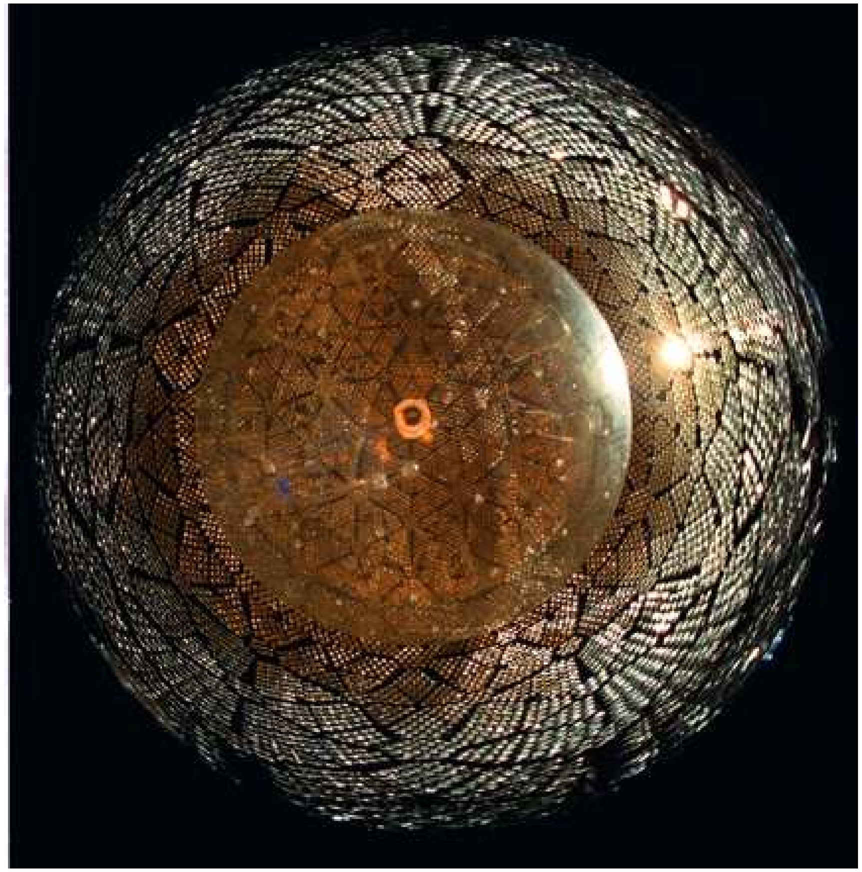
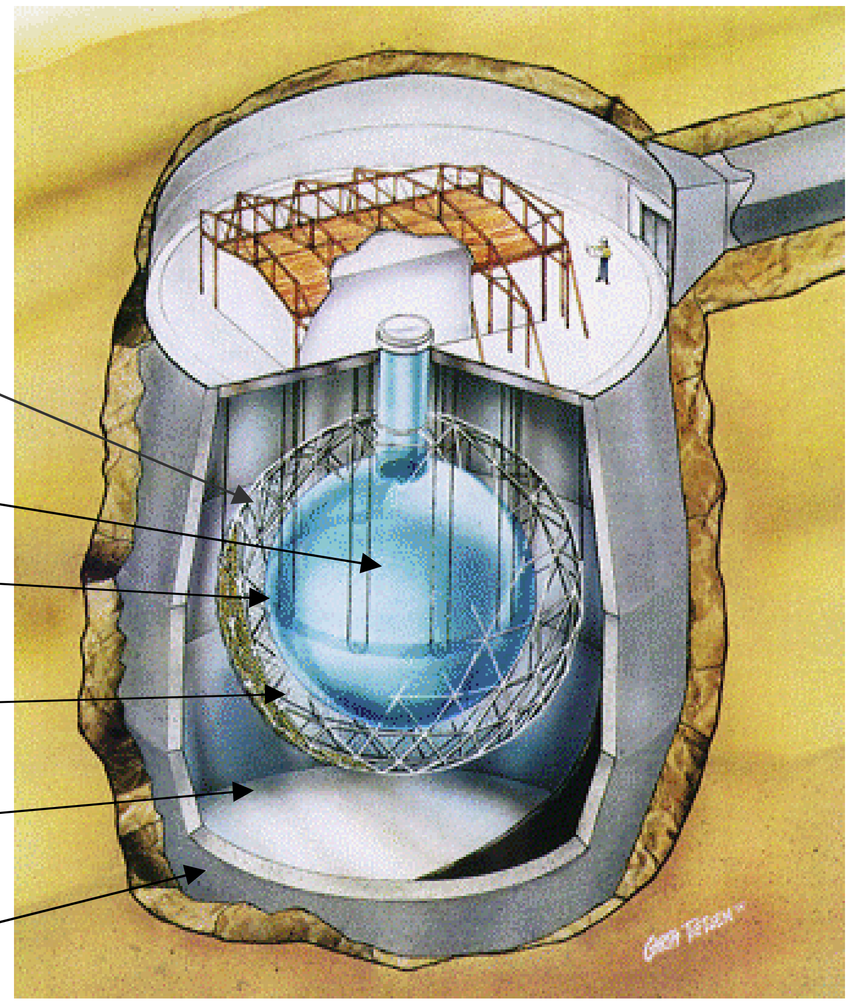
Solar Neutrino Measurements from the Sudbury Neutrino Observatory



Scott Oser
U. of British Columbia

HEP2005 Europhysics
Lisboa, Portugal
July 22, 2005

Sudbury Neutrino Observatory



Solar ν Interactions in SNO

SNO measures primarily ^{8}B neutrinos by three interactions:

Charged Current:

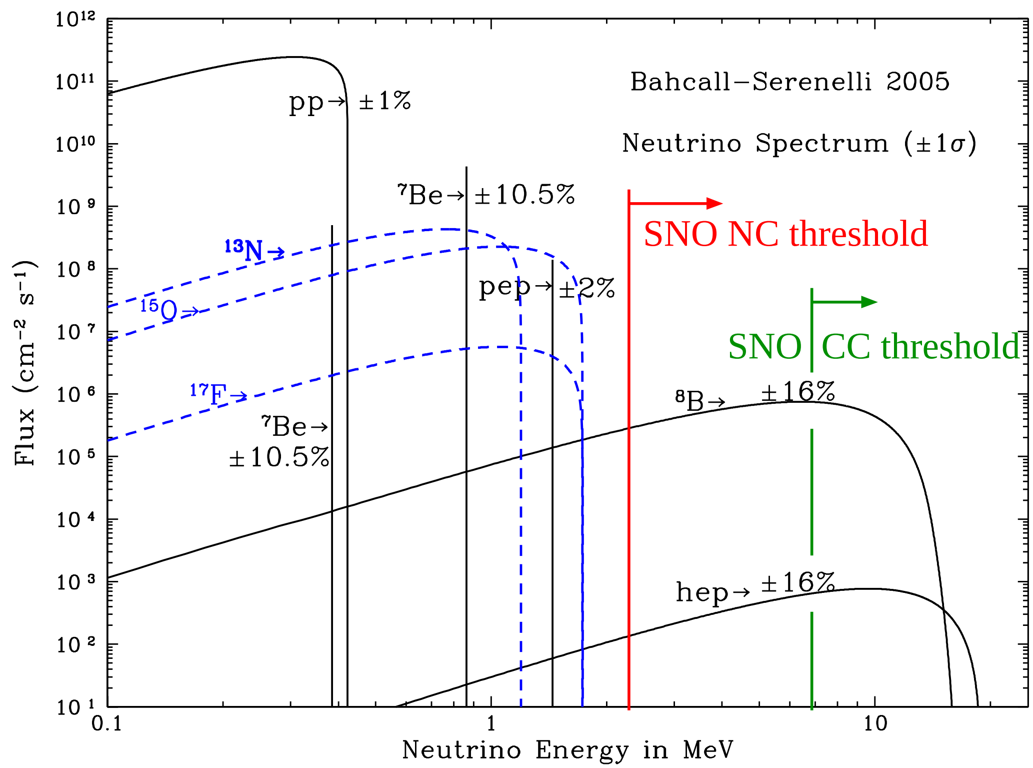
$$\nu_e + d \rightarrow p + p + e^-$$

Neutral Current:

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

Elastic Scattering:

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



For the Large Mixing Angle (LMA) solution to solar neutrino problem:

$$|U_{e2}|^2 \approx \sin^2\theta_{12} \approx \frac{\phi_{CC}}{\phi_{NC}}$$

Three Phases of the SNO Experiment

D_2O Phase

(pure D_20)

Nov 1999 - May 2001

$n + d \longrightarrow t + \gamma$

$(\sigma = 0.0005\, b)$

Detect a Compton-scattered electron from a 6.25 MeV γ

PRL 87, 071301 (2001)

PRL 89, 011301 (2002)

PRL 89, 011302 (2002)

PRD 70, 093014 (2004)

Salt Phase

(D_2O + 0.2% NaCl)

July 2001 - Sept 2003

$n + {}^{35}\text{Cl} \longrightarrow {}^{36}\text{Cl} + \gamma$'s

$(\sigma = 44\, b)$

Detect Compton-scattered electrons from multiple γ's totalling 8.6 MeV

PRL 92, 181301 (2004)

PRL 92, 102004 (2004)

nucl-ex/0502021 $\longrightarrow$ PRC

hep-ex/0507079 $\longrightarrow$ PRD

NCD Phase

(^{3}He counters)

Dec 2004 - Dec 2006

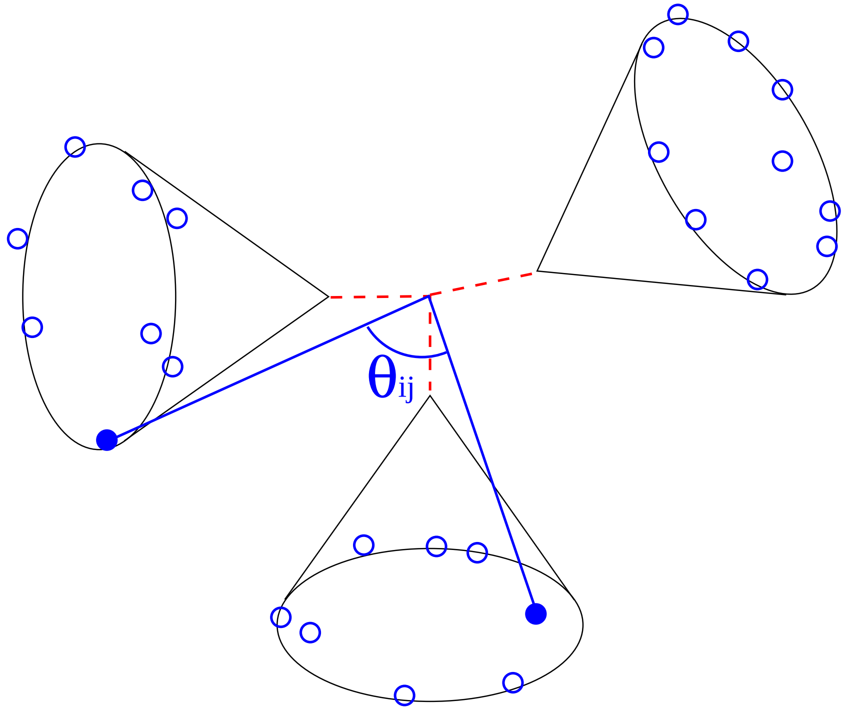
$n + {}^3\text{He} \longrightarrow p + t$

$(\sigma = 5330\, b)$

Detect 764 keV of ionization from the charged particles in ^{3}He proportional counters

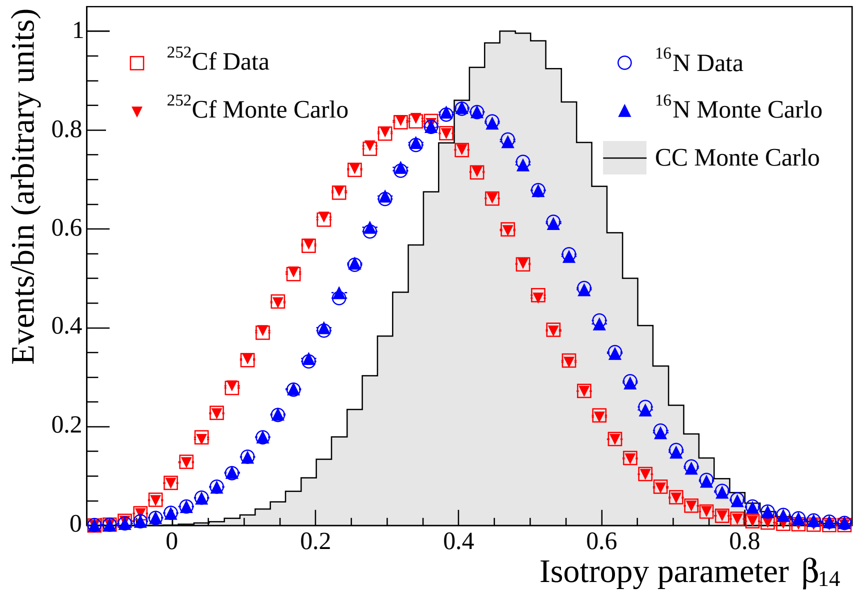
TODAY: fluxes, spectra, and day-night results for the full salt data set, and a periodicity analysis

Separating NC from CC/ES Events With Isotropy



Best CC/NC separation from

$$\beta_{14} \equiv \beta_1 + 4\beta_4$$

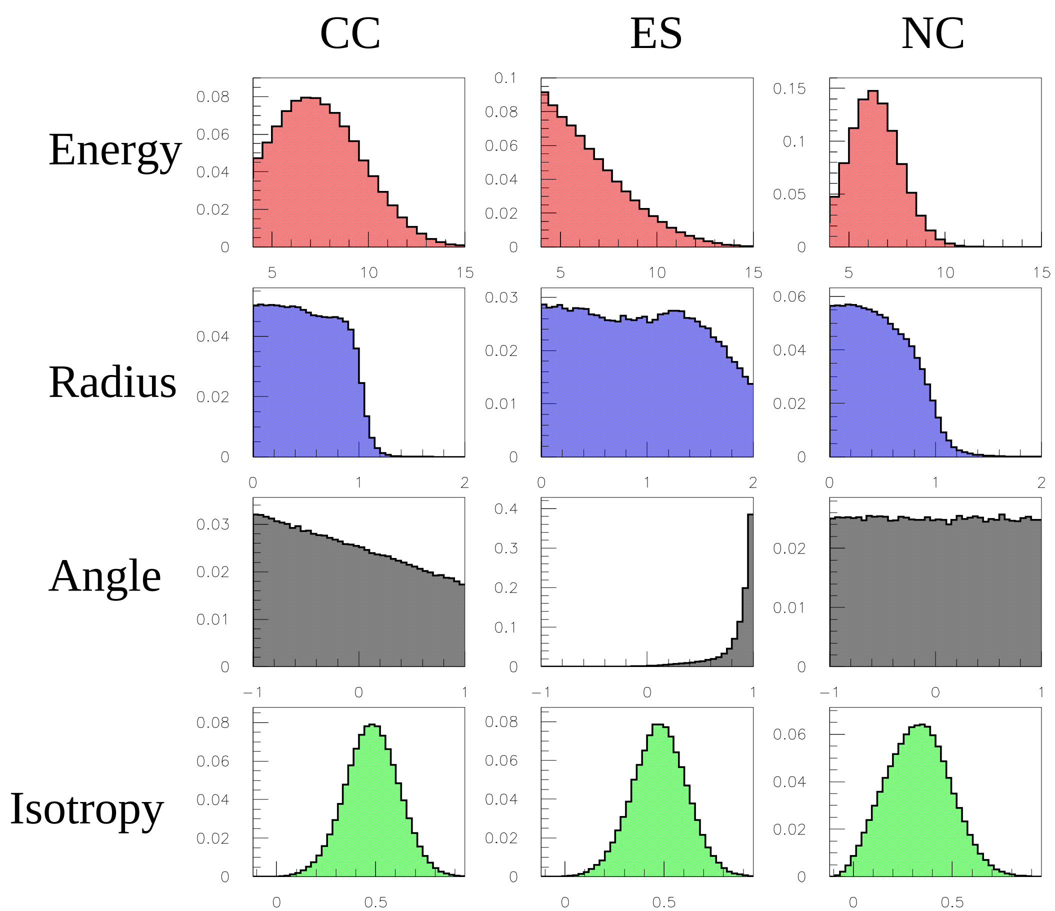


Expand hit pattern in Legendre polynominals using angle θ_{ij} between hit PMTs i and j relative to event vertex:

$$\beta_l = \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} P_l(\cos\theta_{ij})$$

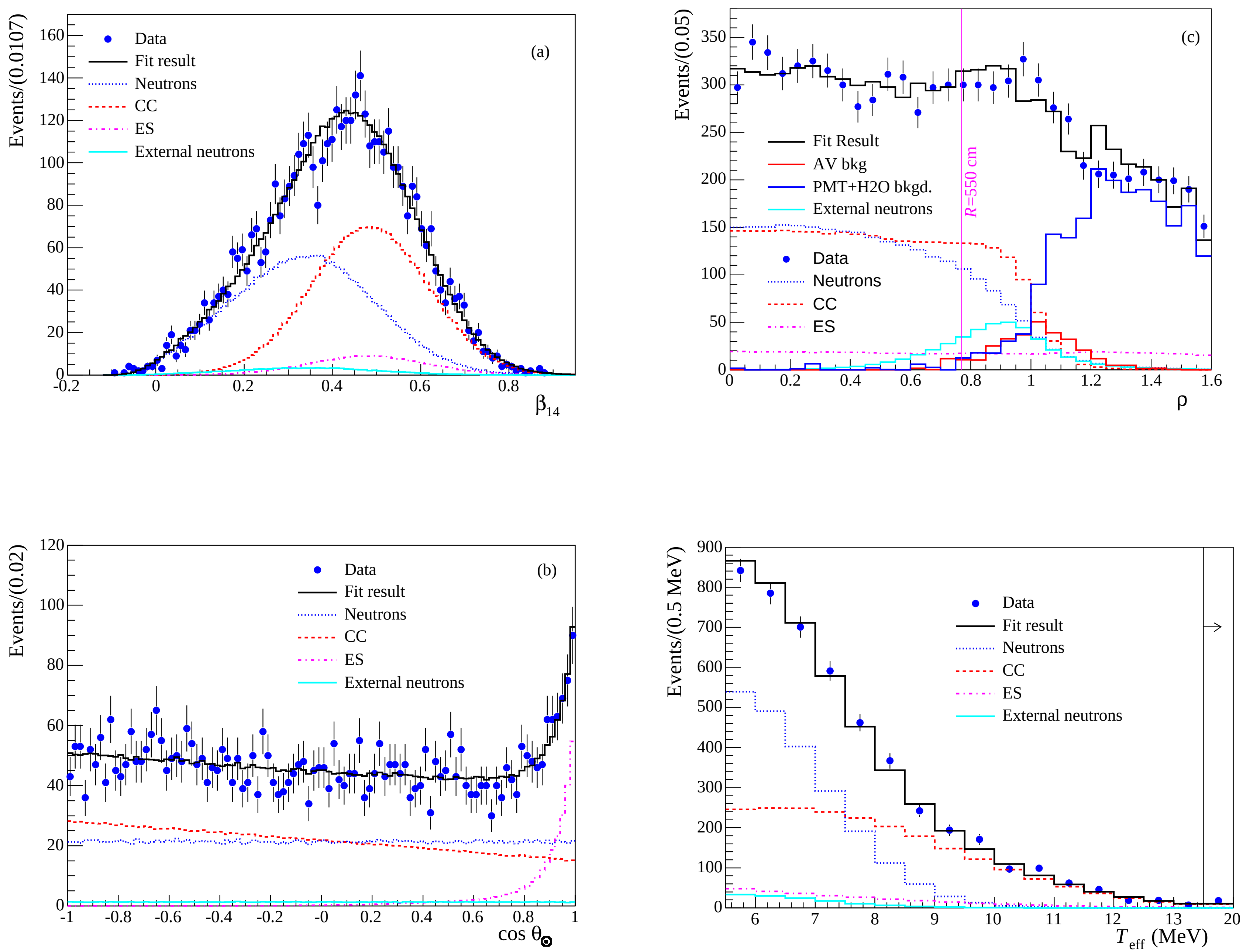
Because neutron captures on ^{35}Cl produce multiple γ's, CC events have very different isotropies from NC events.

Signal Probability Distributions

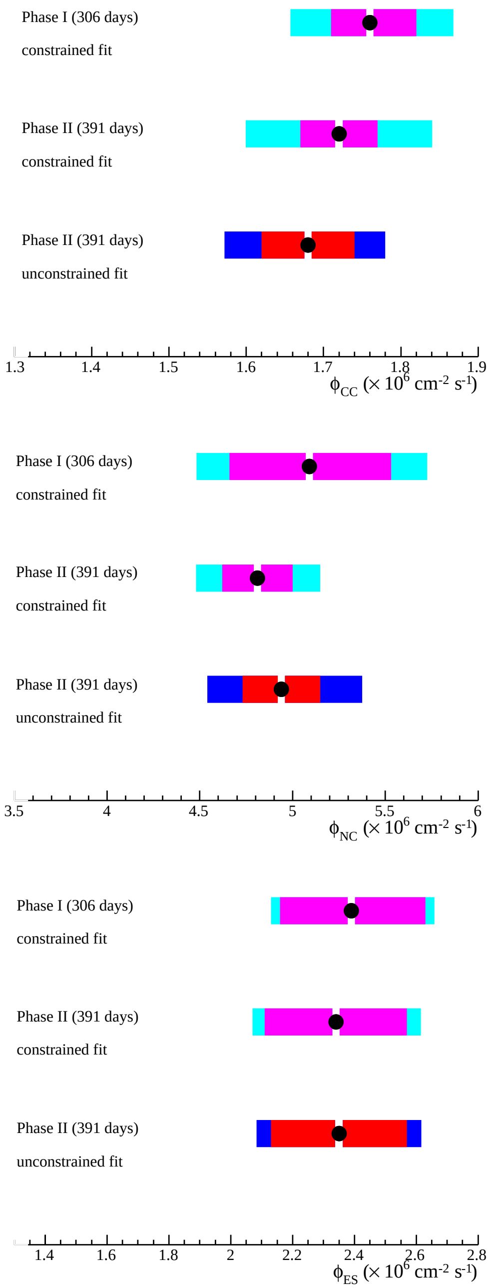


Fit the PDFs to the data to determine fluxes. Leave out the energy PDFs to fit for the spectral shapes.

Results for the full 391-day Salt Phase



Full Salt Phase Data Set: Measured SNO Fluxes



Shape-Unconstrained Fluxes ($\times 10^6$ cm^{-2} sec^{-1})

$$\phi_{CC} = 1.68 \pm 0.06\,(\text{stat.})^{+0.08}_{-0.09}\,(\text{sys.})$$

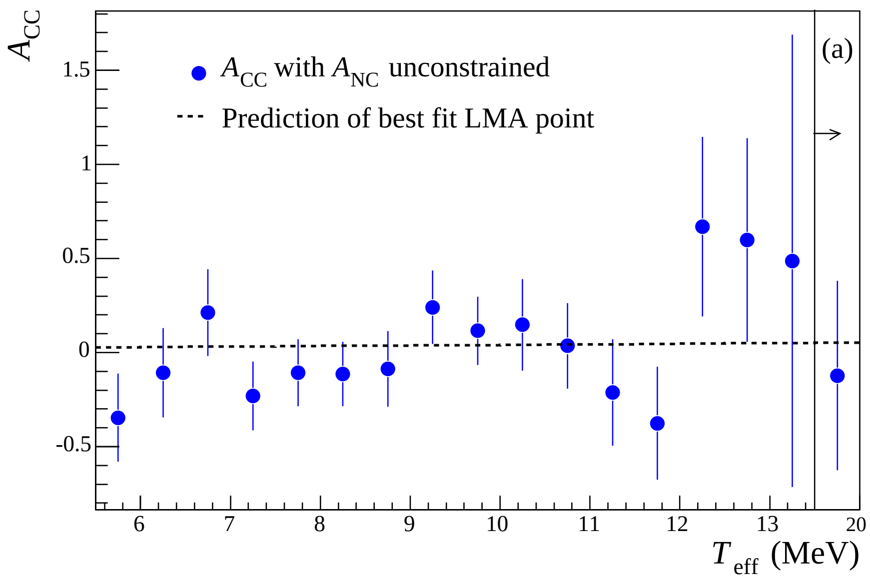
$$\phi_{NC} = 4.94 \pm 0.21\,(\text{stat.})^{+0.38}_{-0.34}\,(\text{sys.})$$

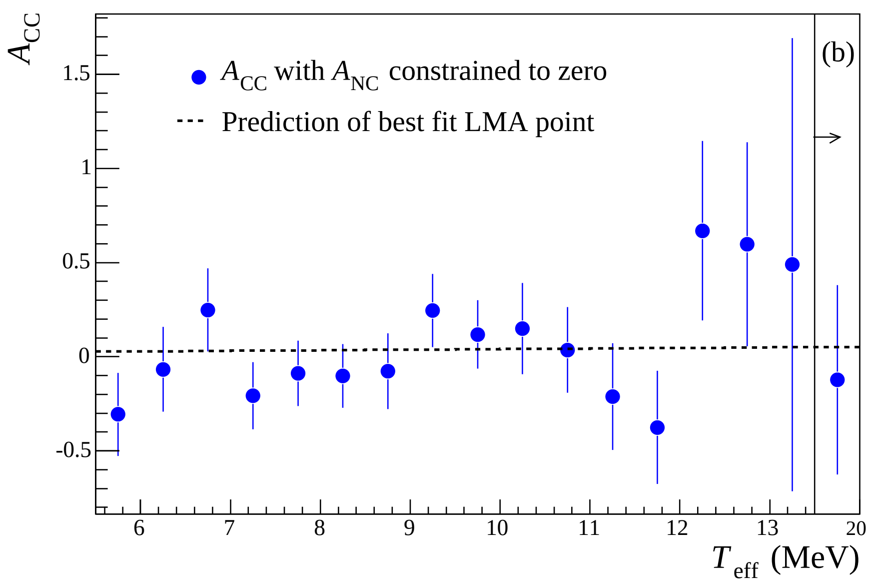
$$\phi_{ES} = 2.34 \pm 0.22\,(\text{stat.})^{+0.15}_{-0.15}\,(\text{sys.})$$

Excellent agreement between:

- shape-constrained and shape-unconstrained results
- D_2O phase and salt phase fluxes

Full Salt Phase Data Set: Day-Night Asymmetries





A non-zero day-night asymmetry would be direct evidence for matter effects:

$$A = \frac{2(N-D)}{N+D}$$

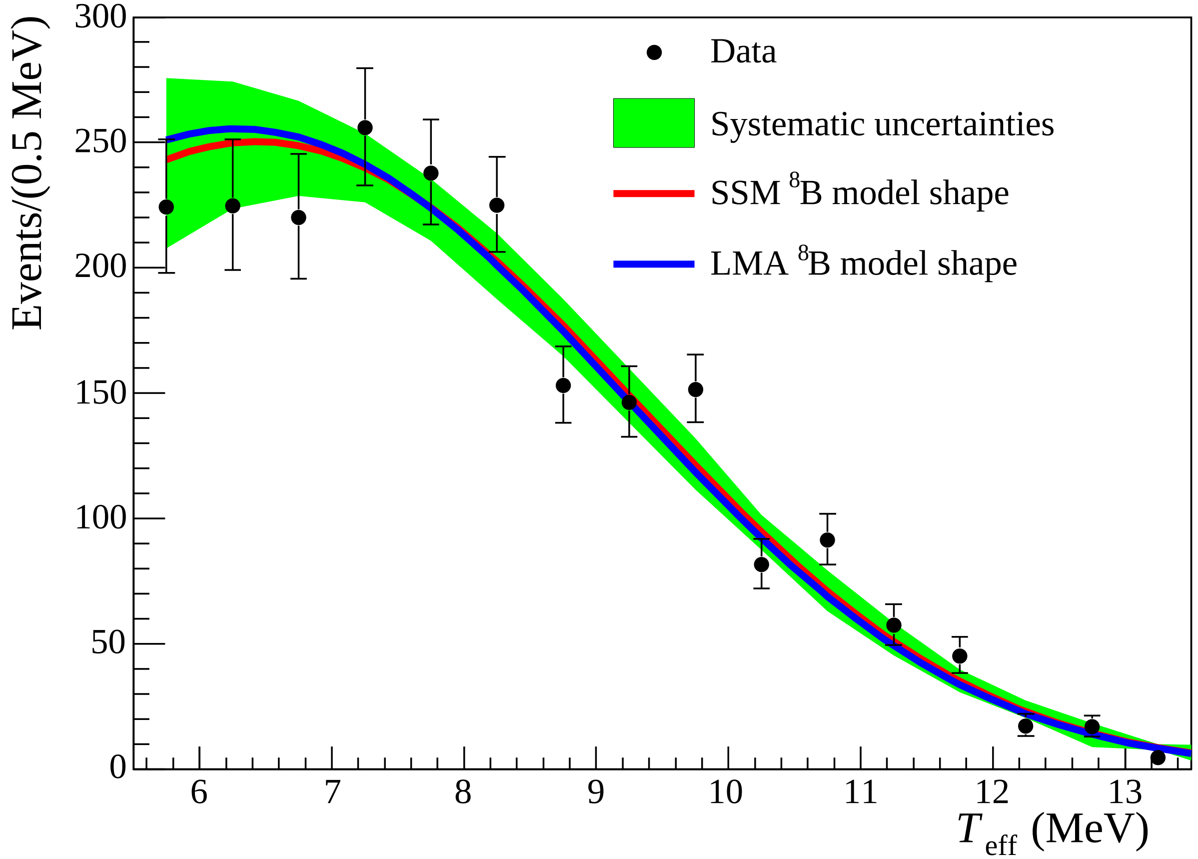
A_{CC}	$-0.056 \pm 0.074 \pm 0.053$
A_{NC}	$+0.042 \pm 0.086 \pm 0.072$
A_{ES}	$+0.146 \pm 0.198 \pm 0.033$

Combined day-night asymmetry from D_2O + salt phase data:

$$A_e = 0.037 \pm 0.040$$

All results consistent with no day-night asymmetries, but also consistent with predictions for best-fit LMA parameters.

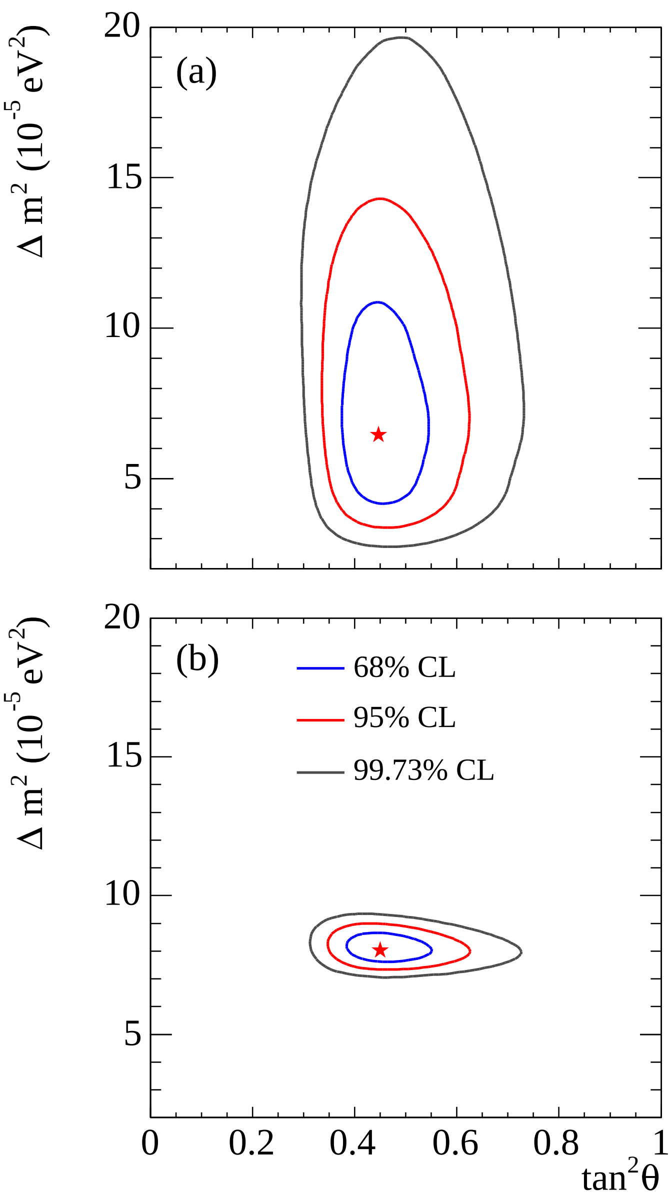
Full Salt Phase Data Set: CC Energy Spectrum



χ^2 for best-fit LMA: 27.2 / 16 d.o.f. (P=0.039)

Generally consistent with LMA expectation

Full Salt Phase Data Set: Mixing Parameters



Best-fit-oscillation parameters (global solar + 766 ton-year KamLAND data): ($\pm 1\sigma$ limits of 2-D parameter region)

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

$$\tan^2\theta = \quad 0.45^{+0.09}_{-0.07}$$

$$\phi(^8\mathrm{B}) = \quad 4.93 \times 10^6\ \mathrm{neutrinos/cm^2/s}$$

Searching for Periodicities in SNO's Data

There are controversial claims that solar neutrino fluxes exhibit periodic variations at solar rotation or r-mode frequencies (eg. Sturrock et al. hep-ph/0409064, hep-ph/0501205).

Such periodicities could be caused by coupling of a neutrino magnetic moment to rotating solar magnetic field structures—resonant spin flavor precession mechanism. Any true variation is evidence for new physics!

SNO has searched for sinusoidal variations at periods between 10 years and 1 day by two methods (hep-ex/0507079):

- Unbinned maximum likelihood search: fit the data to

$$\phi(t) = N\left[1 + A\cos(2\pi f t + \delta)\right]$$

- Lomb-Scargle periodogram

General Periodicity Search

Do a maximum likelihood fit of the event arrival times to:

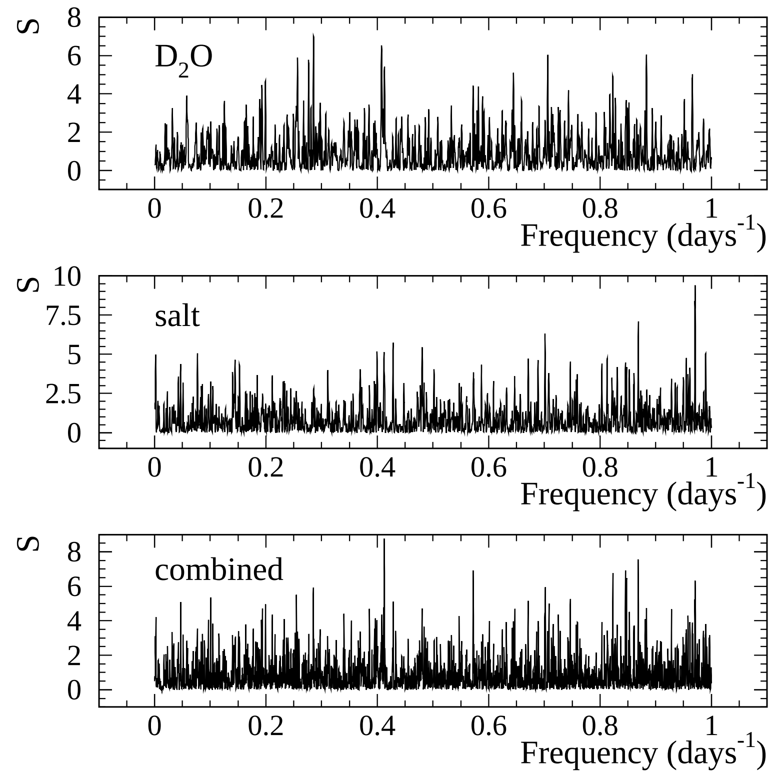
$$\phi(t) = N\left[1 + A\cos(2\pi f t + \delta)\right]$$

At each frequency calculate

$S \equiv \log L_{max} - \log L_{max}(A = 0)$.

For the combined data sets, the biggest value of S occurs at $1/f = 2.4$ days, with $S = 8.8$.

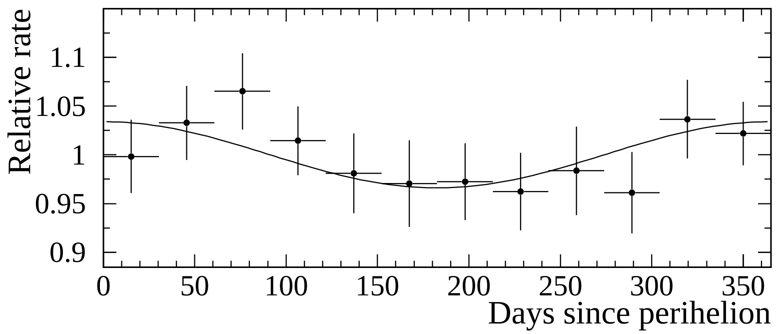
Monte Carlo shows that 35% of simulated data sets give a peak at least as large as this.



No evidence for sinusoidal variations between 10 years and 1 day in the D_2O, salt, or combined data sets.

Periodicities at Frequencies of Interest

Can SNO see the annual flux modulation from the Earth's orbital eccentricity?



Best-fit eccentricity:

$$\epsilon = 0.0143 \pm 0.0086$$

Actual orbital eccentricity:

$$\epsilon = 0.0167$$

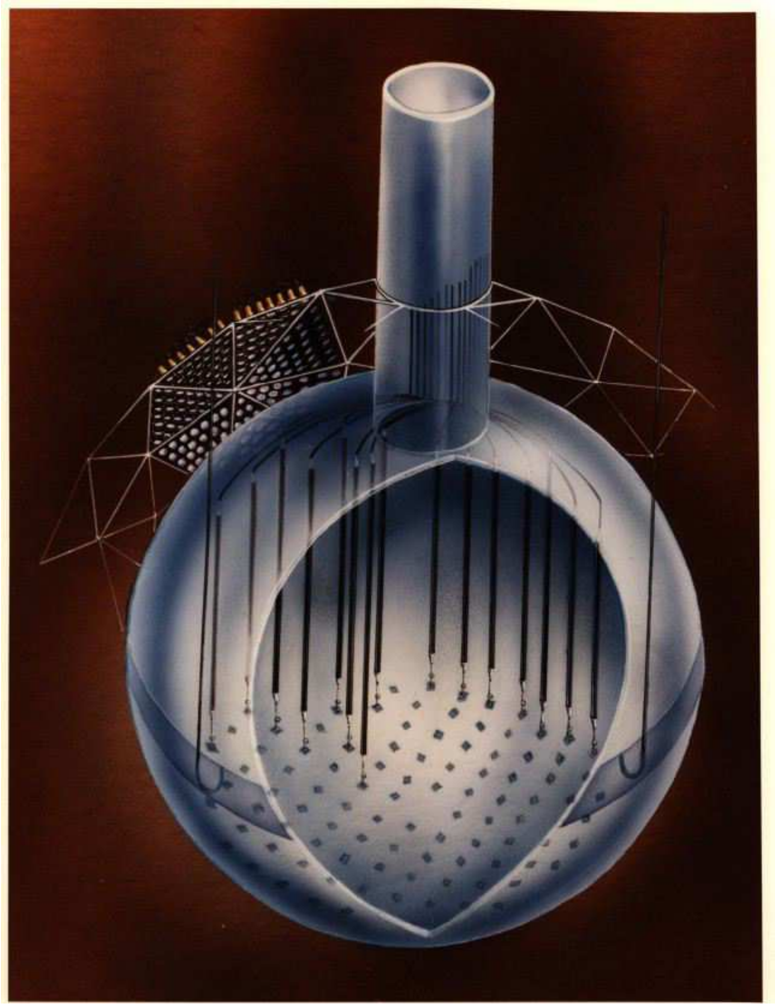
Modulation of Super-K's ES flux

Sturrock *et al.* claim to find evidence for a 7% modulation of the ES flux in Super-Kamiokande's published data at the 99%+ C.L., at a frequency of $f = 9.43 \pm 0.05\ \mathrm{y}^{-1}$ (hep-ph/0501205).

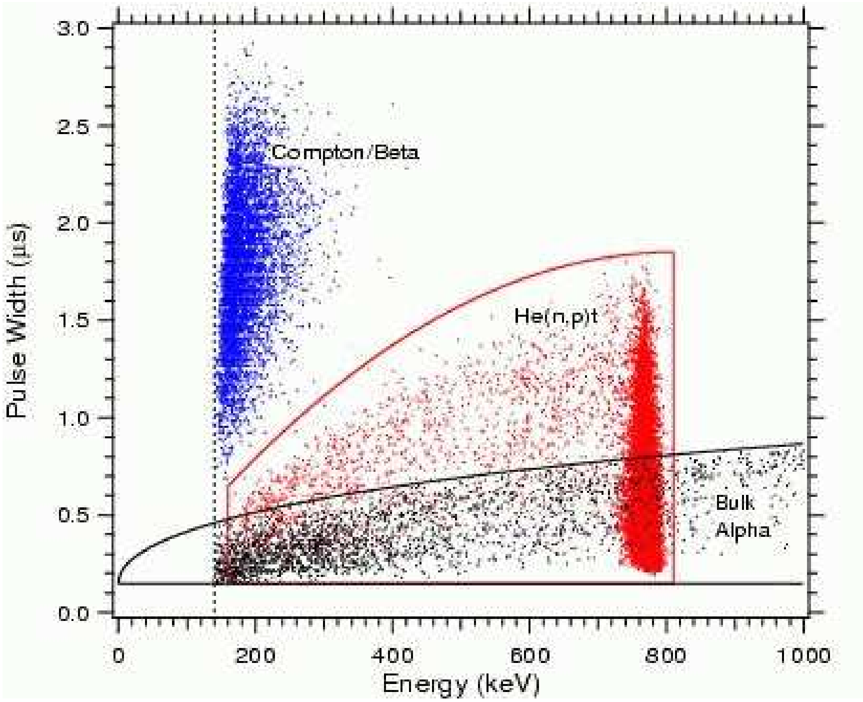
Super-Kamiokande's own analysis claims no evidence for such variation (PRD 68, 092002, 2003).

At this frequency SNO's best-fit amplitude is $(1.3 \pm 1.6)\%$—inconsistent with the hypothesis that there is a 7% modulation of the ^{8}B flux itself.

Neutron Capture Detectors (NCDs)



Main background is from α's in the counters—reject with pulse shape discrimination.



In 2004 SNO installed an array of ^{3}He proportional counters to provide an independent means of measuring neutrons—breaks CC/NC covariance.

Production data-taking began in January 2005—first results next summer.

The Future of SNO

The SNO experiment will end on December 31, 2006. D_2O will be returned to AECL.

Three options for the SNO cavity itself:

1. Sandfill — not favored!

2. SNO+: fill the acrylic vessel with liquid scintillator

   - Primary scientific objective: pep neutrinos
   - Also: geo-neutrinos, supernova, 240 km baseline for reactor neutrinos
   - More information:

     http://www.int.washington.edu/talks/WorkShops/dusel_wkshp/People/Chen_M/Chen_DUL.pdf

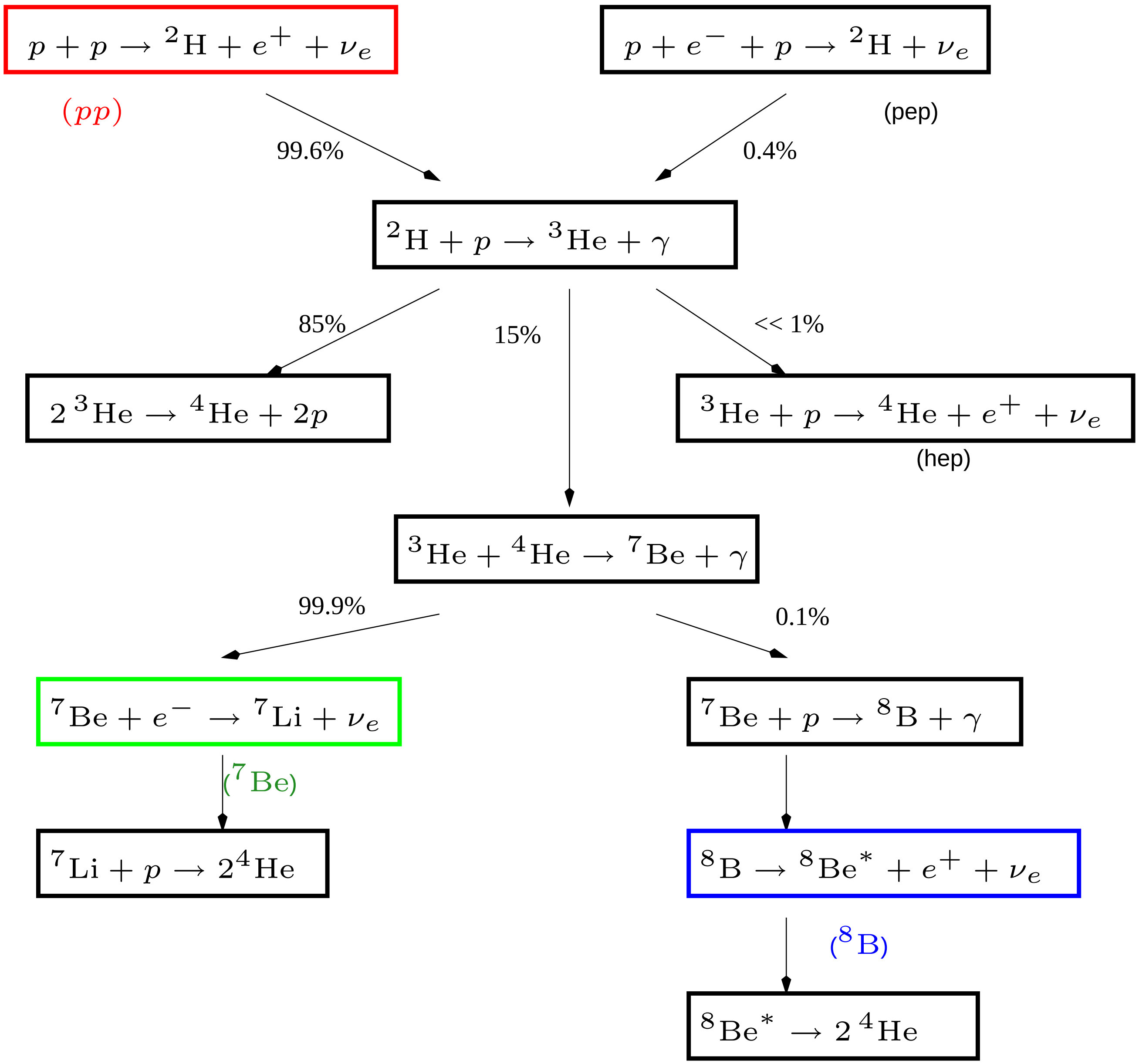
3. Empty the cavity and convert it to lab space for SNOLAB.

Conclusions

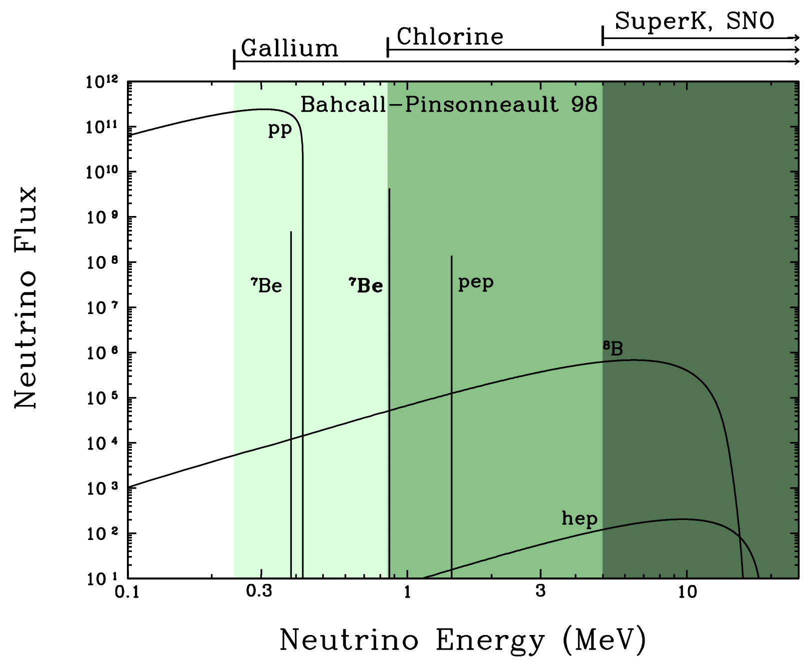
- SNO salt data confirms solar neutrinos change flavour, measures fluxes with no assumptions about oscillation mechanism
- Results in agreement with solar model and MSW mechanism
- Maximal mixing in solar sector ruled out.
- No positive evidence for day-night effects or spectral distortions
- Search for periodic variations in ^{8}B flux shows no effect
- Lots more to come ... NCD results in 2006

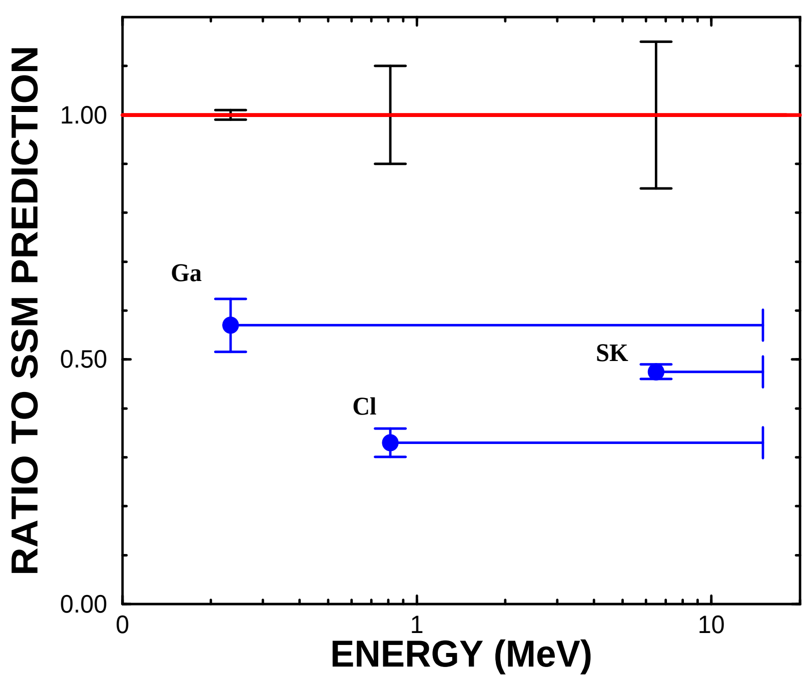
Backup slides follow

The *pp* Chain


$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$
(pp)
99.6%
$p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_e$
(pep)
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%
${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$
$({}^7\mathrm{Be})$
${}^7\mathrm{Li} + p \rightarrow 2\,{}^4\mathrm{He}$
${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$
${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e$
$({}^8\mathrm{B})$
${}^8\mathrm{Be}^* \rightarrow 2\,{}^4\mathrm{He}$

Radiochemical Results





Chlorine (Homestake) Experiment:

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

$R_{exp} = 2.56 \pm 0.16 \pm 0.16$ SNU

$R_{SSM} = 7.6^{+1.3}_{-1.1}$ SNU

(Ap.J. 496, p. 505)

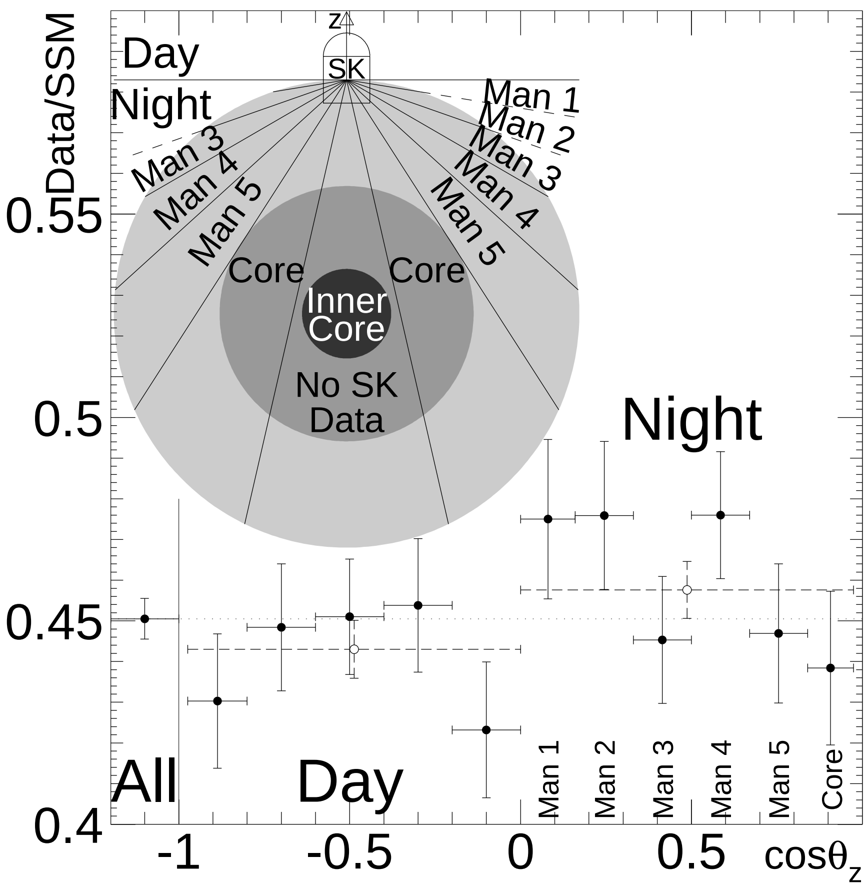
Gallium Experiments:

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

Experiment		Rate
SAGE	=	$70.8^{+5.3}_{-5.2}\ {}^{+3.7}_{-3.2}$ SNU
GNO/Gallex	=	$74.1\ {}^{+6.7}_{-6.8}$ SNU
SSM	=	128^{+9}_{-7} SNU

(astro-ph/0204245, hep-ex/0006034)

Super-Kamiokande



$\nu_a + e^- \rightarrow \nu_a + e^-$

Rate $\propto \phi(\nu_e) + \frac{1}{6}\phi(\nu_{\mu\tau})$

$R_{exp} =$

$0.465 \pm 0.005^{+0.014}_{-0.012} \times$ SSM

Elastic Scattering Day-Night

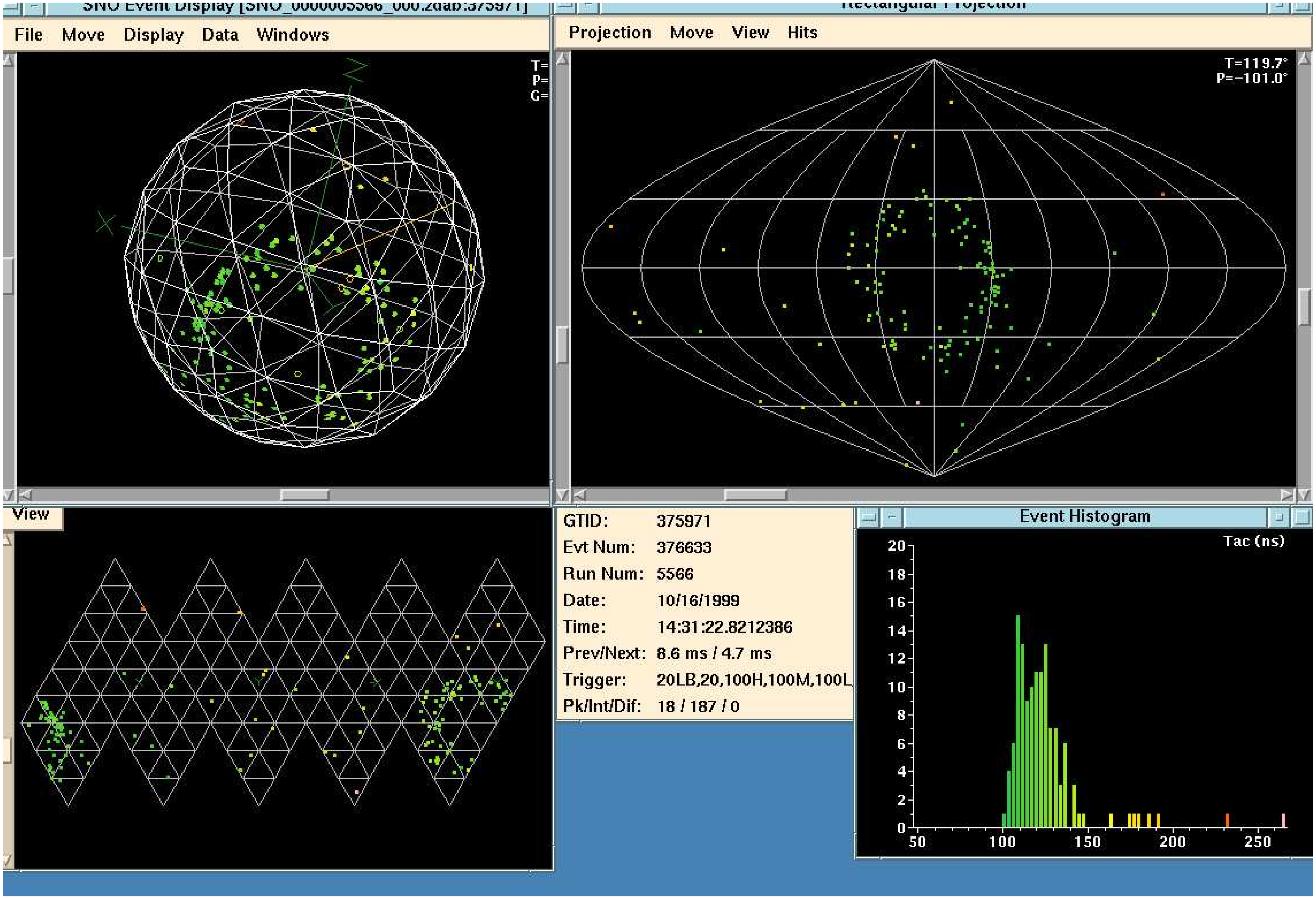
Asymmetry:

$$\frac{N-D}{\frac{1}{2}(N+D)} = 2.1\% \pm 2.0\%^{+1.3\%}_{-1.2\%}$$

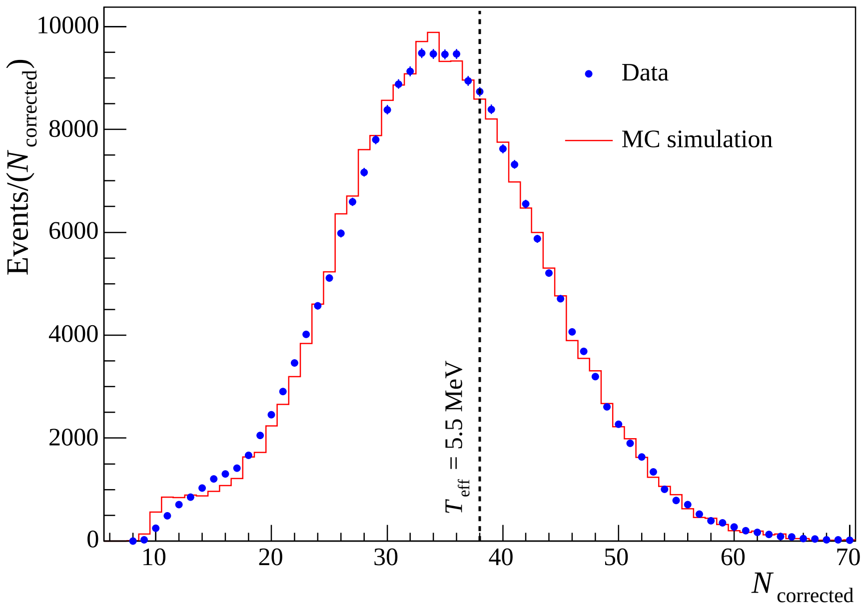
(hep-ex/0106064, hep-ex/0206075)

No evidence for day-night effect or spectral distortions

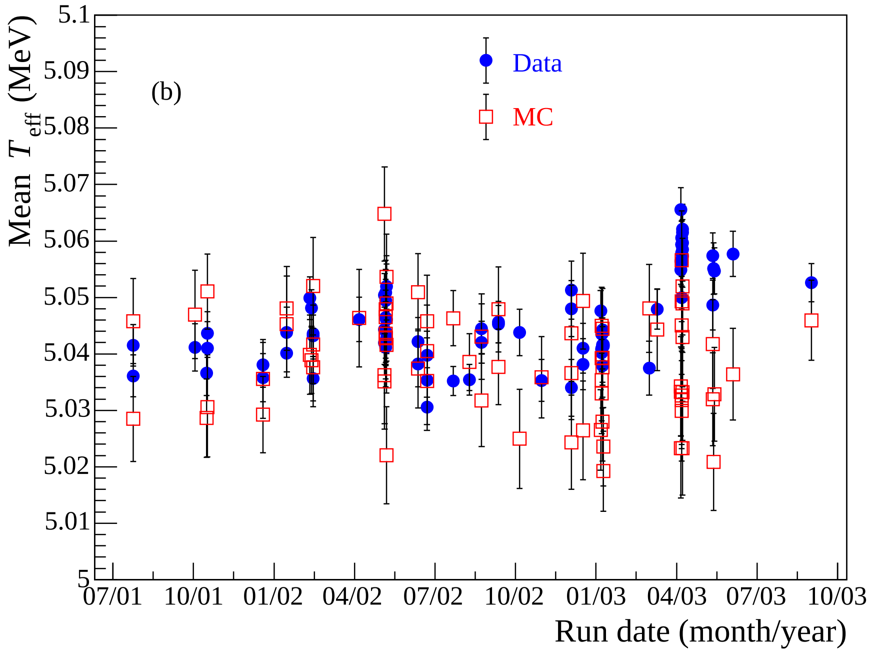
Event Display–Neutrino Event



Energy Calibration

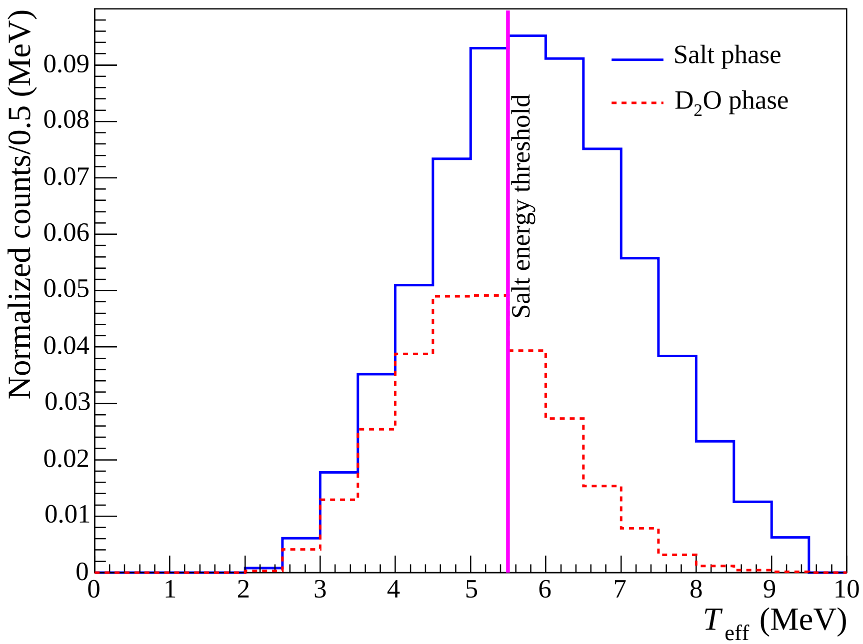


Primary energy calibration done with ^{16}N source—6.1 MeV γ-rays

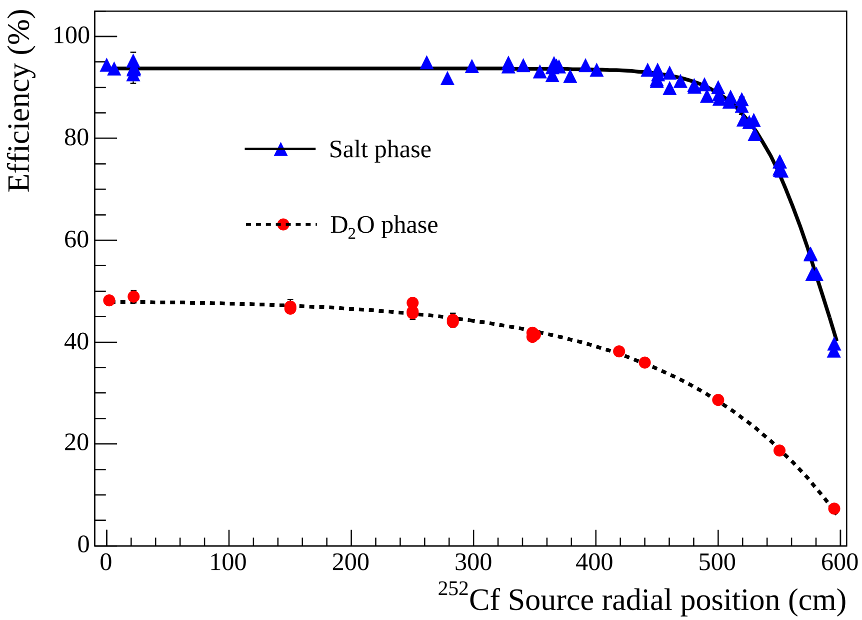


Time-varying attenuation lengths in the water are modelled in the Monte Carlo simulation.

Neutron Response in SNO's D_2O and Salt Phases

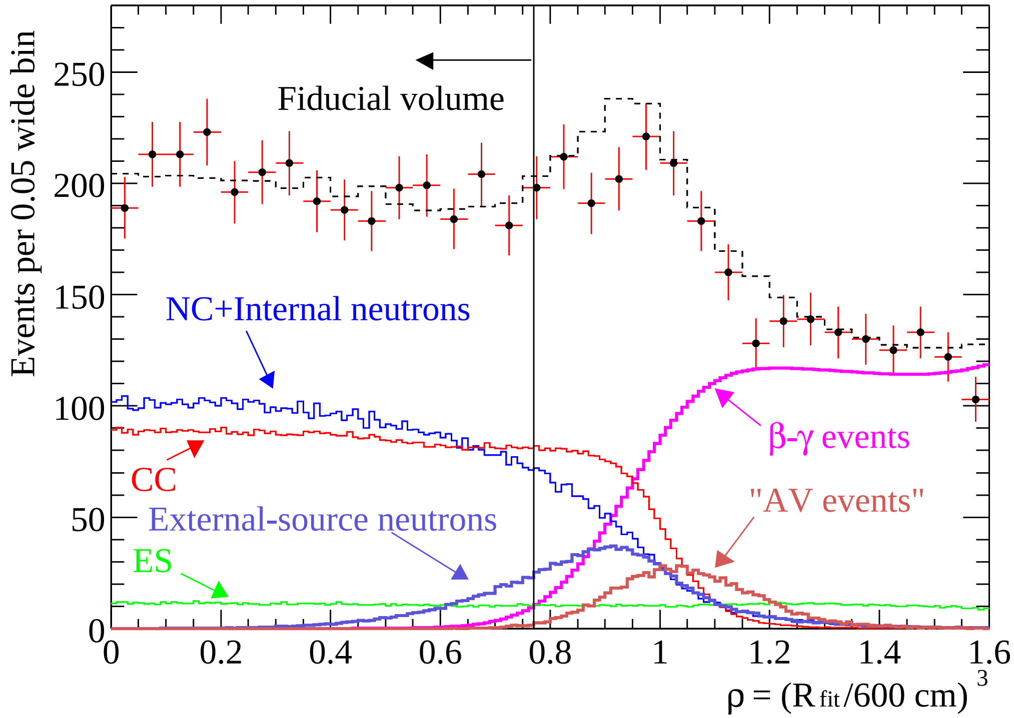


Neutron signal in salt produces larger energy deposit.



Large increase in neutron capture efficiency with salt.

External Neutron Background



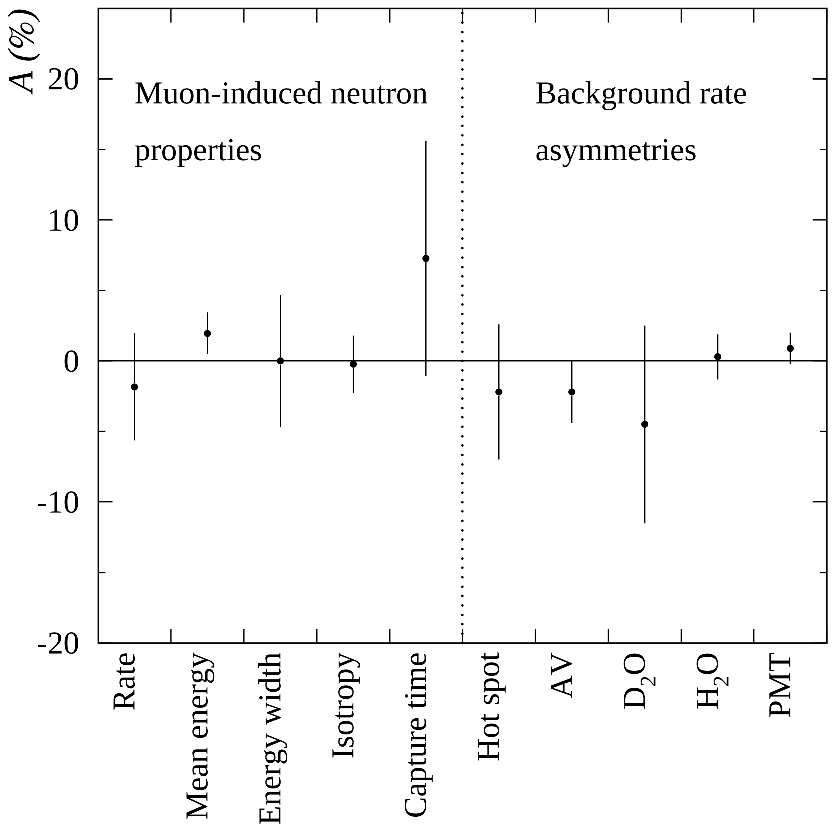
Neutrons produced near edge of D_2O by external radioactivity

Had very small capture efficiency in pure D_2O; high capture efficiency of salt makes these a large background

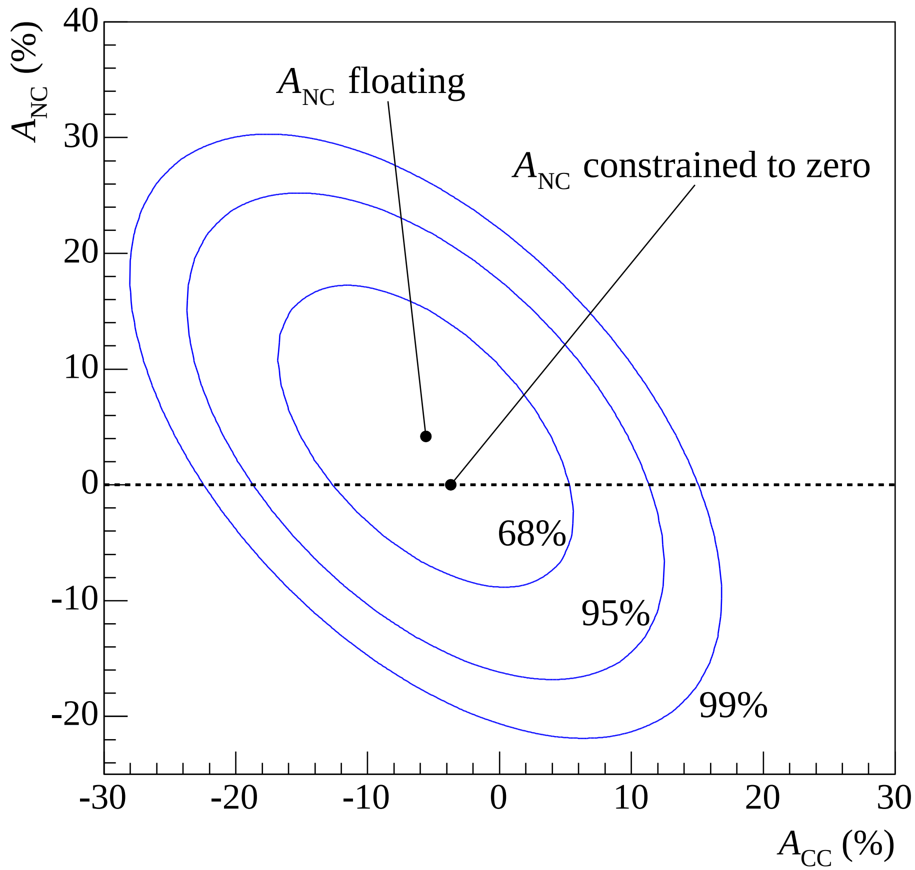
Cannot assay material inside the acrylic!

Have distinctive radial distribution, so include as additional PDF and fit for amplitude from the data

Day-Night Systematics



Diurnal stability of detector verified with muon-induced neutrons and radioactive background rates.



Correlations between asymmetries on the CC and NC rates