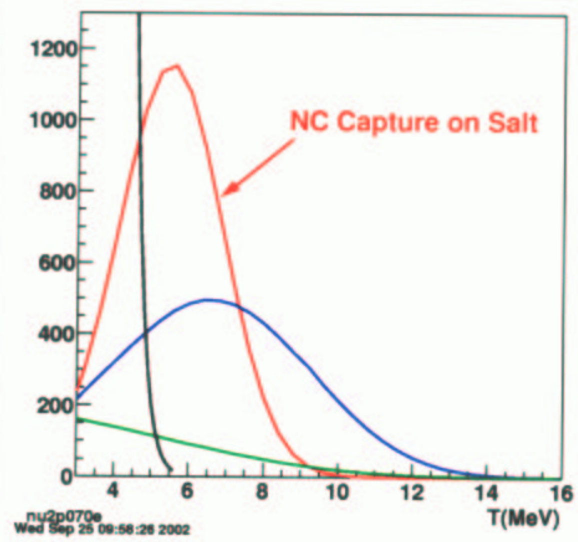

CAUTION

Summary

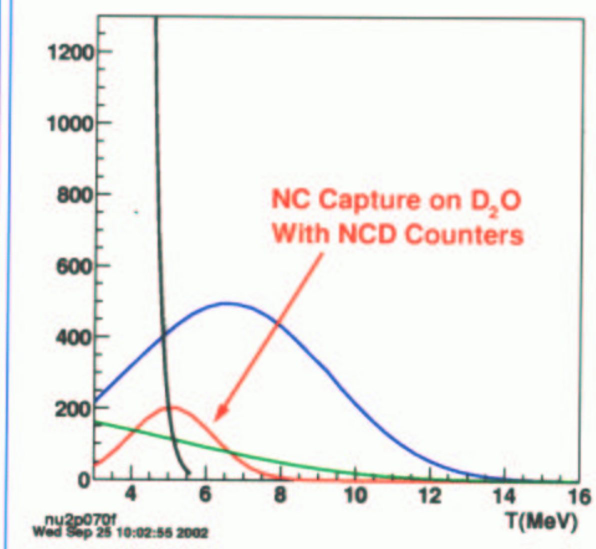
Pure D_2O Phase



Salt Phase



NCD Phase



- Confirm the D_2O Neutral Current Measurement with the Salt and NCD measurements.
- Improve the NC measurement by breaking the NC/CC correlations.
- Improve statistics of the CC Day/Night Asymmetry.
- Different NC Day/Night Asymmetry Measurement (NCDs).

Conclusions

- First detection of a total active neutrino flux from the sun.

  ⇒ In good agreement with SSM predictions.

- Direct observation of non-electron active solar neutrino flux

  ⇒ Strong evidence of Neutrino Flavor Conversion.

  ⇒ Two flavor $\nu_e \rightarrow \nu_s$ oscillation hypothesis excluded.

- Only weak evidence of earth regeneration of solar neutrinos.

- LMA strongly favored.