New Physics Results from SNO

Presentation to the High Energy Physics Advisory Panel

July 13, 2001

Snowmass, Colorado

Eugene W. Beier/University of Pennsylvania

The Sudbury Neutrino Observatory Collaboration

A Collaboration of Chemists, Nuclear Physicists,

and Particle Physicists:

Canada	United States
Carleton U.	Brookhaven Nat. Lab.
U. British Columbia	Lawrence Berkeley Nat. Lab.
U. of Guelph	Los Alamos Nat. Lab.
Laurentian U.	U. of Pennsylvania
Queen’s U.	U. of Washington

U.K.

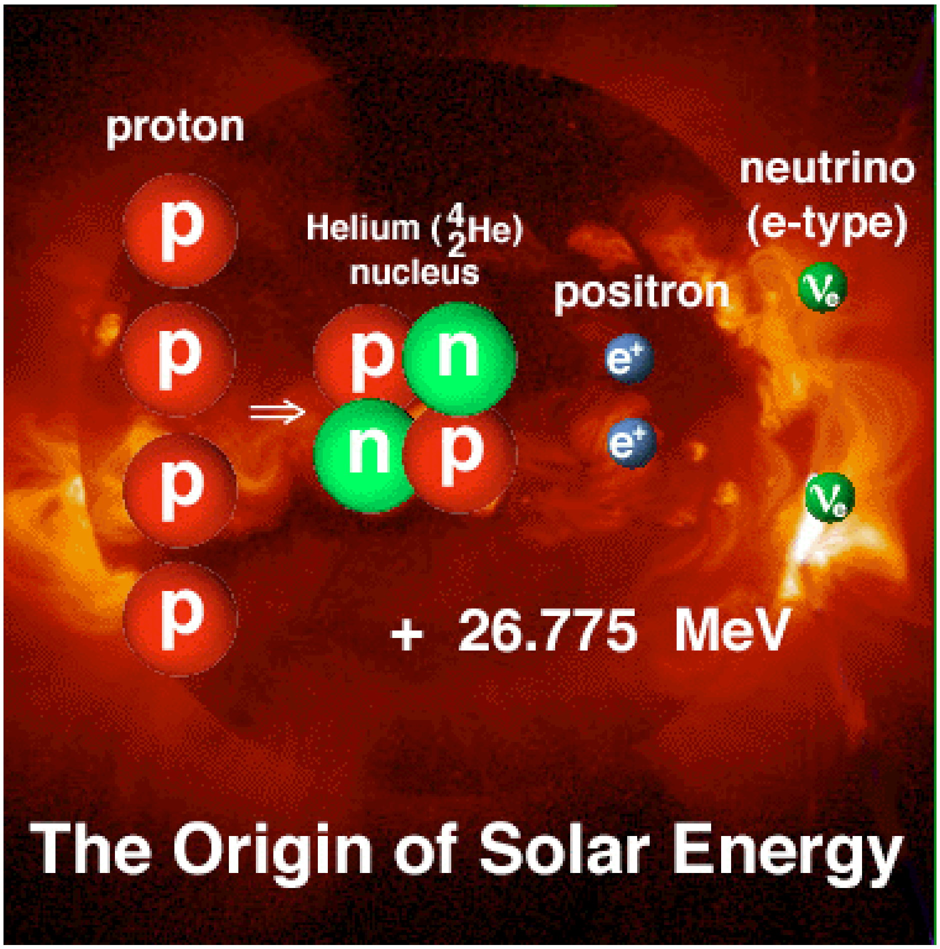
U. of Oxford

Outline

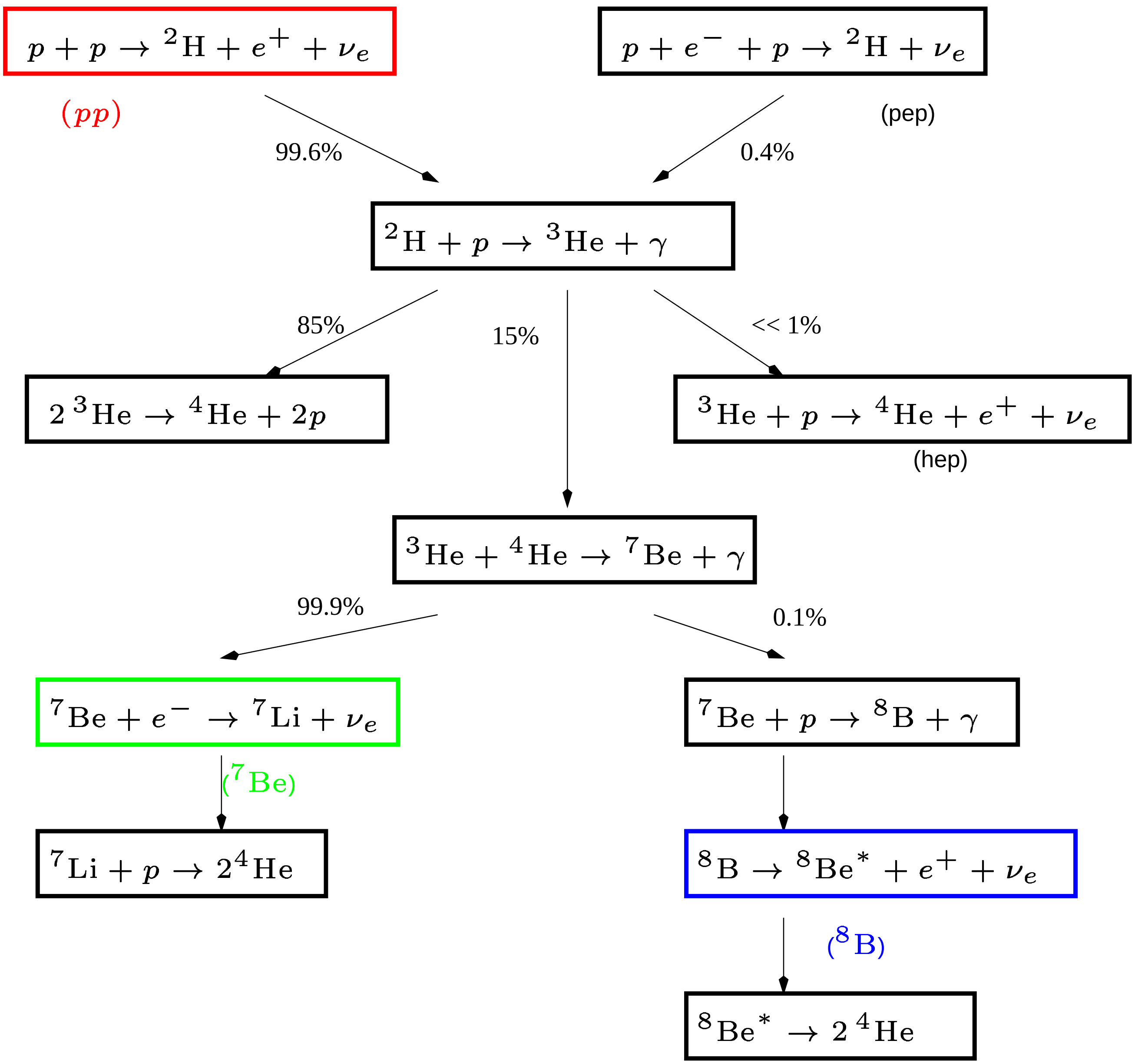
1. Solar Neutrino Science
2. Solar ν Detection in SNO
3. Detector response.
4. Data Reduction
5. Results and Conclusions.

How the Sun Consumes Its Fuel

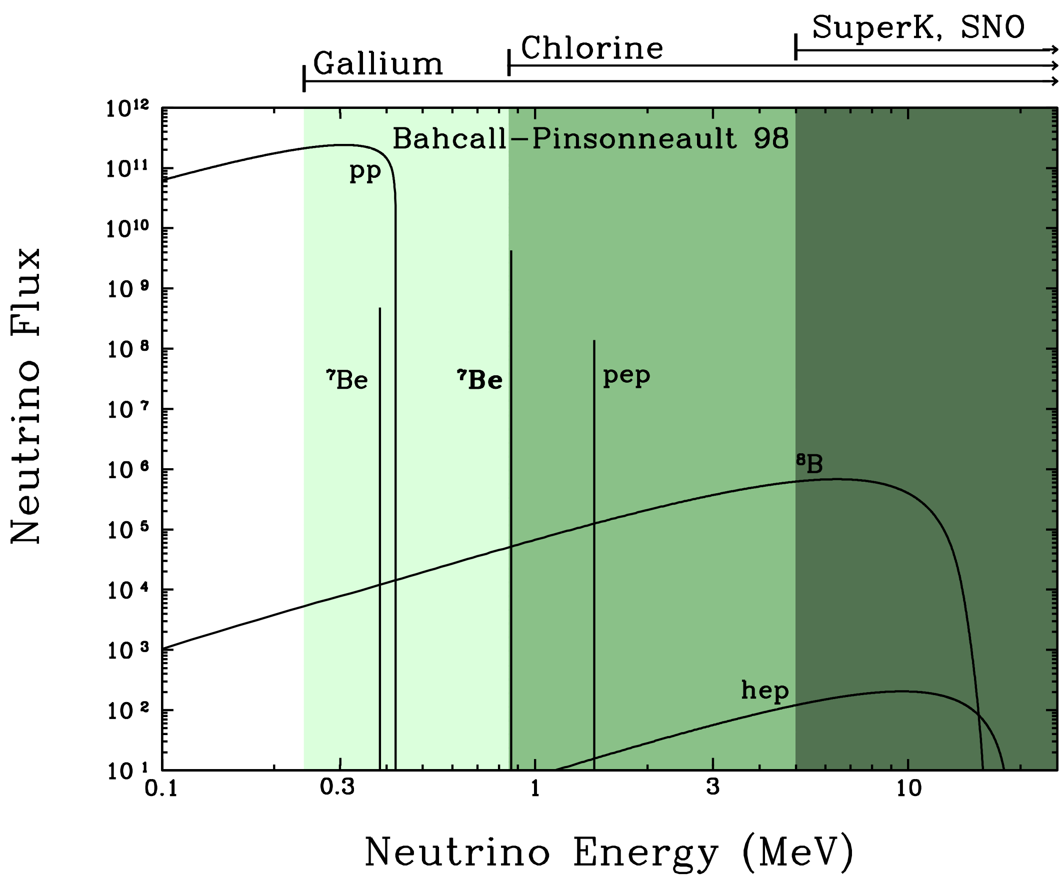
The basics of Nuclear Fusion



The pp Chain


$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$
(pp)
$p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_e$
(pep)
99.6%
0.4%
${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$
85%
15%
<< 1%
$2\,{}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$
${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$
(hep)
${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$
99.9%
0.1%
${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$
$({}^7\mathrm{Be})$
${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$
${}^7\mathrm{Li} + p \rightarrow 2\,{}^4\mathrm{He}$
${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e$
$({}^8\mathrm{B})$
${}^8\mathrm{Be}^* \rightarrow 2\,{}^4\mathrm{He}$

Solar Neutrino Spectra

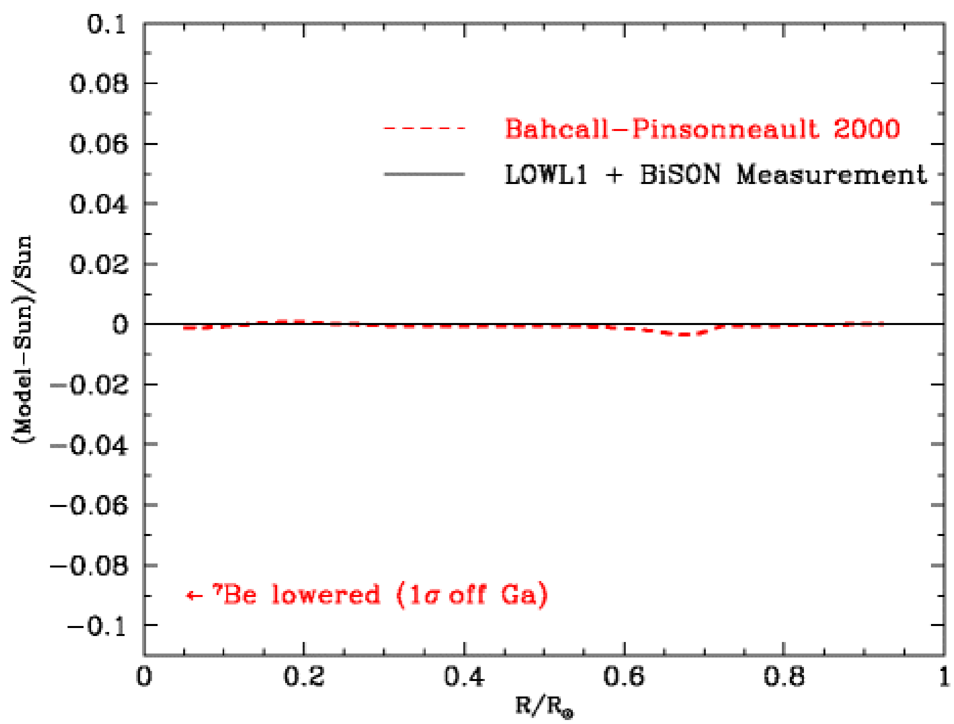


→ **Spectra determined by nuclear physics, not solar model.**

Predictions of Standard Solar Models

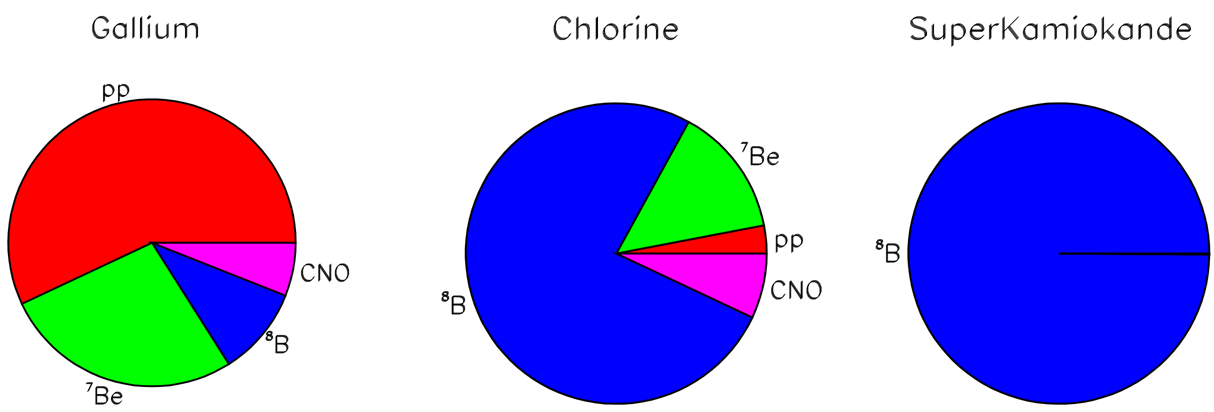
- Solar evolution
- Neutrino fluxes
- Solar density profile

→ Testable through helioseismology

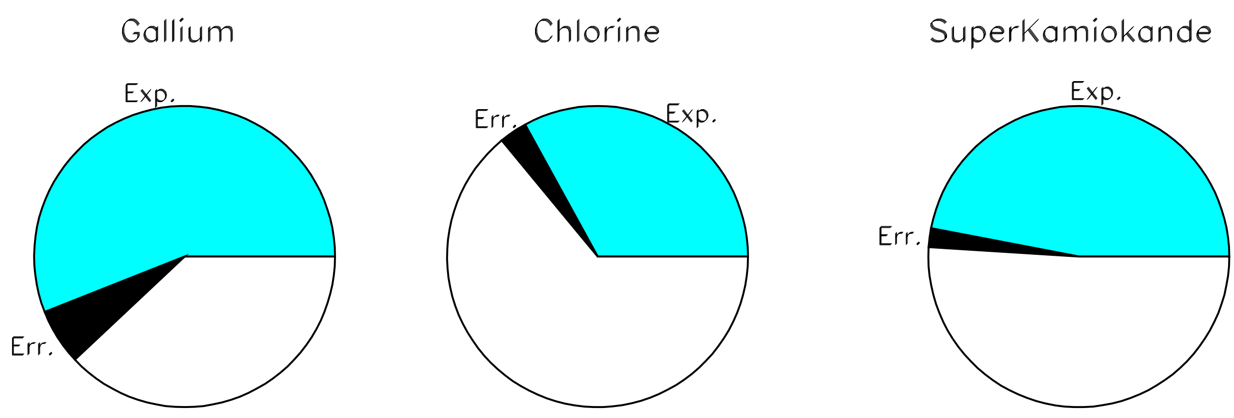


The Solar Neutrino Problem

- BAD: All experiments show a flux deficit of 30-60%.
- WORSE: Flux suppression is energy dependent.
  - Standard Solar Model Predictions:

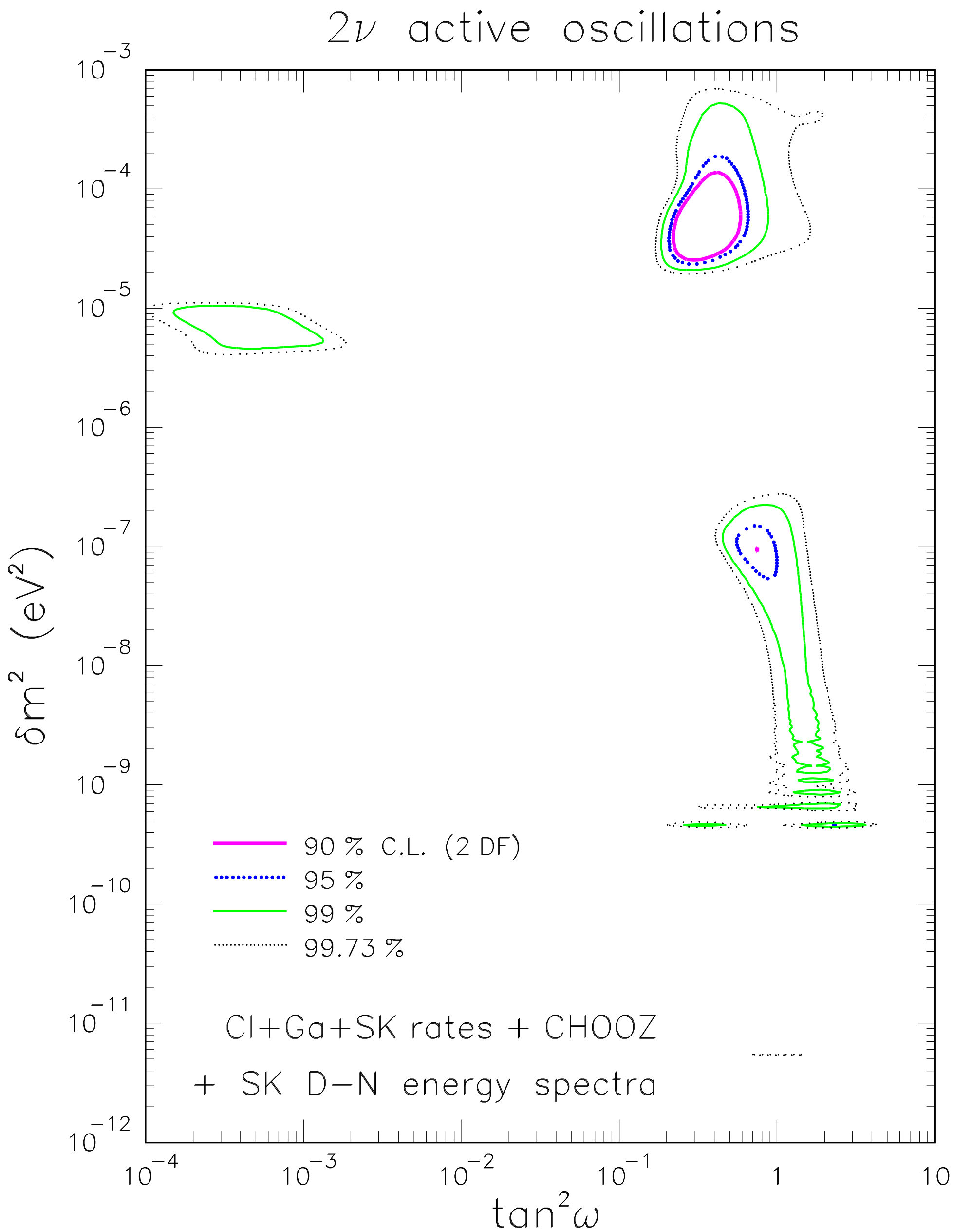


  - Measurements:



→ Does this indicate neutrino oscillations?

Pre-SNO: $\Delta m^2_{12}, \sin^2 2\theta_{12}$



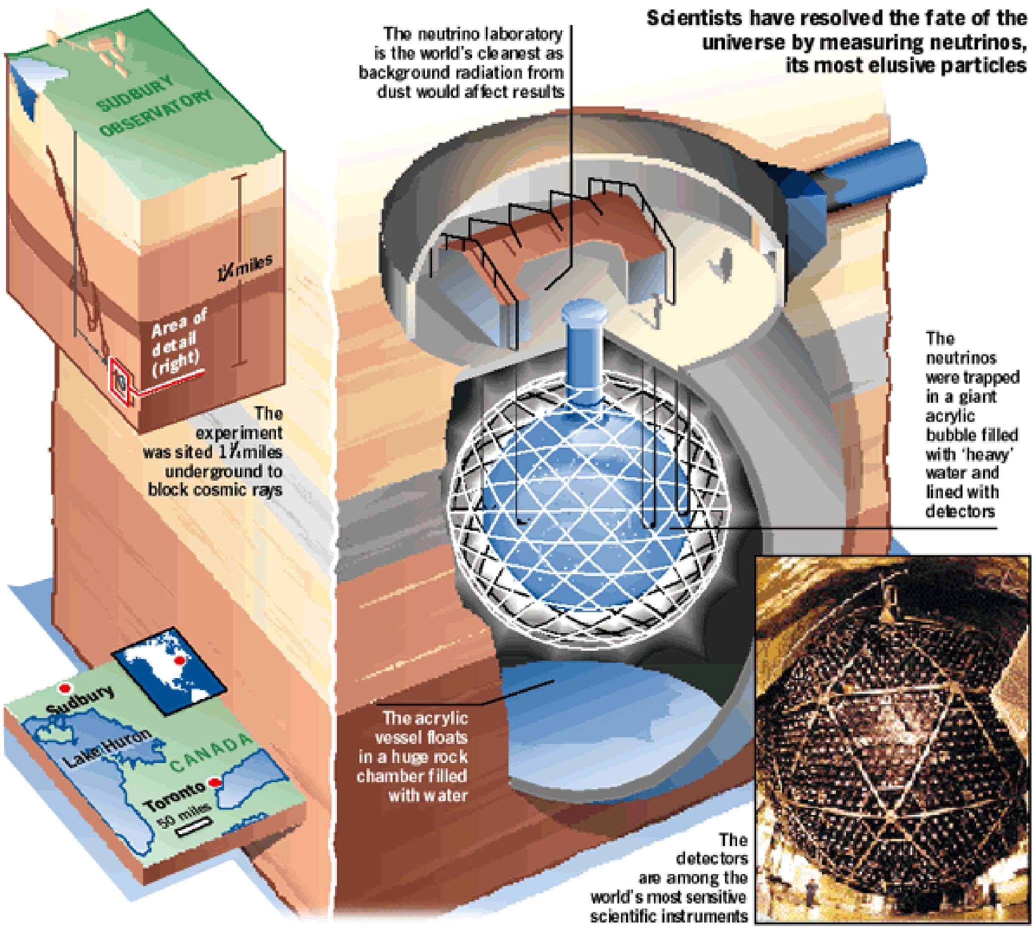
(*Fogli, Lisi, Montanino, and Palazzo*)

Rates only analysis favor "Small Mixing Angle" solution, including SuperK Day-Night spectra favors (upper) "Large Mixing Angle."

Neutrino Oscillation Signatures

- Neutrinos other than ν_e are visible through NC interactions.
- Spectral distortion of the fundamental β decay spectrum.
- Temporal modulations of ν_e flux other than that from the eccentricity of the earth's orbit.

The Sudbury Neutrino Observatory



(*The Times of London*)

The SNO Experiment

$\rightarrow$ Goal of SNO is to make a direct test of the oscillation hypothesis.

Three reactions for solar ν detection:

$\nu_e + d \rightarrow p + p + e^-$ (Charged Current—CC)

$\nu_x + d \rightarrow p + n + \nu_x$ (Neutral Current—NC)

$\nu_{e,(\mu,\tau)} + e \rightarrow \nu_{e,(\mu,\tau)} + e^-$ (Elastic Scattering—ES)

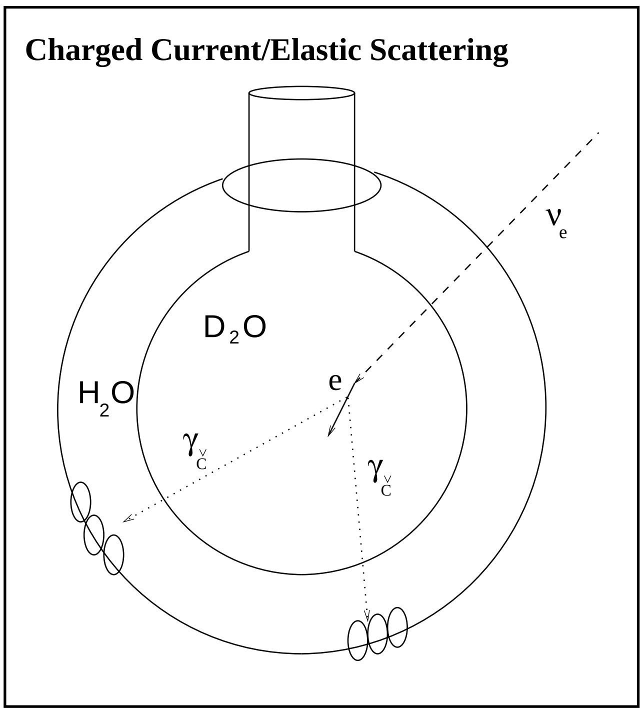
$\rightarrow$ CC/NC (or CC/ES) yields fraction of solar ν_e's at earth relative to total flux of neutrinos from the sun.

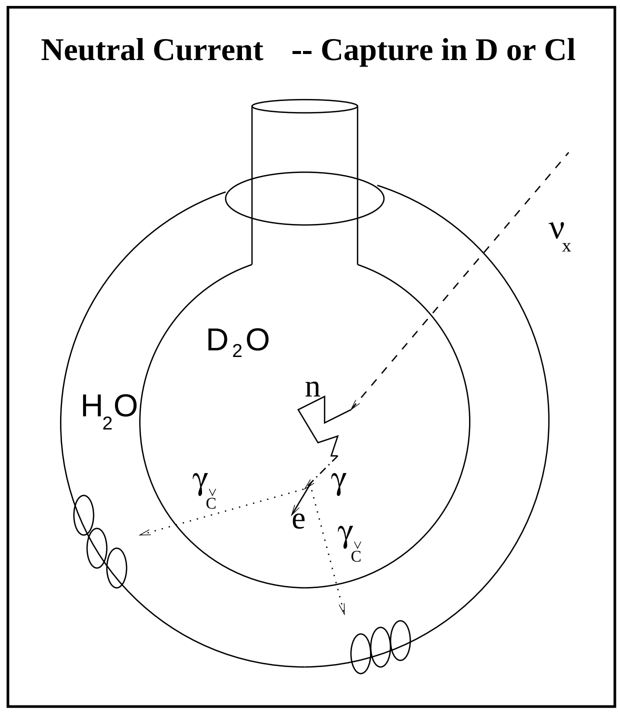
$\rightarrow$ Even more: CC is sensitive measure of ν_e spectrum.

$\rightarrow$ AND: ES provides comparison to other experiments such as Super-Kamiokande.

Detection Processes

- CC and ES reactions produce relativistic electron directly.
- NC reaction frees a neutron; detectable either with capture in D_2O or Cl additive, eventually with ^{3}He proportional counters.





Obtain Detector Response Through Calibrations

- Electronics— Pedestals and timing.

  $\rightarrow$ Built-in programmable pulsers.

- Phototube Response— Timing corrections and gains.

  $\rightarrow$ Laser source with sub-ns timing.

- Optics— Attenuation, scattering, reflectivity.

  $\rightarrow$ Laser source.

- Energy— Response (PMTs/MeV) and resolution as a function of position and direction.

  $\rightarrow$ ^{16}N source (Tagged 6.1 MeV γ).

  $\rightarrow$ pT source (19.8 MeV γ).

  $\rightarrow$ Triggered U and Th $\beta - \gamma$ sources.

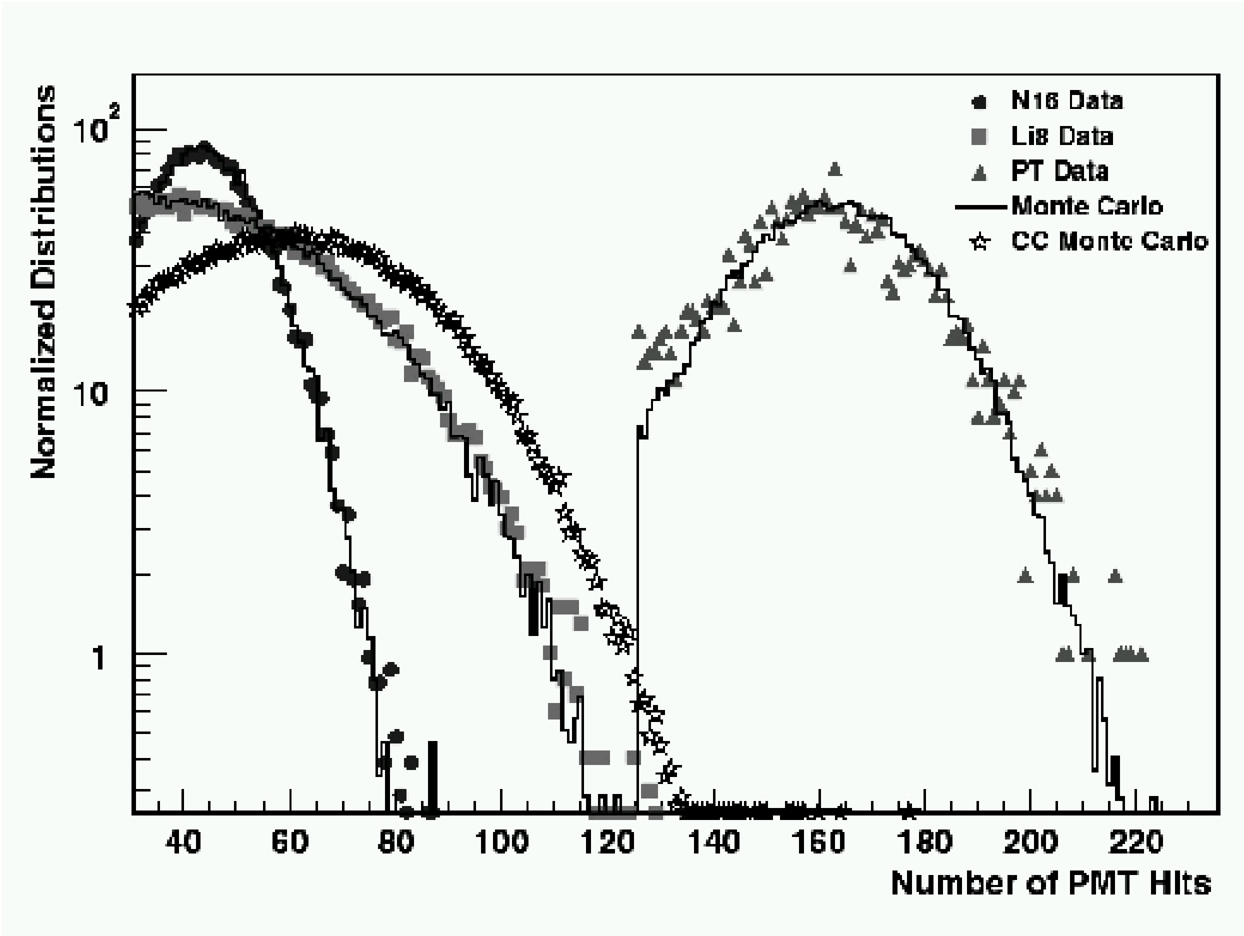
- Electrons— Event characteristics and energy response over ^{8}B energy range.

  $\rightarrow$ ^{8}Li high energy tagged β source.

- Neutrons— Capture and detection efficiency.

  $\rightarrow$ 252Cf and tagged ^{17}N source.

More Calibrations

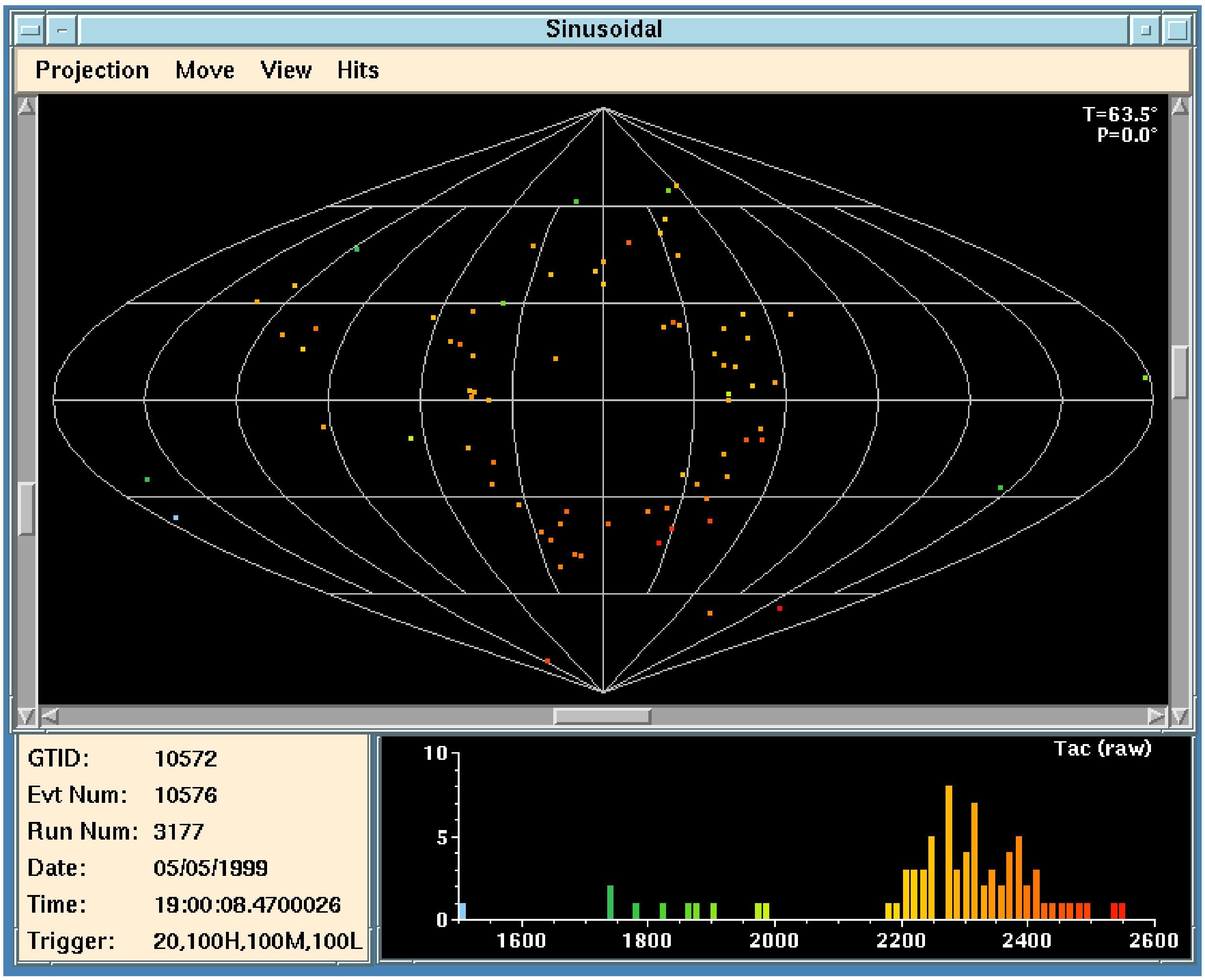


Energy response (data and simulation) for:

- ^{16}N - 6.13 MeV γs.
- ^{8}Li - 16 MeV endpoint βs (degraded by energy loss in target chamber.
- $p(t,\gamma)^4He$ - 19.8 MeV γs.

along with simulation of the simulated CC spectrum.

Solar Neutrino Candidate

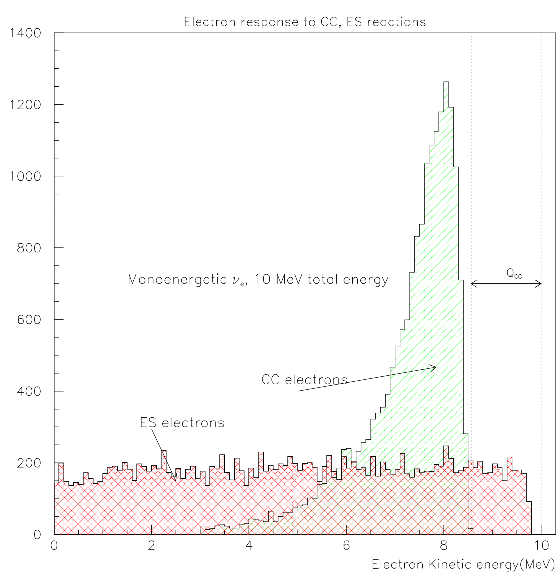


Background Measurement and Rejection

- Low Energy (< 4 MeV)
  - Periodic assays of both D_2O and H_2O.
  - Measurement with low energy data and cal. sources
  - $\rightarrow$ Photodisintegration of D by U, Th γ's dangerous for NC measurement!
- High Energy (> 4 MeV)
  - Number of γ's from rock and steel measured using events in H_2O and γ calibration sources
  - $\rightarrow$ Fiducial volume cut reduces number in signal sample.
  - $\rightarrow$ Preliminary analyses show level is $<$ few percent of signal
  - Spallation products from cosmics eliminated by time coincidence
- Instrumental (flashers, neck light, etc.)
  - Charge and average charge
  - Tube time structure
  - Event time correlations (bursts)
  - Veto tube tags

Characteristics of HE Solar ν Signal in Pure D_2O

- Radial Distribution
  - ES will be in both D_2O and H_2O
  - CC should show excess of events inside D_2O
- Angular Distribution
  - ES will show strong peak near $\cos\theta_\odot = 1$
  - CC falls $\sim (1 - \frac{1}{3}\cos\theta_\odot)$
- Energy Spectrum
  - Recoil electrons from CC reaction have narrow distribution around incident ν_e energy.



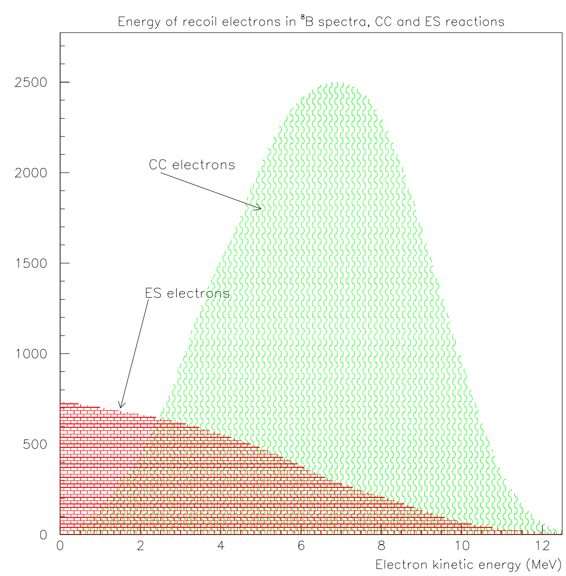


Table 1: Data reduction steps.

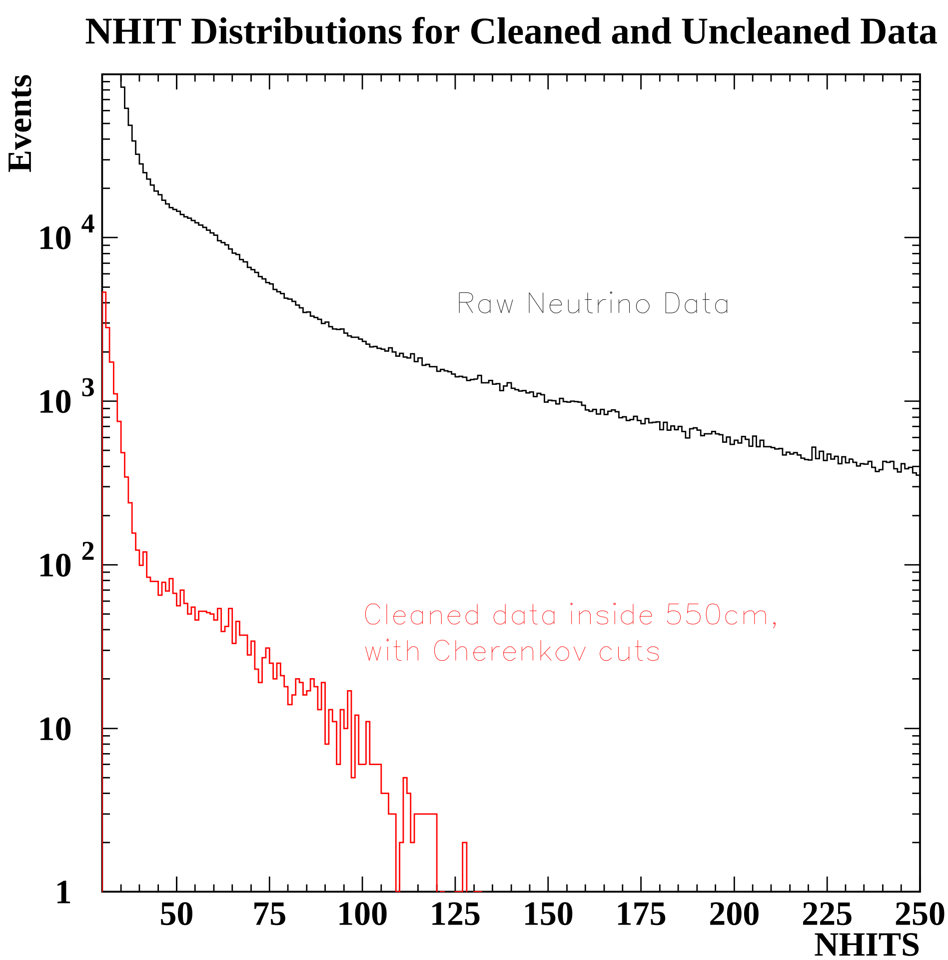
Analysis step	Number of events
Total event triggers	355 320 964
Neutrino data triggers	143 756 178
$N_{\mathrm{hit}} \geq$30	6 372 899
Instrumental background cuts	1 842 491
Muon followers	1 809 979
High level cuts[a]	923 717
Fiducial volume cut	17 884
Threshold cut	1 169
Total events	1 169

[a] Reconstruction figures of merit, prompt light, and $\langle\theta_{ij}\rangle$.

Pass 1 Data Analysis

Most event triggers are from instrumental backgrounds – pulsed sources of light from discharging insulators in the detector. The biggest sources are the PMTs.

The first pass at the data removes these events using ony the time, charge, and geometry of the event - not reconstruction or cuts derived from higher order analysis.



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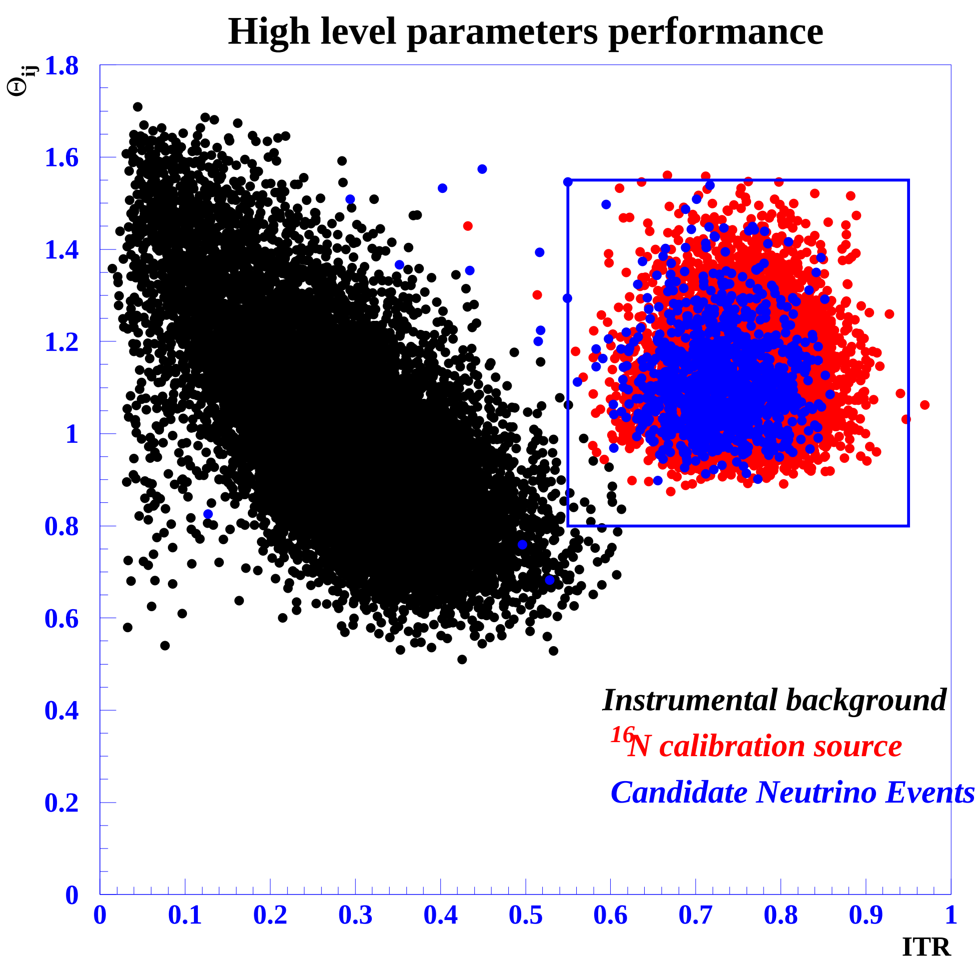
High level cuts

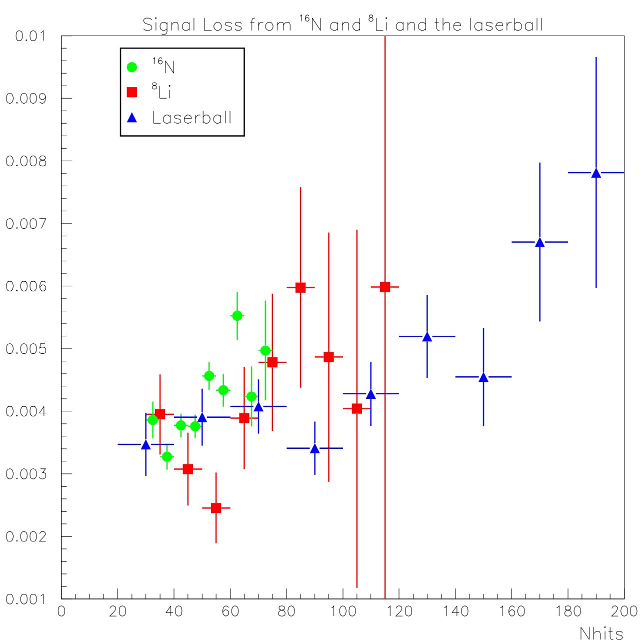
Next apply high level cuts – cuts that use information derived from the primitive information, such as reconstruction.

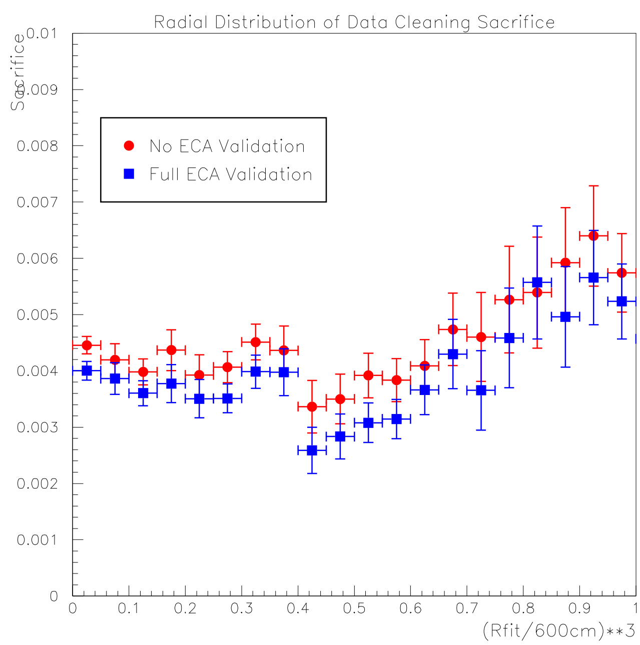


Signal loss in analysis

Use triggered β and γ sources to measure the signal loss as a function of energy ($N_{\rm hit}$), position, and angle. The signal loss in the analysis is $1.4^{+0.7}_{-0.6}\%$.

(Figures below are from first pass cuts - high level cuts increase signal loss.)





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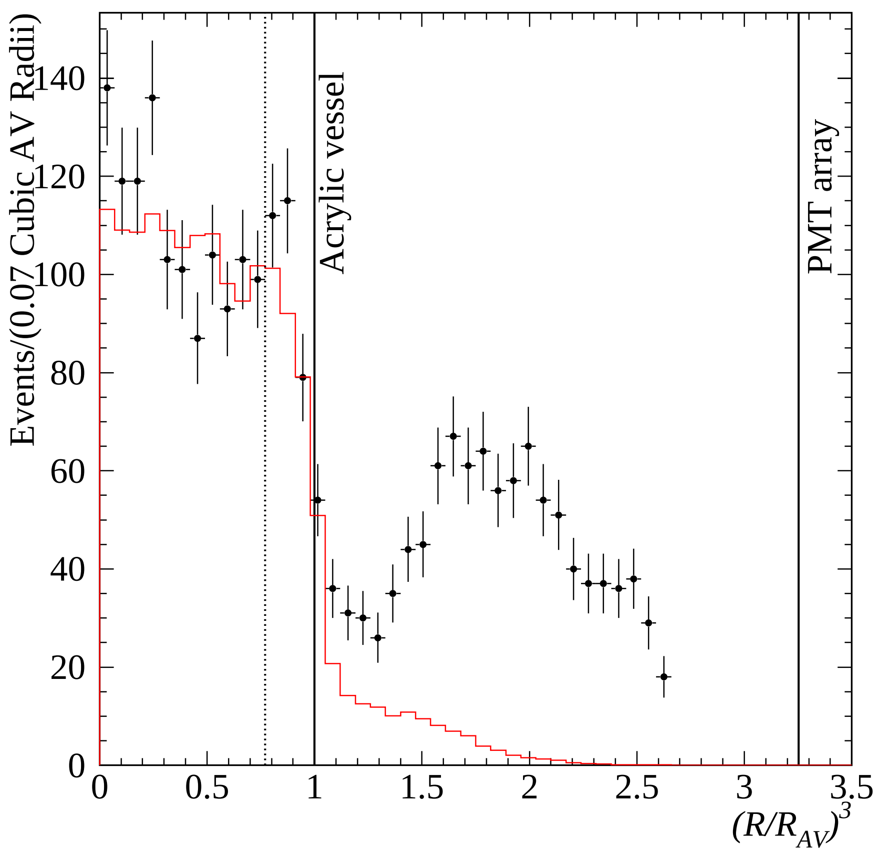
Fiducial volume cut

- Make energy threshold cut at 6.75 MeV.
- Make fiducial volume cut at R=5.50 meters.

(Reduce backgrounds from the region exterior to the acrylic vessel R_{AV}=6.00 meters, and systematics associated with optics and reconstruction near that boundary.)

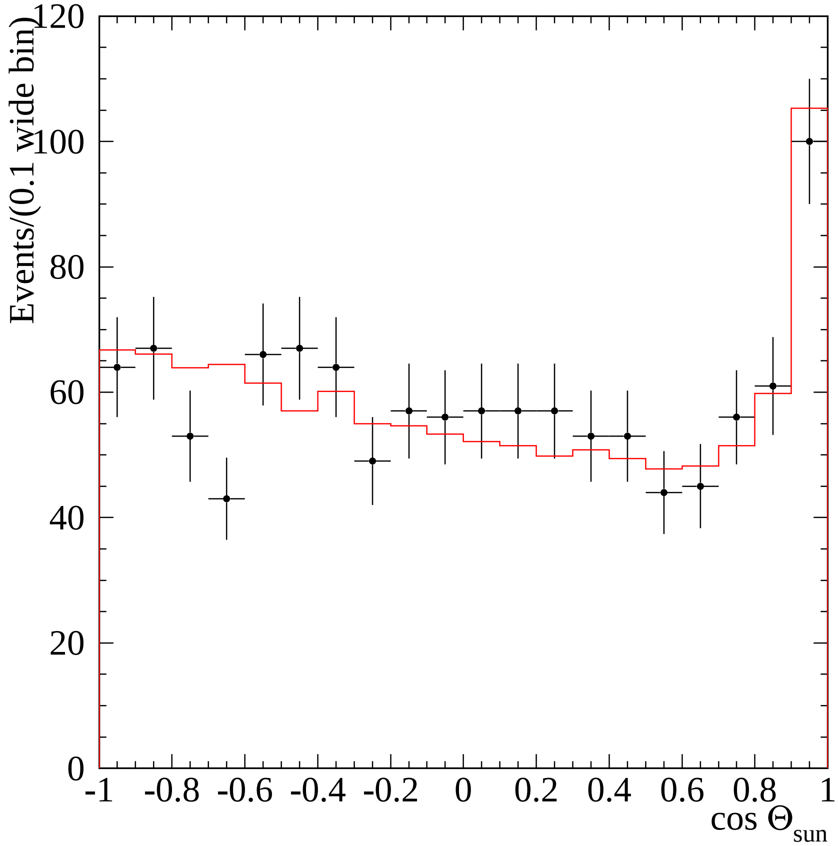


χ^2 = 15 for 11 bins inside fiducial volume.

Final data set

The final data set is 1169 events.

The angular distribution of events with respect to the direction from the Sun shows an ES peak and a continuum with the characteristic slope of the CC reaction, and a uniform background from neutrons.



χ^2 = 19.5 for 18 DOF.

Systematic errors

Energy scale and reconstruction dominate systematic errors:

Table 2: Systematic error on fluxes.

Error source	CC error (percent)	ES error (per cent)
Energy scale (± 1.4%)	-5.2, +6.1	-3.5 ,+5.4
Energy resolution	±0.5	±0.3
Energy scale non-linearity	±0.5	±0.4
Vertex accuracy	±3.1	±3.3
Vertex resolution	±0.7	±0.4
Angular resolution	±0.5	±2.2
High energy γ's	-0.8, +0.0	-1.9, +0.0
Low energy background	-0.2, +0.0	-0.2, +0.0
Instrumental background	-0.2, +0.0	-0.6, +0.0
Trigger efficiency	0.0	0.0
Live time	±0.1	±0.1
Cut acceptance	-0.6, +0.7	-0.6, +0.7
Earth orbit eccentricity	±0.1	±0.1
^{17}O, ^{18}O	0.0	0.0
Experimental uncertainty	-6.2, +7.0	-5.7, +6.8
Cross section	3.0	0.5
Solar Model	-16, +20	-16, +20

Results

Assume that the ^{8}B neutrinos emitted by the Sun are ν_e and that the spectrum is given by ^{8}B β-decay and measured by Ortiz, *et al.*.

Use maximum likelihood to extract numbers of CC, ES, and neutron events.

Then the SNO data above the threshold of 6.75 MeV determine the integrated flux:

$$\phi_{\rm SNO}^{\rm CC} = 1.75 \pm 0.07\,({\rm stat.})^{+0.12}_{-0.11}\,({\rm sys.}) \pm 0.05\,({\rm theor.}) \times 10^6\,{\rm cm}^{-2}{\rm s}^{-1}$$

$$\phi_{\rm SNO}^{\rm ES} = 2.39 \pm 0.34 ({\rm stat.})^{+0.16}_{-0.14}\,({\rm sys.}) \times 10^6\,{\rm cm}^{-2}{\rm s}^{-1}$$

The difference between these results is:

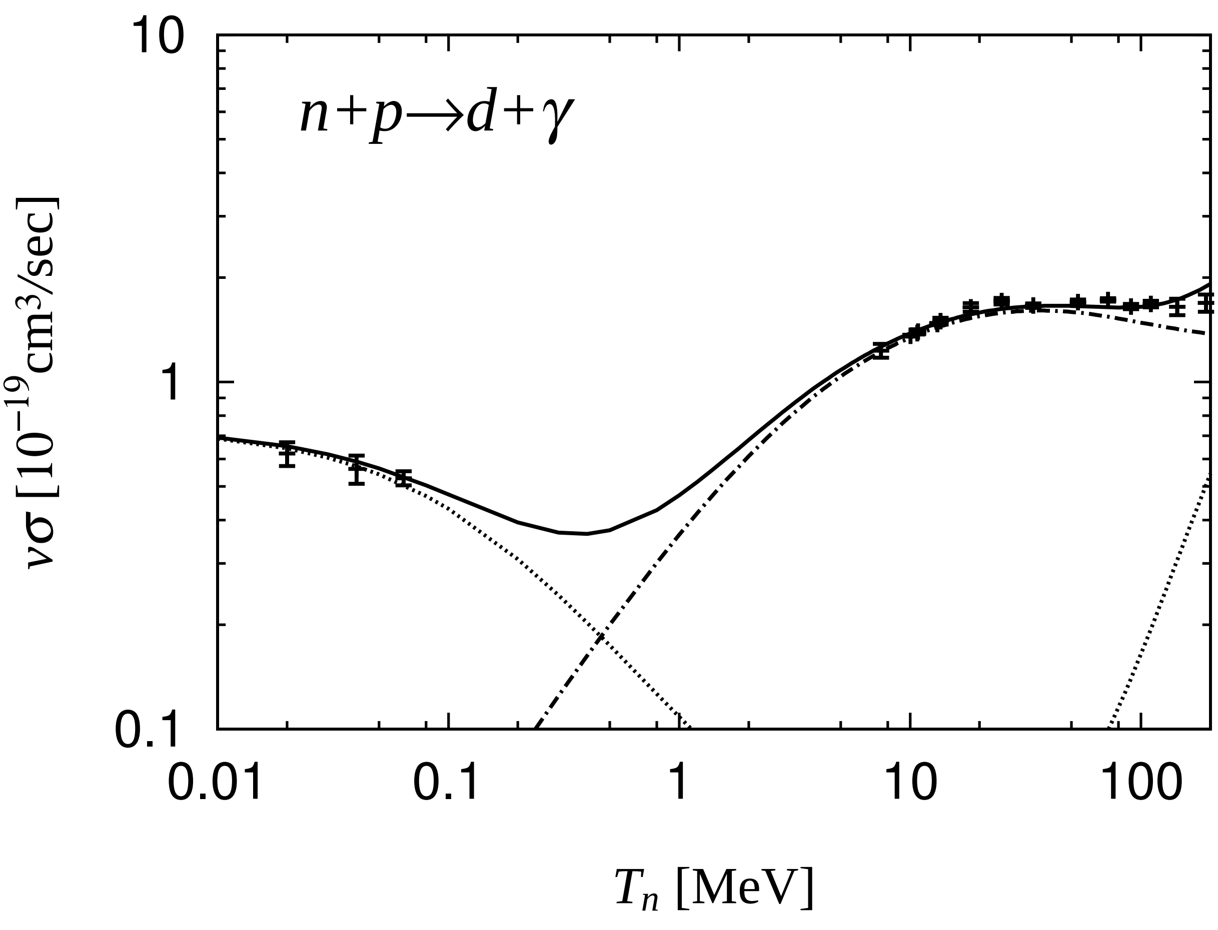
$$\phi_{\rm SNO}^{\rm ES} - \phi_{\rm SNO}^{\rm CC} = 0.64 \pm 0.40 \times 10^6\,{\rm cm}^{-2}{\rm s}^{-1}$$

which is 1.6 σ.

Results

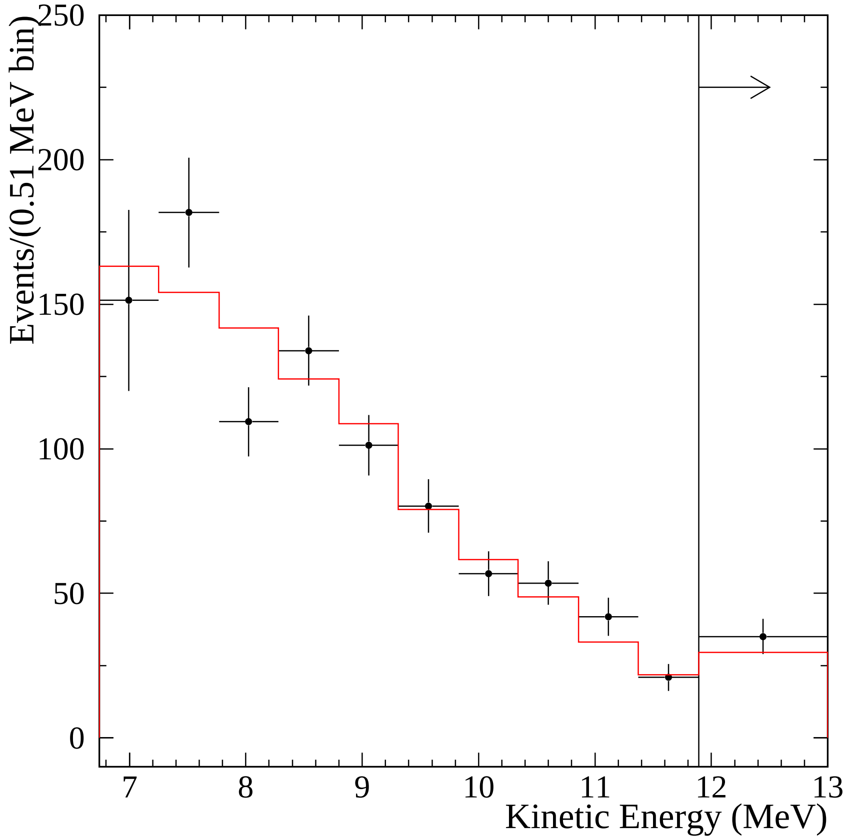
Theoretical CC cross section is calculated by Kubodera, et al. using a potential model, and Butler *et al.,* using an effective field theory model. Uncertainty is quoted as $\pm$3% by Butler, *et al.*.

- $\overline{\nu}_e + d \rightarrow e^+ + n + n$ is measured to 13% at Bugey.
- Here is some $n + p \rightarrow d + \gamma$ data and calculated cross sections that show the basic deuteron physics is understood:



Results

Repeat maximum likelihood analysis for signal extraction using 11 energy bins and no spectral constraint on the signal. The resulting CC spectrum is:



The histogram is the Monte Carlo prediction including the Ortiz, *et al.*, spectrum.

Is this correct?

Signal loss in analysis would underestimate the CC flux.

- Signal loss and bias in signal loss have been measured using β and γ Čerenkov sources. The volume weighted signal loss is $1.4^{+0.7}_{-0.6}\%$.

Other analysis issues would overestimate the CC flux.

- Including omitted processes (radiative corrections and hep neutrinos) reduces the CC flux. Radiative corrections are $< 4\%$, probably $\sim 1\%$, hep most likely $< 1\%$.

- Contamination from instrumental backgrounds (measured to be $< 0.2\%$) would reduce CC flux.

Interpretation

Comparison to Super-Kamiokande:

SNO CC (pure ν_e):

$$\phi_{\mathrm{SNO}}^{\mathrm{CC}} = 1.75 \pm 0.07\,(\mathrm{stat.})^{+0.12}_{-0.11}\,(\mathrm{sys.}) \pm 0.05\,(\mathrm{theor.}) \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Super-Kamiokande ES, assuming all events are ν_e:

$$\phi_{\mathrm{SK}}^{\mathrm{ES}} = 2.32 \pm 0.03\,(\mathrm{stat.})^{+0.08}_{-0.07}\,(\mathrm{sys.}) \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}.$$

Difference:

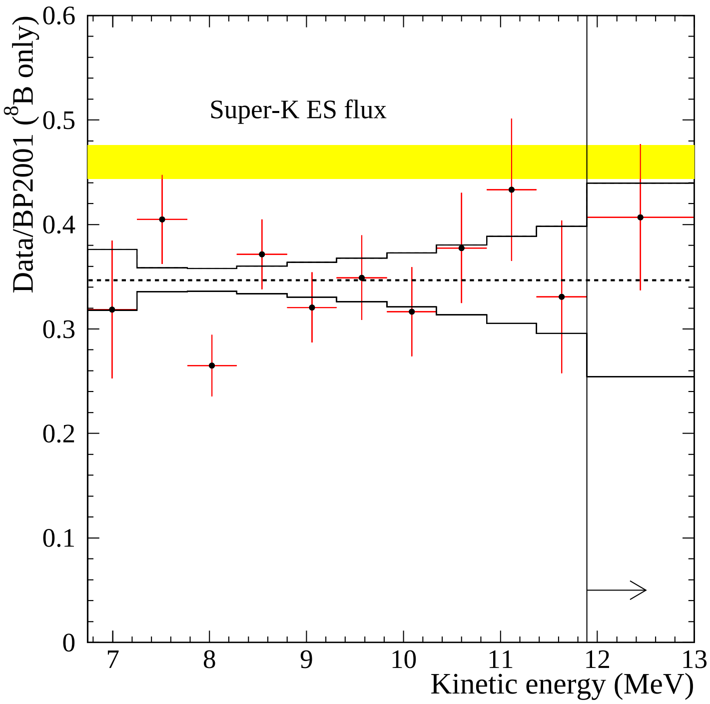
$$\phi_{\mathrm{SK}}^{\mathrm{ES}} - \phi_{\mathrm{SNO}}^{\mathrm{CC}} = 0.57 \pm 0.17 \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

where the errors are added in quadrature.

The probability that the SNO result is a downward fluctuation of the SK result is 0.04%, or 3.3σ.

Spectrum vs. SuperK spectrum

The spectrum is everywhere lower than the SuperK spectrum. The band shows the SNO correlated and uncorrelated systematic errors.



χ^2 = 11.7 for 10 DOF.

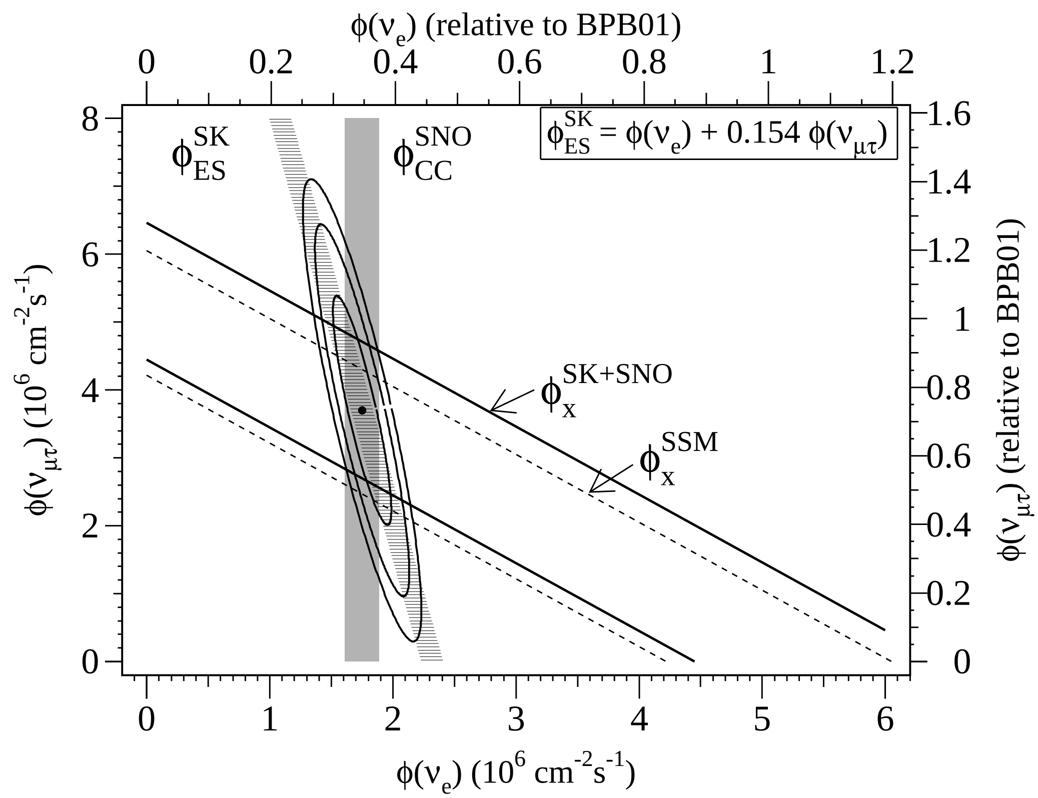
Interpretation

Assume neutrino oscillation to an active flavor accounts for the SK-SNO difference in fluxes.

$$\phi_{ES}^{SK} = \phi(\nu_e) + 0.154\phi(\nu_{\mu\tau})$$

$$\phi_{CC}^{SNO} = \phi(\nu_e).$$

Extract $\phi(\nu_{\mu\tau})$.



Ellipses are 68%, 95%, and 99% joint probability contours.

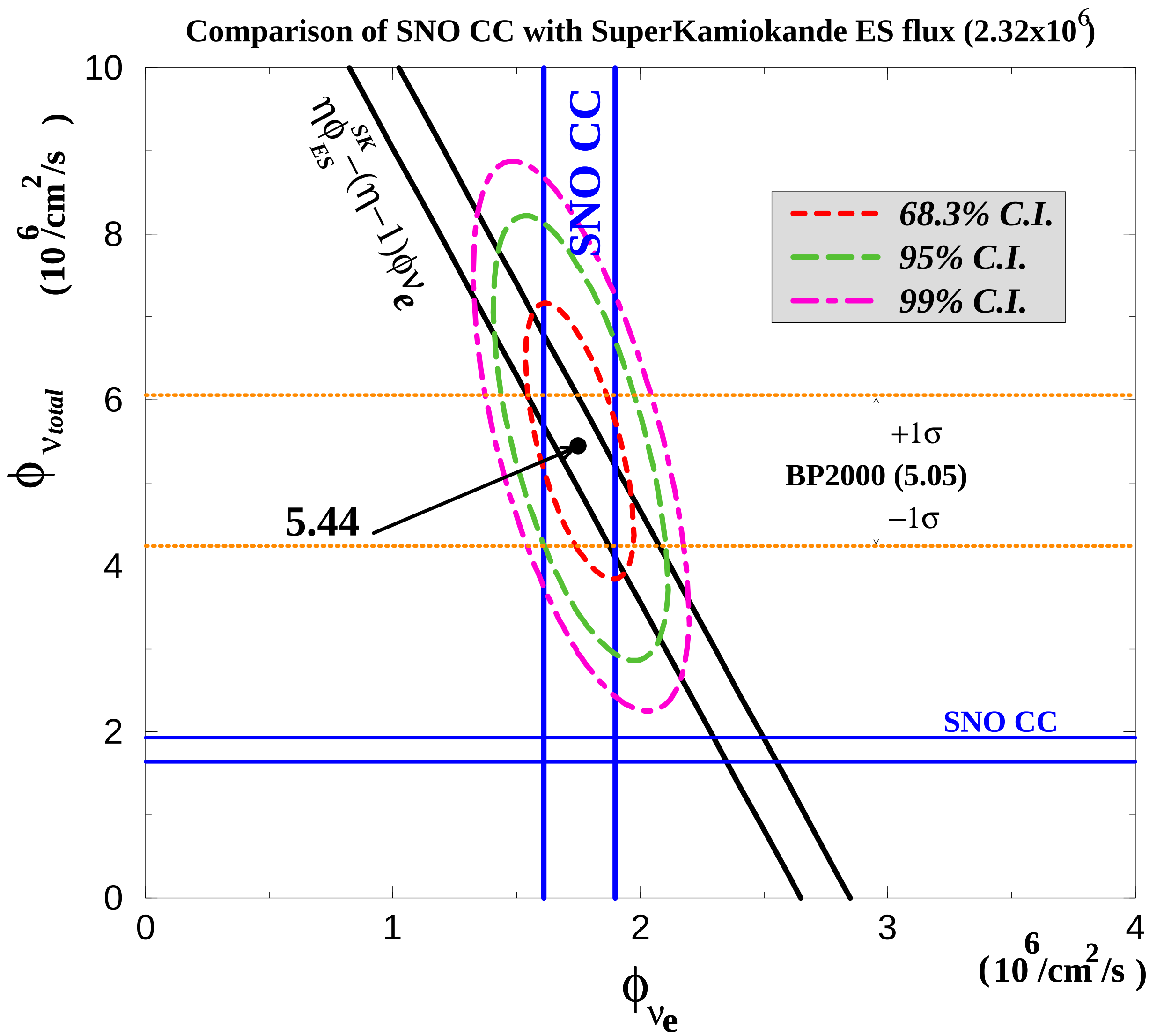
Interpretation

The non-electron neutrino flavor content deduced is:

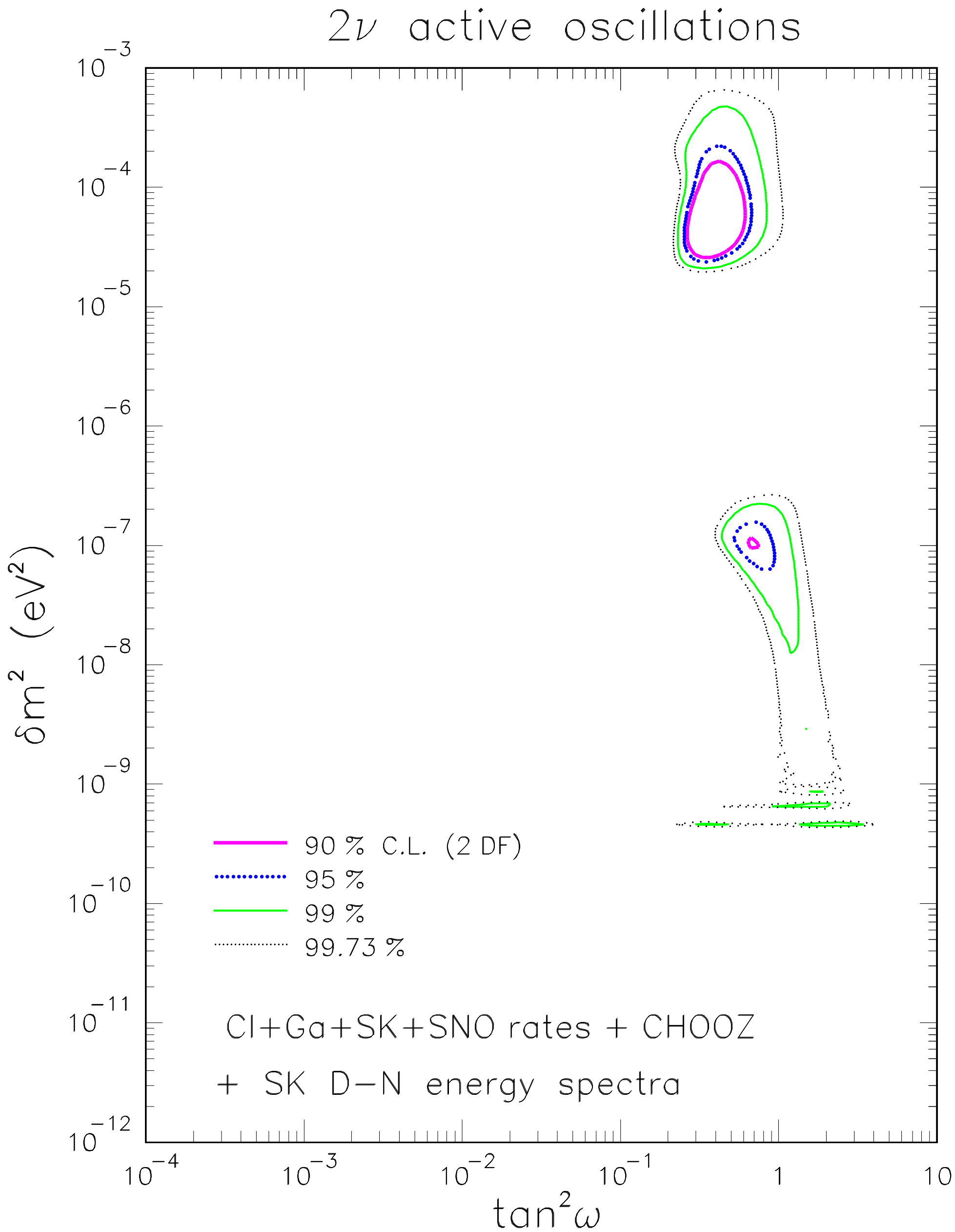
$$\phi(\nu_{\mu\tau}) = 3.69 \pm 1.13 \times 10^6 \text{ cm}^{-2}$$

The total active ^{8}B neutrino flux is $\phi(\nu_x) = \phi(\nu_e) + \phi(\nu_{\mu\tau})$:

$$\phi(\nu_x) = 5.44 \pm 0.99 \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$



Post-SNO: $\Delta m^2_{12}, \sin^2 2\theta_{12}$



(*Fogli, Lisi, Montanino, and Palazzo*)

But a more general analysis leaves room for the SMA solution.

Conclusions and Future Work

Conclusions

- SNO and SuperK results show that solar neutrinos undergo flavor transformation.
- Total deduced flux agrees well with Standard Solar Model predictions.

Future work

- Make precise CC/NC measurement to increase significance of present result.
- Use spectral and temporal CC data to limit paramter space for oscillations.
- Can the presence of sterile neutrinos in the solar sector be established or refuted?