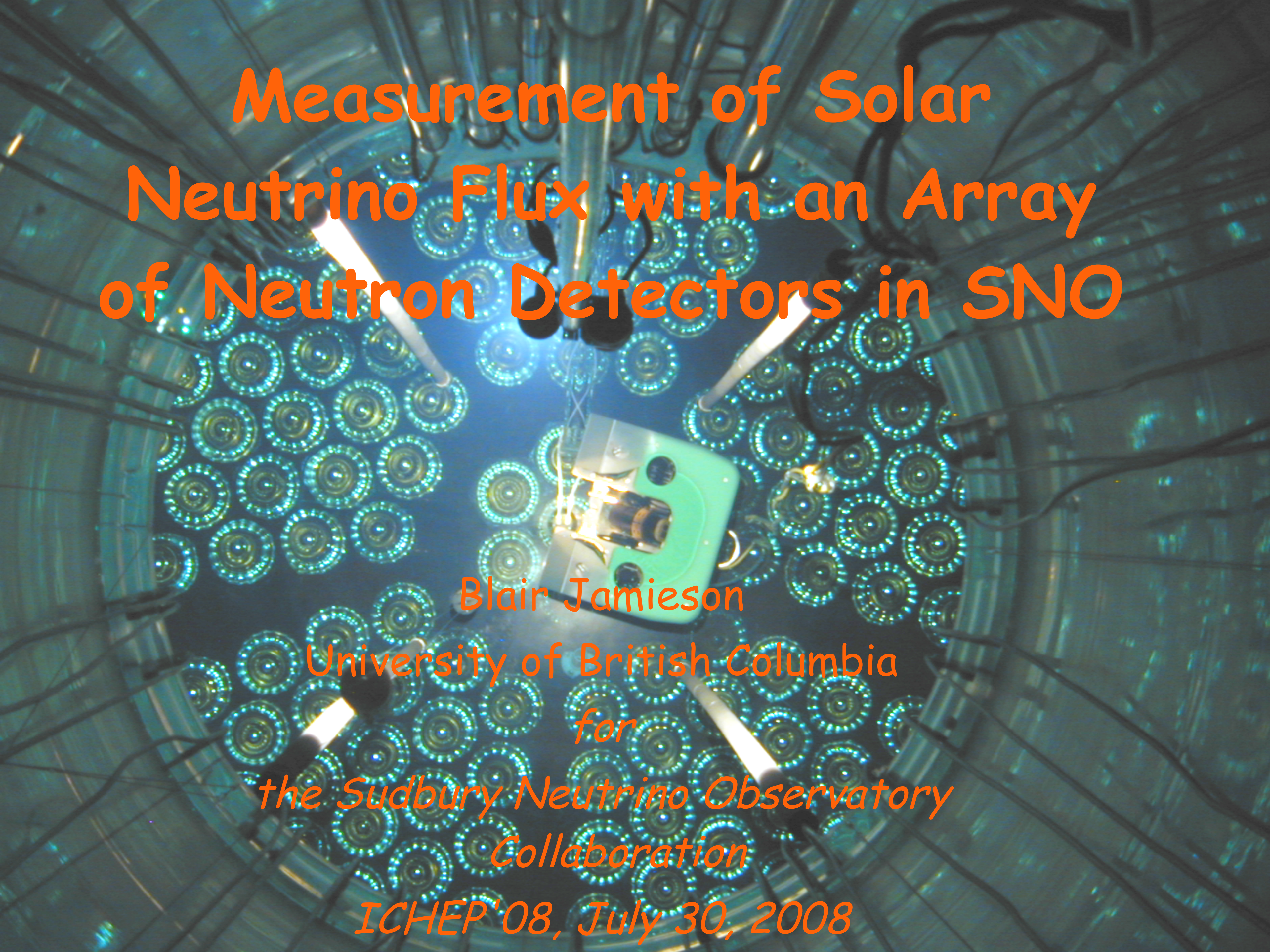


Measurement of Solar Neutrino Flux with an Array of Neutron Detectors in SNO

Blair Jamieson

University of British Columbia

for

the Sudbury Neutrino Observatory Collaboration

ICHEP'08, July 30, 2008

SNO

6000 mwe overburden

1000 tonnes D_2O

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shield H_2O

Support Structure for 9500 PMTs, 60% coverage

5300 tonnes Outer Shield H_2O

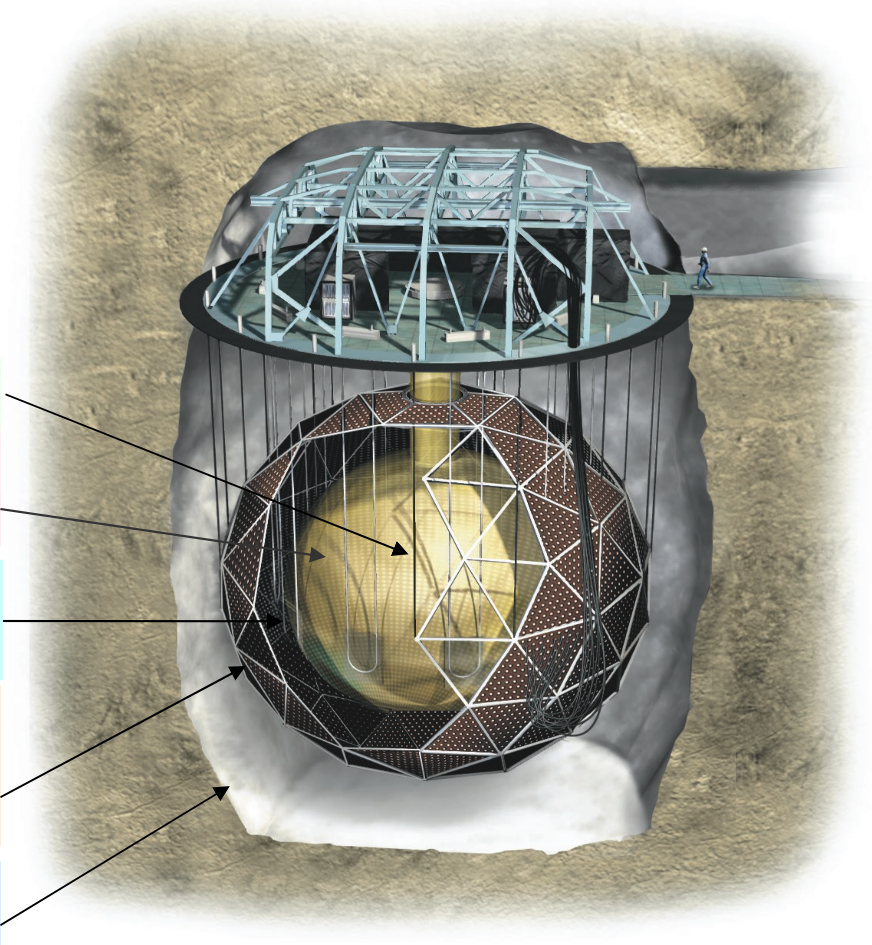


Image courtesy National Geographic

3 Reactions:

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \text{ES}$$

$$\nu_e + d \rightarrow p + p + e^- \quad \text{CC}$$

$$\nu_x + d \rightarrow p + n + \nu_x \quad \text{NC}$$

3 neutron detection methods:

$$n + d \rightarrow t + \gamma + 6.25 \text{ MeV}$$

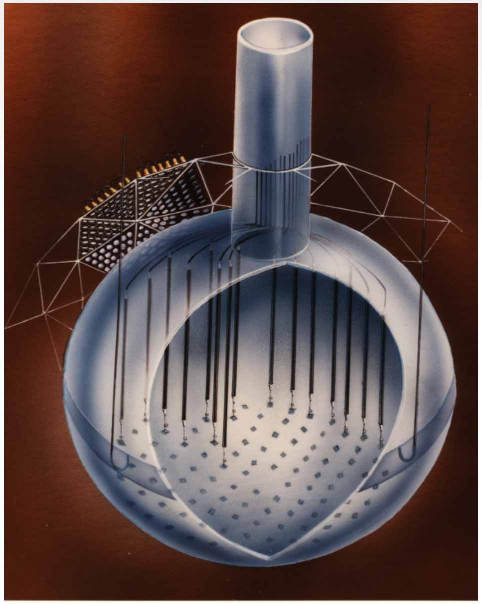
$$n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma + 8.6 \text{ MeV}$$

$$n + {}^{3}He \rightarrow p + t + 0.76 \text{ MeV}$$

3 Phases:

- Just D_2O
- D_2O + 2 tonnes NaCl
- D_2O + ^{3}He Proportional Counters (“NCDs”)

Why use NCDs?

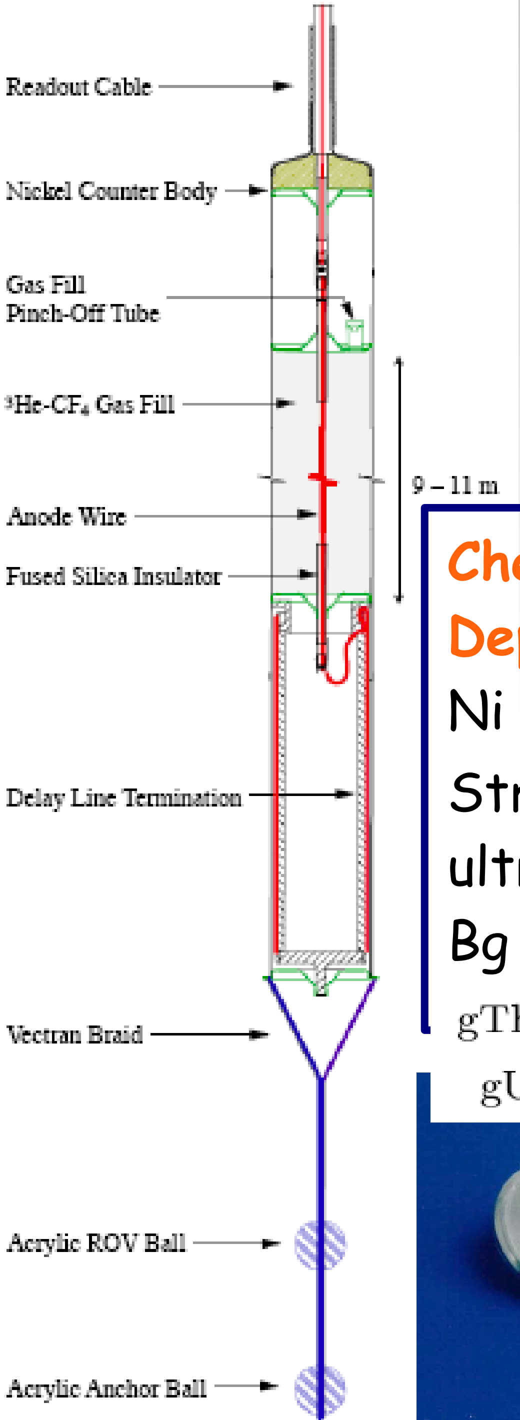


The features:

- Different systematics from other Phases.
- Separate signal paths: neutron capture no longer competes with CC events in Cherenkov light.
- Break correlation between CC and NC signals.
- CC spectrum contamination by 6.25-MeV capture gammas reduced by capture in NCD array, and determined independently.

The difficulties:

- Signal rate low: ~1000 neutrons/year detected.
- Ultra-low background materials needed.
- Some light loss (~10%) due to array.
- Complexity.



Phase III

Counters 2 - 3m long laser-welded together and deployed by a submersible vehicle.

36 strings of ^{3}He, 4 strings of ^{4}He on a 1 x 1 m grid.

Total length 398 m

Chemical Vapor Deposition (CVD):

Ni + 4CO « Ni(CO)$_4$

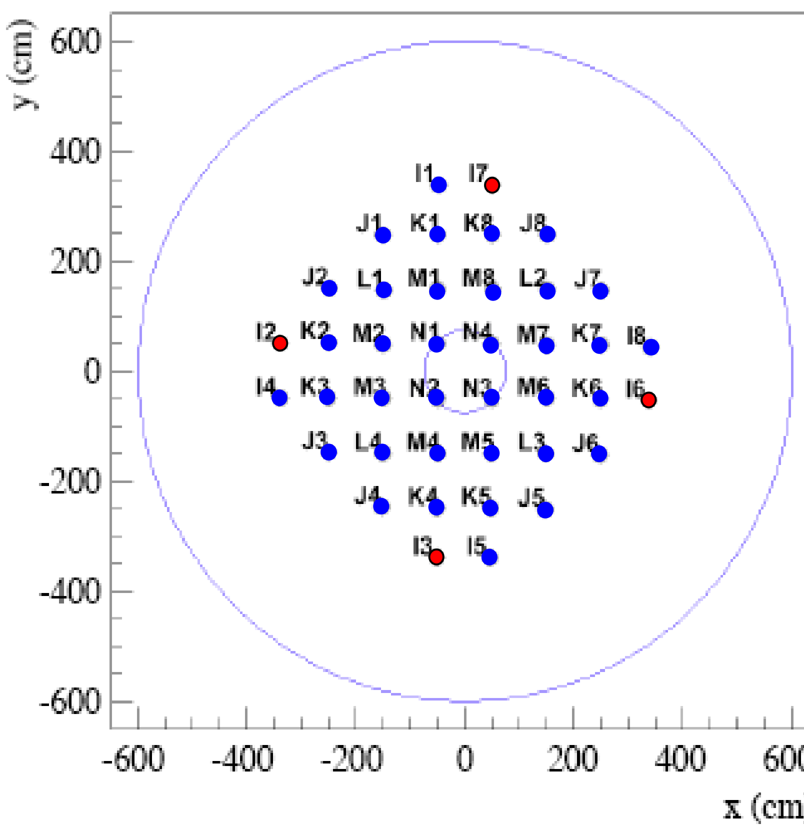
Strong

ultra-pure Ni

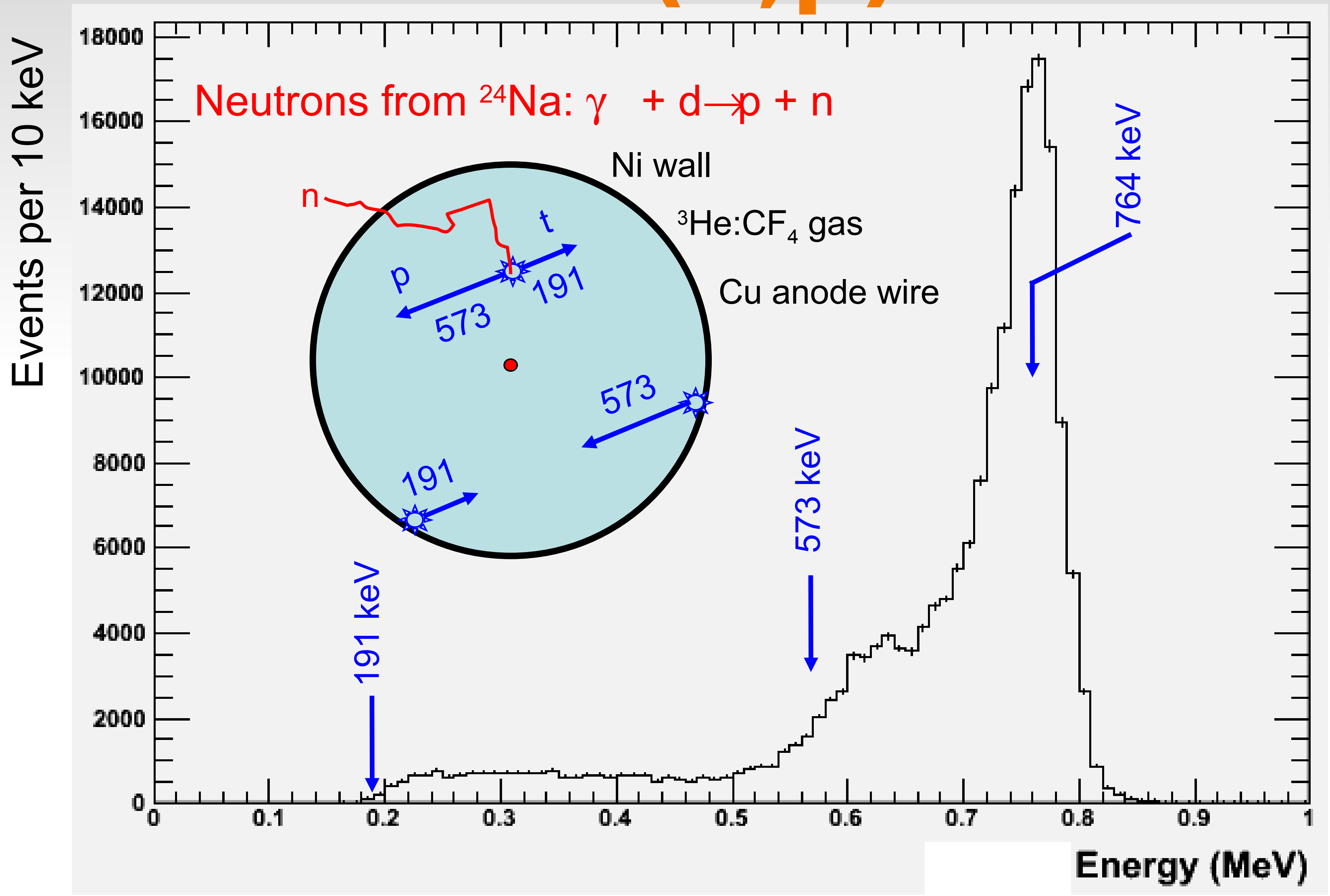
Bg rate < 0.01 prev. best

$$gTh/gNCD = 3.43^{+1.49}_{-2.11} \times 10^{-12}$$

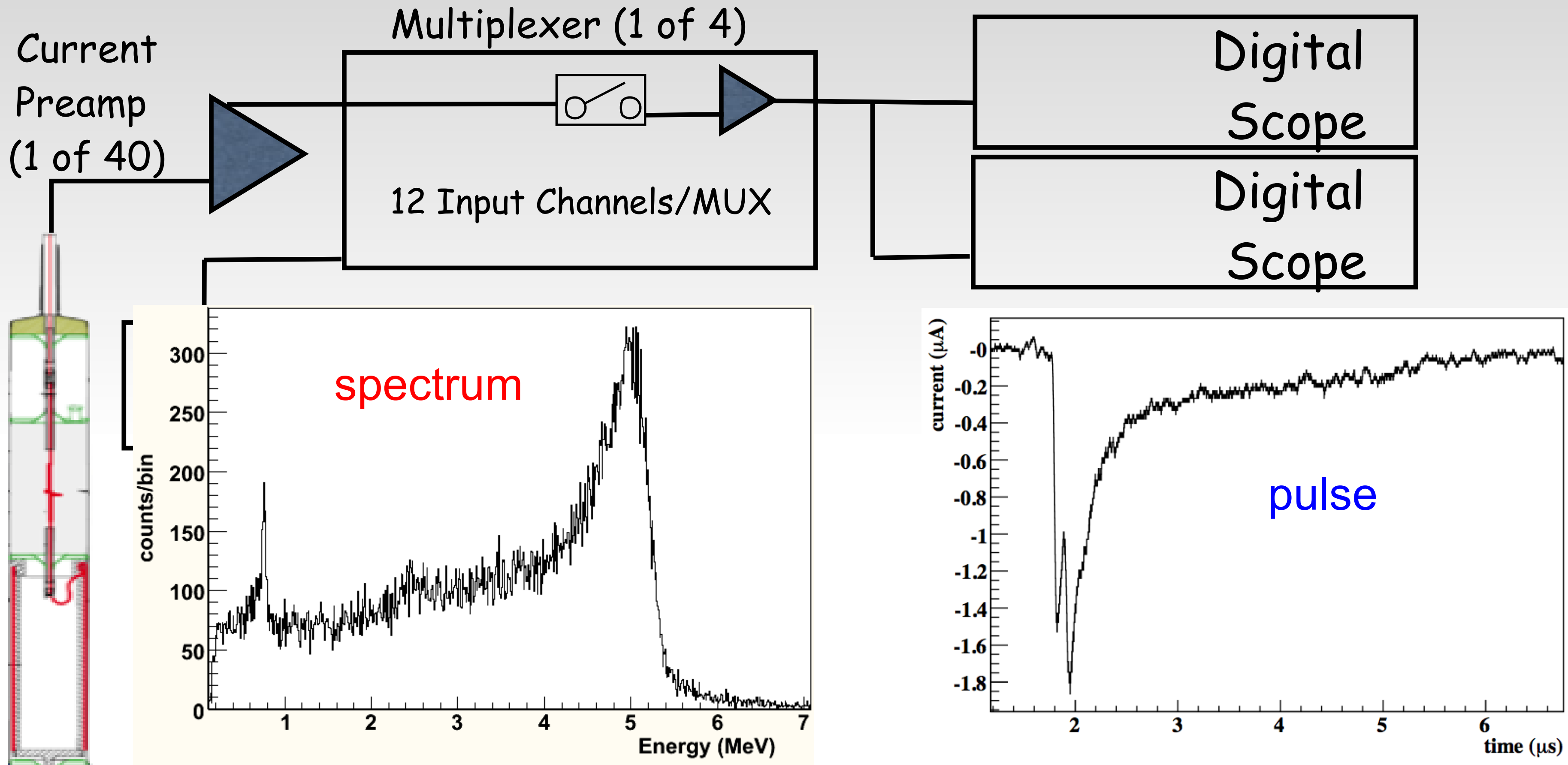
$$gU/gNCD = 1.81^{+0.80}_{-1.12} \times 10^{-12}$$

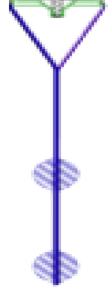


Energy Spectrum from $^3He(n,p)t$



NCD Electronics - Data Acquisition




- Ionization current pulses digitized for detailed analysis.
- Currents integrated by analog circuits for precise, nearly dead-time free, charge measurement.

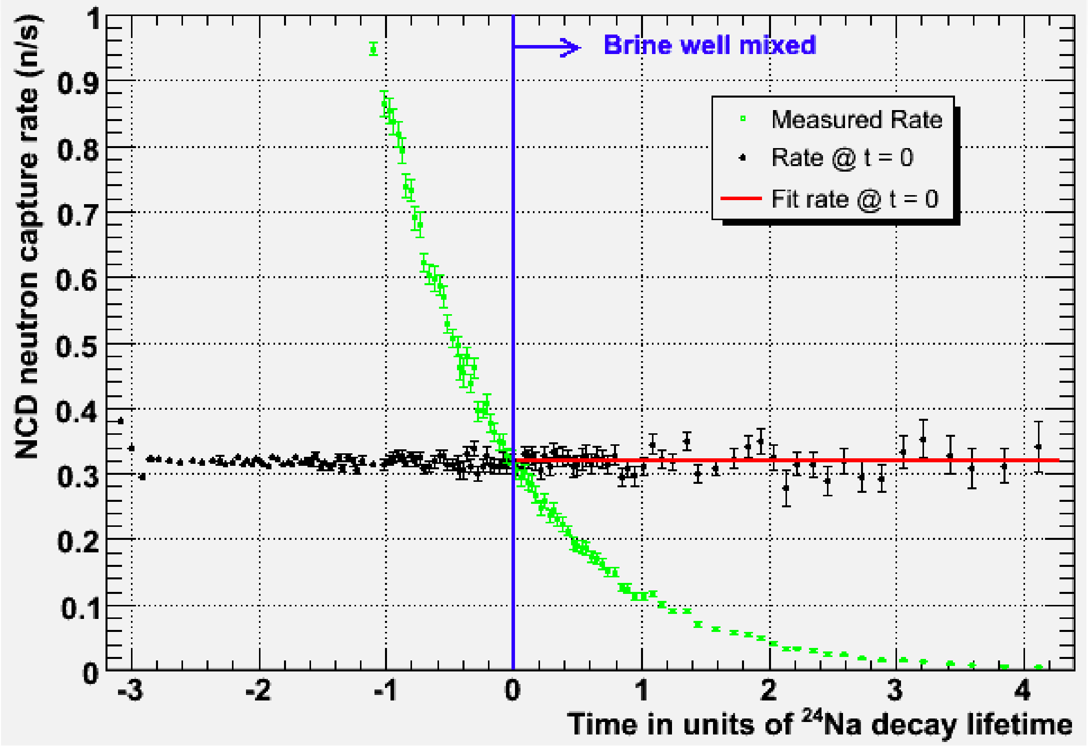
Calibrating the Neutron Efficiency

- Solar neutrinos produce neutrons uniformly in the D_2O.
- Monte Carlo based on Los Alamos “MCNP” code yields efficiency of 0.210(3).
- Time-series analysis (which is independent of source strength) of neutron bursts from ^{252}Cf fission confirms Monte Carlo precision.

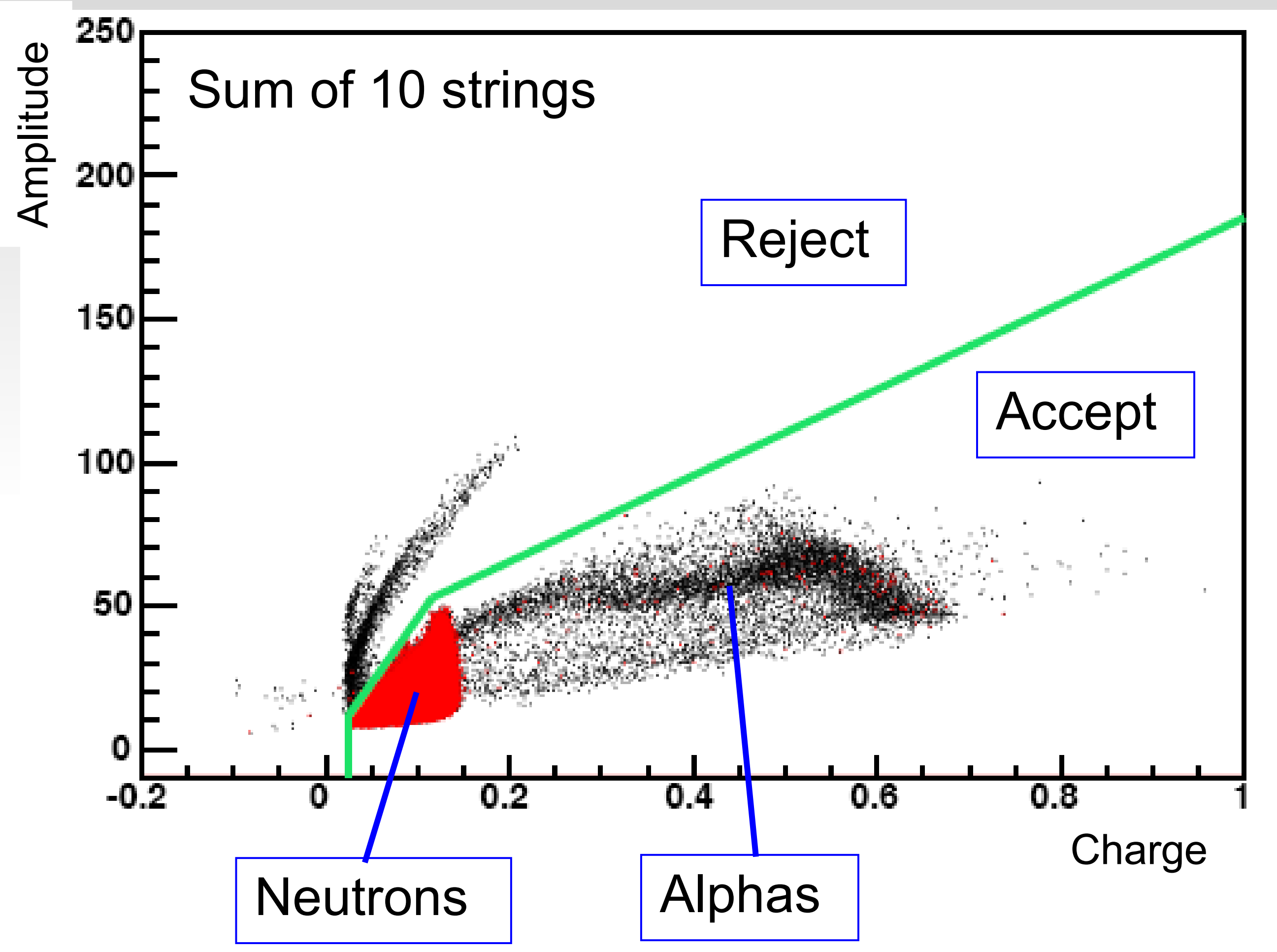
- Neutron efficiency can also be measured experimentally: Dissolve ^{24}NaCl brine in the D_2O, mix well.

- 15-hr ^{24}Na: 2.75-MeV γ breaks up deuteron, liberates a neutron.

- A uniform source!



Cutting instrumental events



- Ionization events easily separated from instrumentals
- 6 strings with high instrumental were dropped from analysis

Blind Analysis

Three blindfolds for the analysts:

- First month of neutrino data open

- Then only 20% open to 12/05 to finalize instrumental background cuts

- Thereafter include hidden fraction of neutrons that follow muons, AND

- Omit an unknown fraction of candidate events

Detailed internal documentation, review by "topic committees"

Box Opened May 2, 2008

• Results presented are as found, except…

• Difference between uncertainties from 3 signal-extraction codes: "Pilot errors" corrected, no change in central values, uncertainties agree.

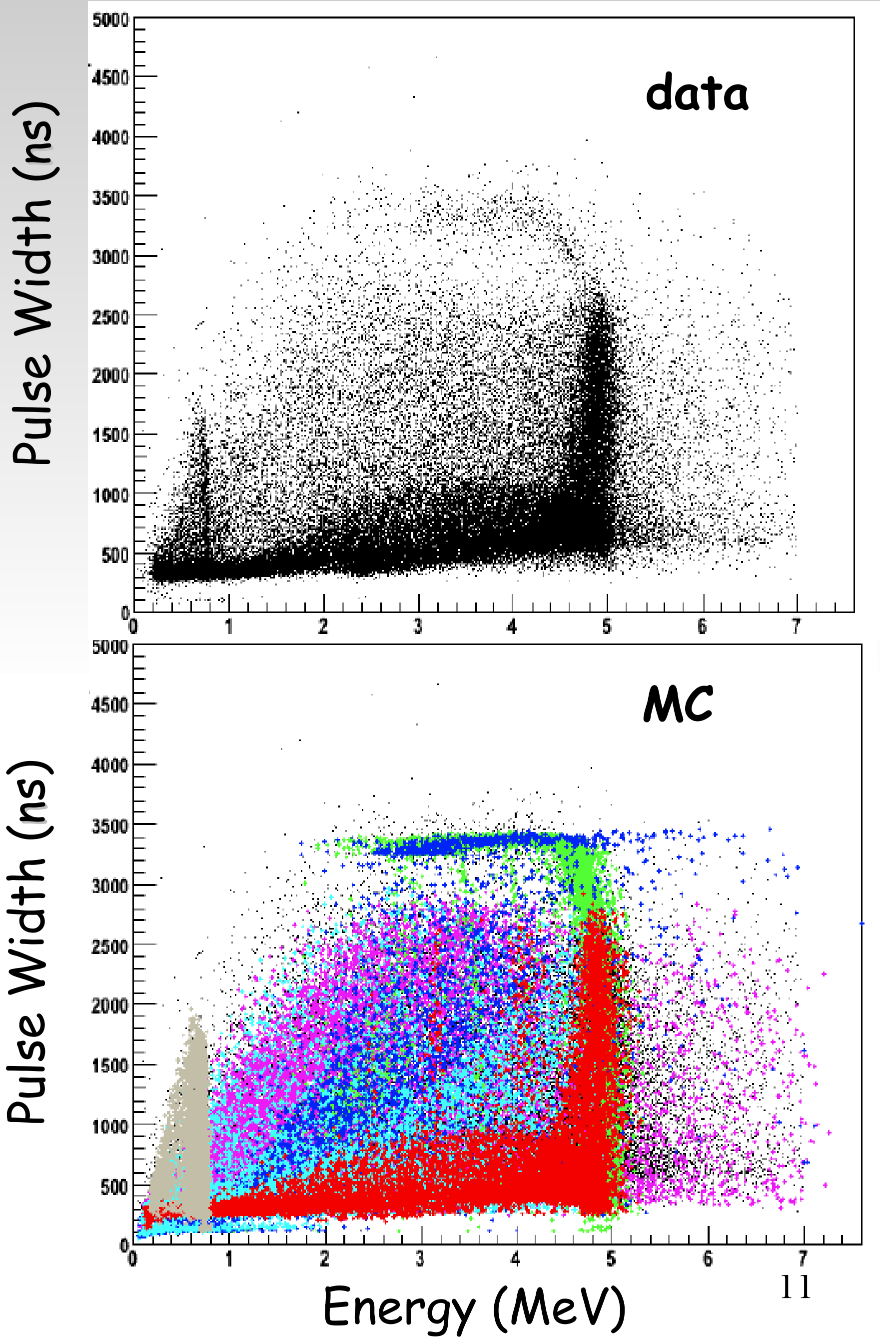
• An incorrect algorithm in fitting the peak value of the ES posterior distributions replaced.

Backgrounds

Source	PMT neutrons	NCD neutrons
D_2O Radioactivity	7.6 ± 1.2	28.7 ± 4.7
Atmospheric ν , ^{16}N	24.7 ± 4.6	13.6 ± 2.7
Other backgrounds	0.7 ± 0.1	2.3 ± 0.3
NCD Bulk PD, $^{17,18}O(\alpha,n)$	$4.6^{+2.1}_{-1.6}$	$27.6^{+12.9}_{-10.3}$
NCD hotspots	17.7 ± 1.8	64.4 ± 6.4
NCD cables	1.1 ± 1.0	8.0 ± 5.2
External-source neutrons	20.6 ± 10.4	40.9 ± 20.6
TOTAL	77^{+12}_{-10}	185^{+25}_{-22}

NCD Simulation Results

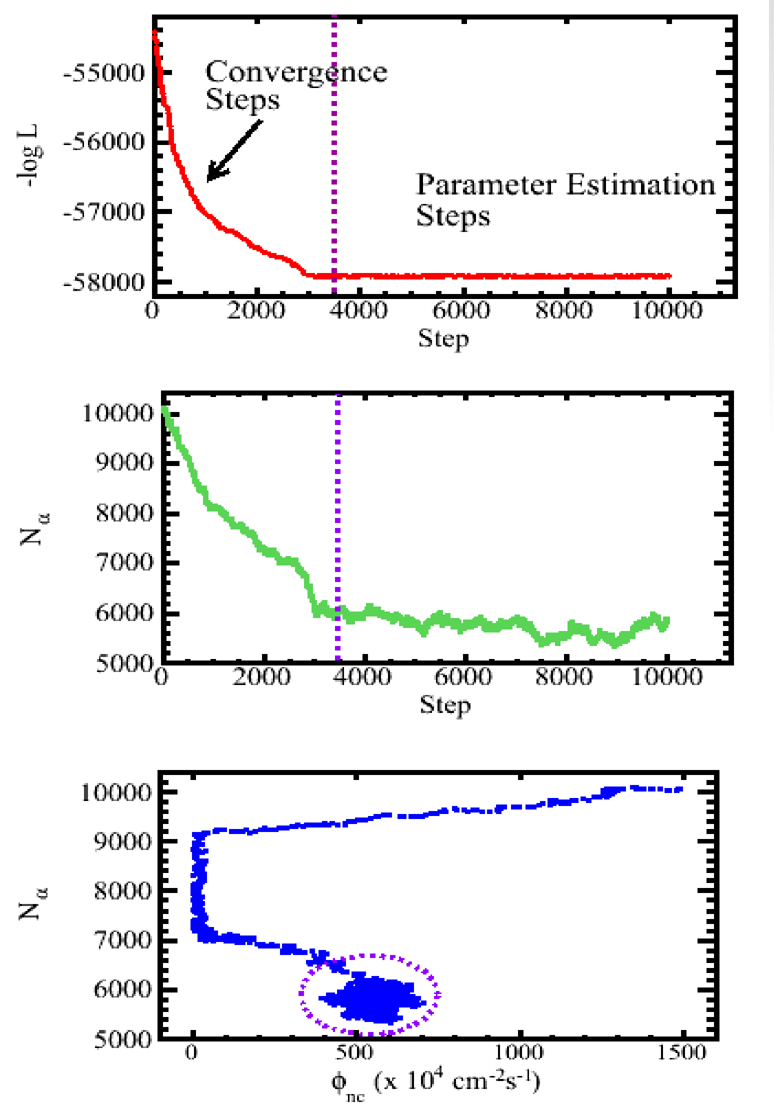
- **model:**
  - alpha energy loss
  - alpha energy straggling
  - alpha multiple scattering
  - electron-ion pair generation
  - electron drift, diffusion
  - electron multiple scattering
  - ion mobility
  - electron avalanche
  - space charge
  - signal generation
  - propagation through electronics
- **from calibration data:**
  - Po/Bu ratio
  - energy scale
  - energy resolution
  - alpha depth
  - contributions from different parts of the NCD



neutron signal
surface polonium decay
bulk U and Th decay
wire polonium decay
wire bulk decay
insulator polonium decay
insulator bulk U and Th decay

Markov-Chain Monte Carlo: A random walk that samples parameter space with probabilities ∝ the likelihood function

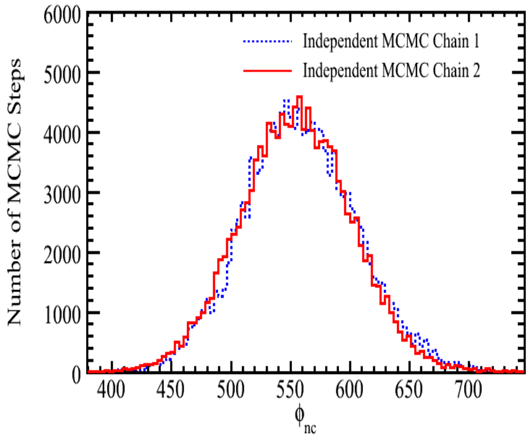
- Float 27 Flux parameters ($\phi_{NC}, \phi_{CC1...13}, \phi_{ES1...13}$) and 35 Systematic uncertainty parameters (efficiency, MC input, scale/resol, n backgrounds,...)

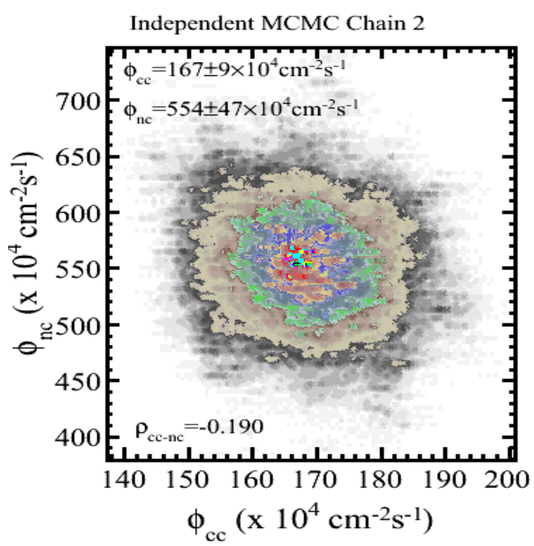


- Results are posterior distributions and correlations between all of the fit parameters

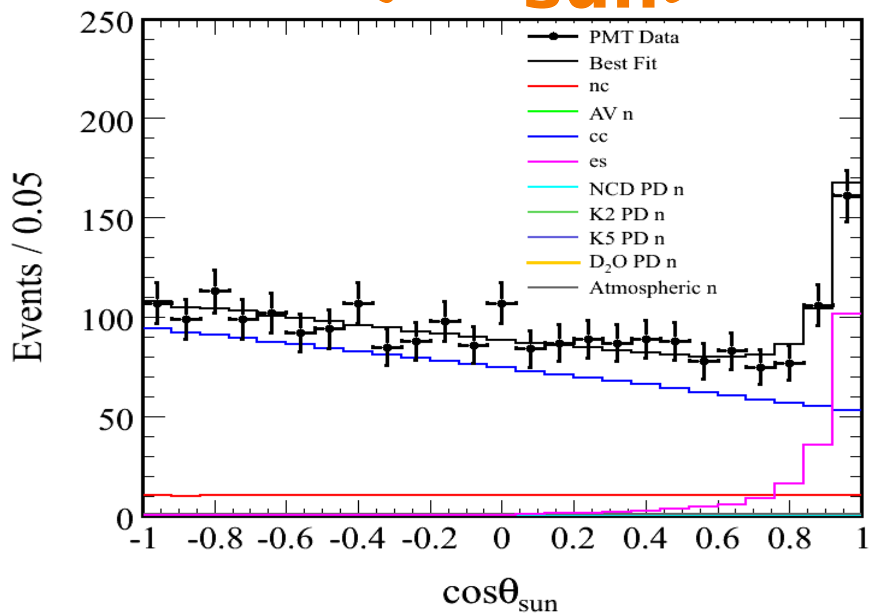
- Convergence check by comparing posterior

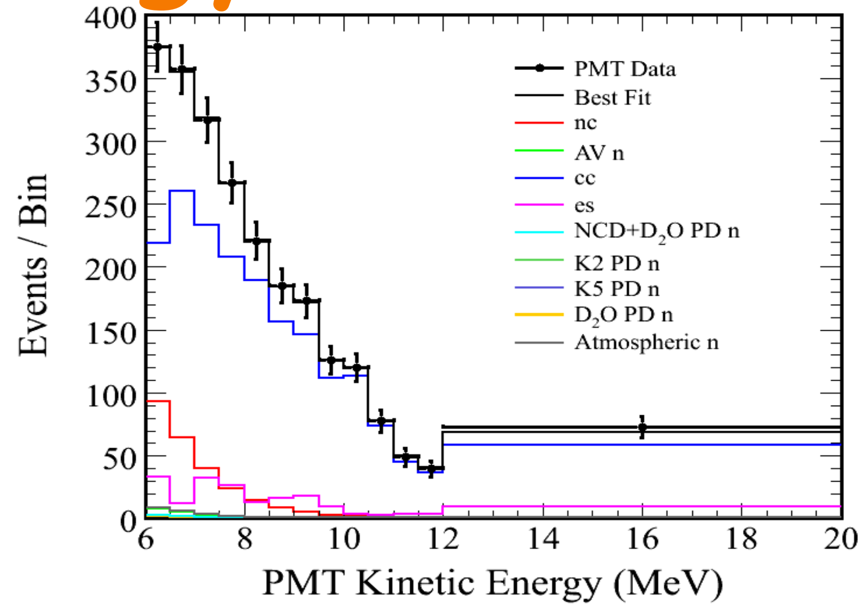
$\phi_{nc}^{chain1}=555 \pm 47 \times 10^4 cm^{-2}s^{-1}$
$\phi_{nc}^{chain2}=554 \pm 47 \times 10^4 cm^{-2}s^{-1}$

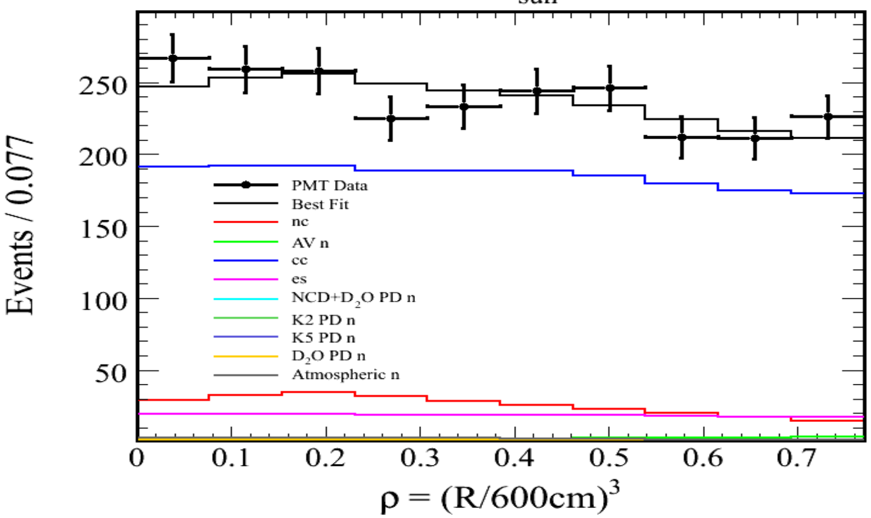


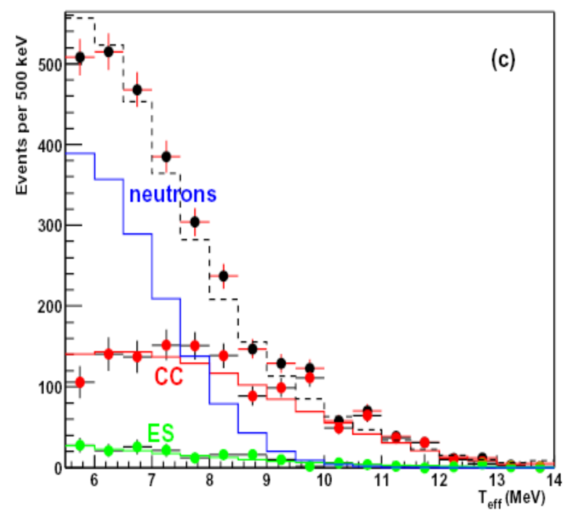


Fit PMT Distributions : $\cos(\theta_{sun})$, Energy, Radius



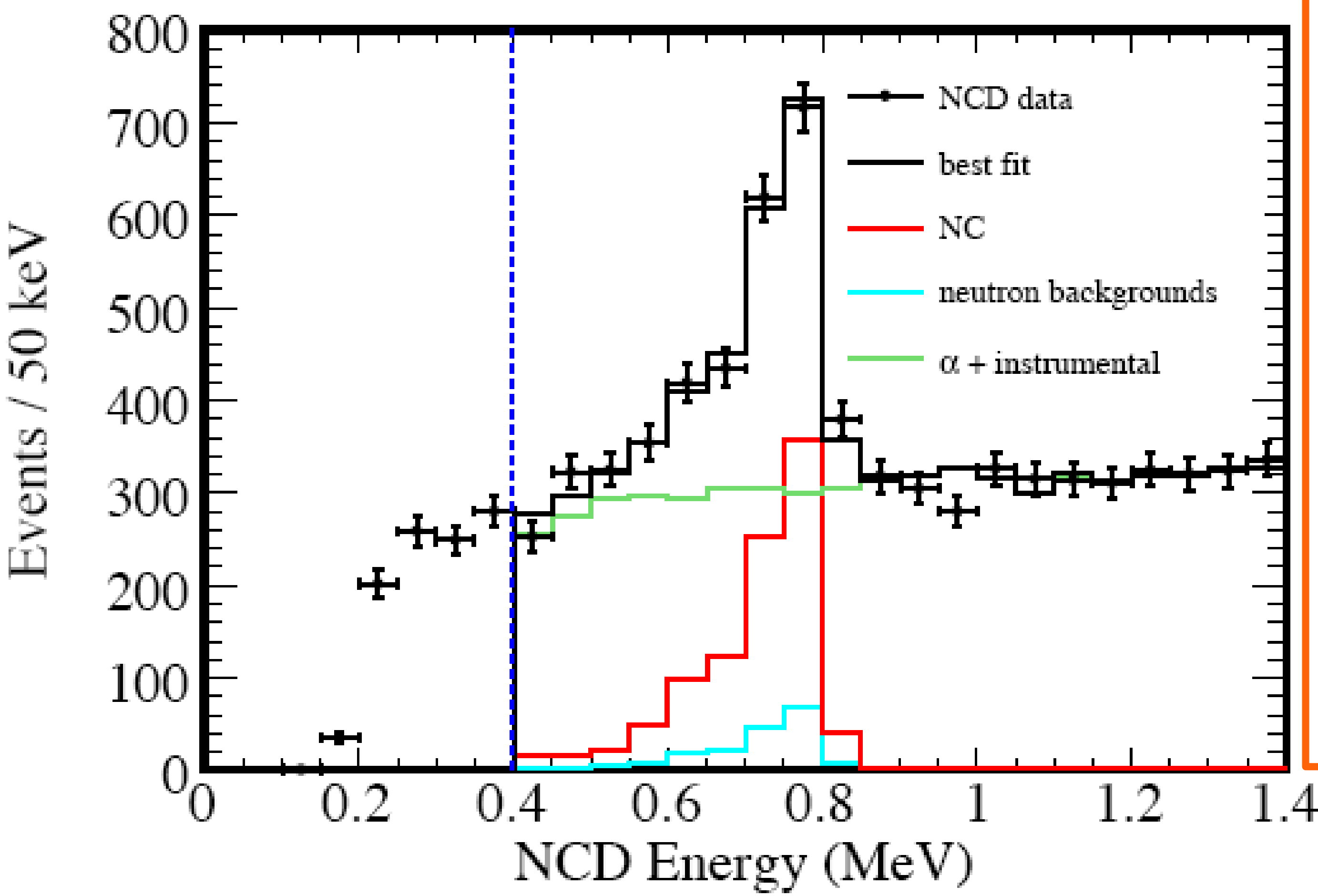






Data from salt phase

Neutrons from solar neutrino interactions

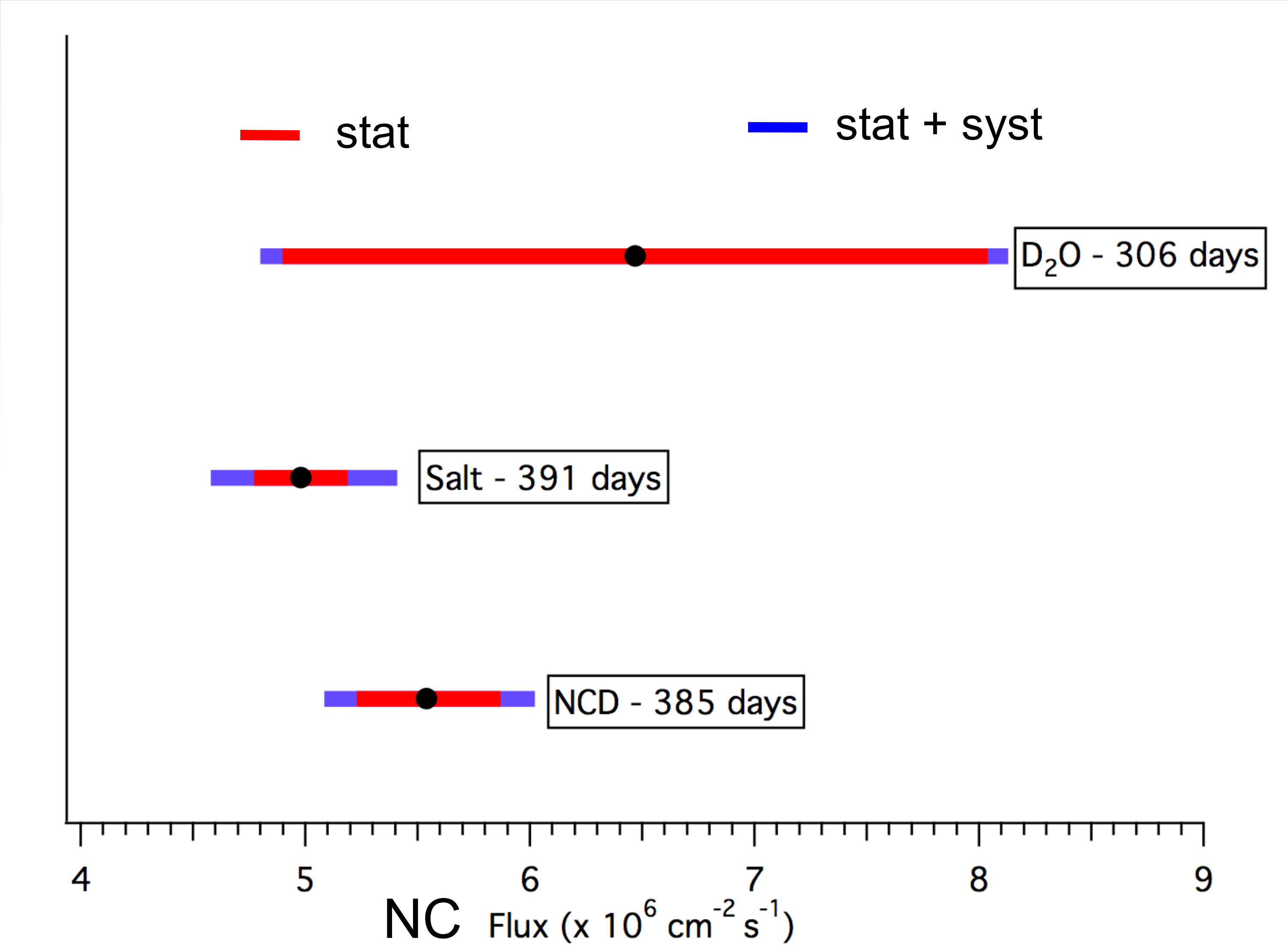


NC Signal:
983 ± 77

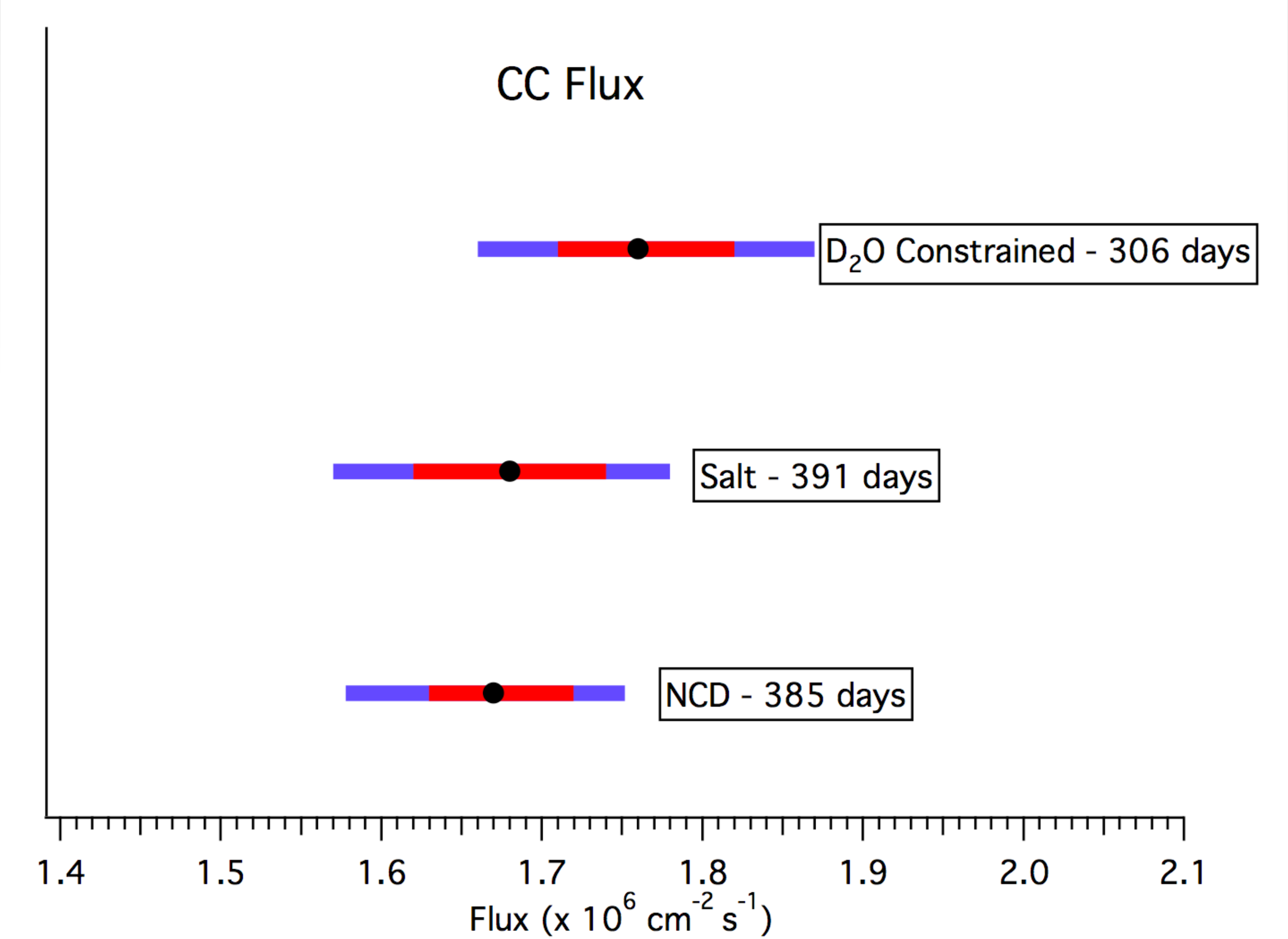
Neutron background:
185 ± 25

Alphas and Instrumentals:
6126 ± 250
(0.4 to 1.4 MeV)

SNO NC Flux: 3 Phases

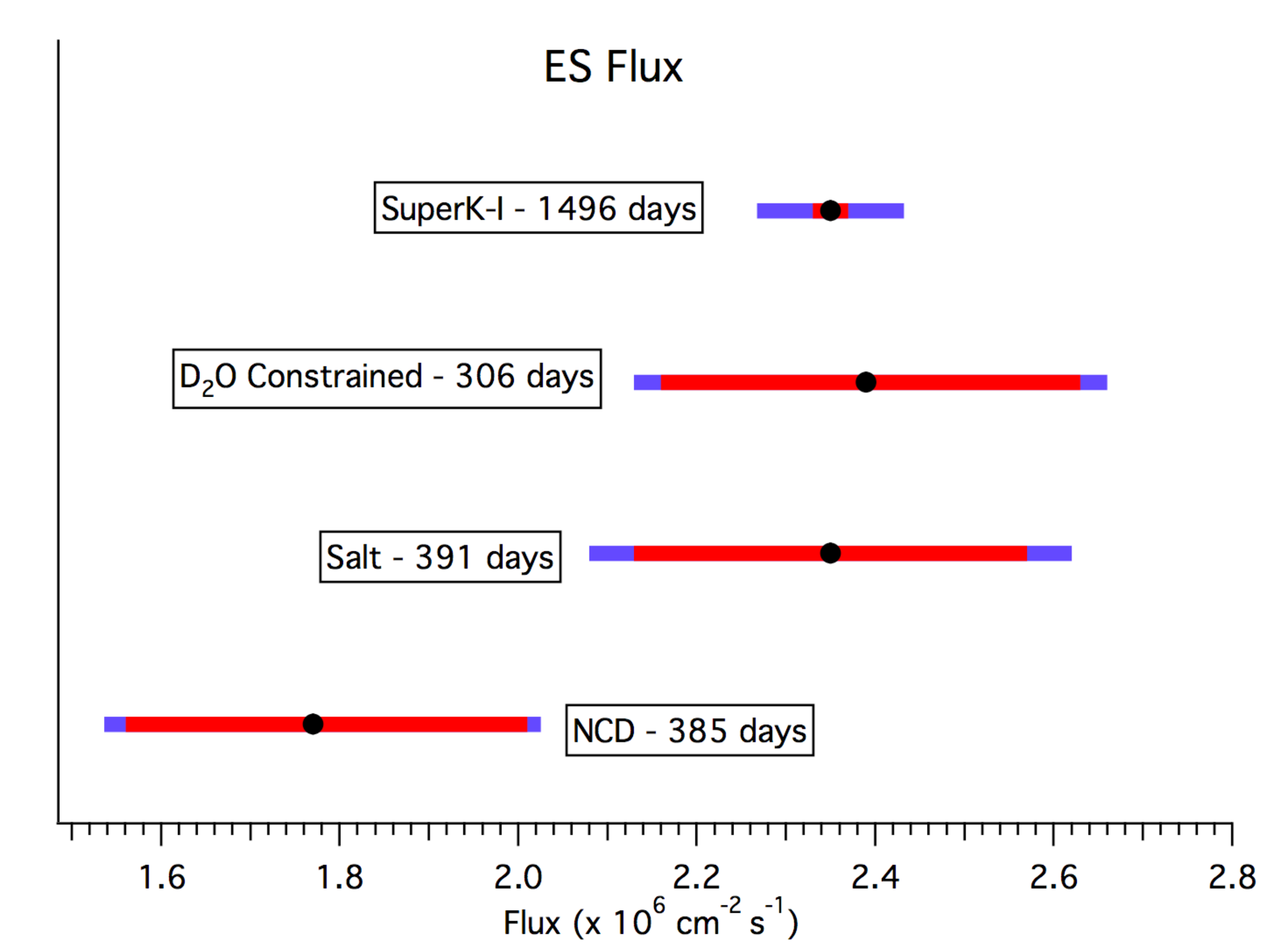


SNO CC Flux: 3 Phases



SNO, S-K ES Flux

p-value for consistency of NC/CC/ES in the salt & NCD phases + D_2O NC(unconstr) is 32.8%



Results for SNO NCD Phase & Super-K

Preliminary

Fluxes

($10^4\ cm^{-2}\ s^{-1}$)

ν_e: 167(9)

ν_{ES}: 177(26)

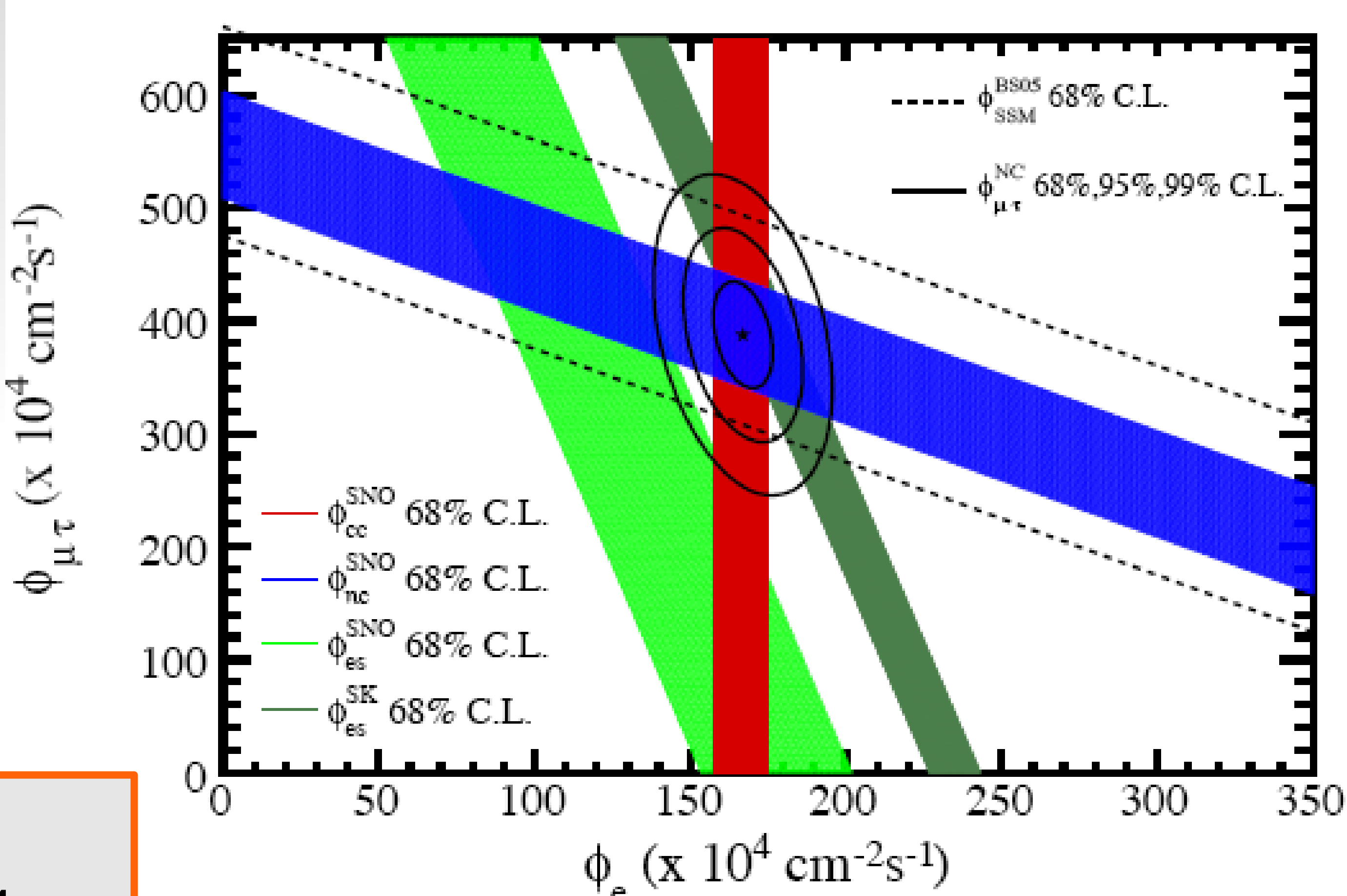
ν_{total}: 554(48)

ν_{SSM}: 569(91)

$\phi_{CC} = \nu_e$

$\phi_{ES} = \nu_e + 0.154\ \nu_{\mu\tau}$

$\phi_{NC} = \nu_e + \nu_{\mu\tau}$



$\phi_{SSM} = 569(1\pm0.16) \times 10^4\ cm^{-2}\ s^{-1}$
(BSB05-OP: Bahcall, Serenelli, Basu Ap. J. 621, L85, 2005).
Super-K: PRD 73, 112001, 2006

2-Neutrino Oscillation Contours

2-neutrino mixing model.
Marginalized 1-σ unc.
All SNO phases.
KamLAND: PRL 94, 081801 (2005).

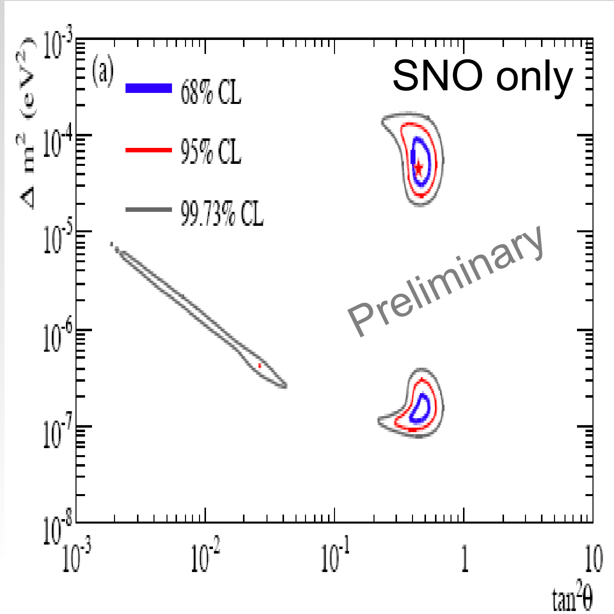
$$\sin^2\theta_{12} \sim \frac{\phi_{CC}}{\phi_{NC}} = 0.301 \pm 0.033\,(tot)$$

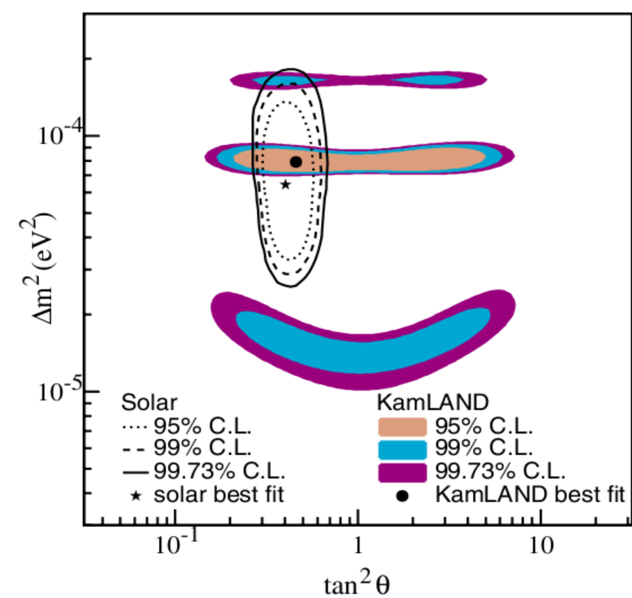
$$\Delta m^2 = 7.94^{+0.42}_{-0.26} \times 10^{-5}\ \text{eV}^2$$

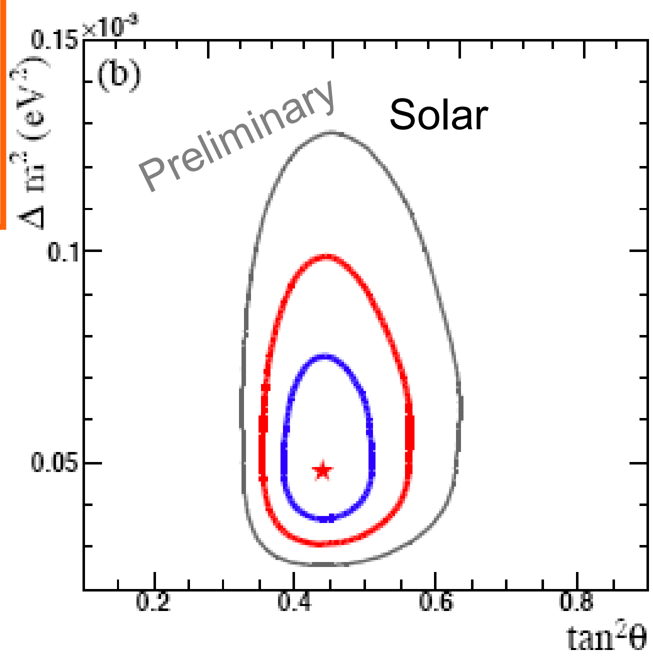
$$\tan^2\theta = 0.447^{+0.047}_{-0.043}$$

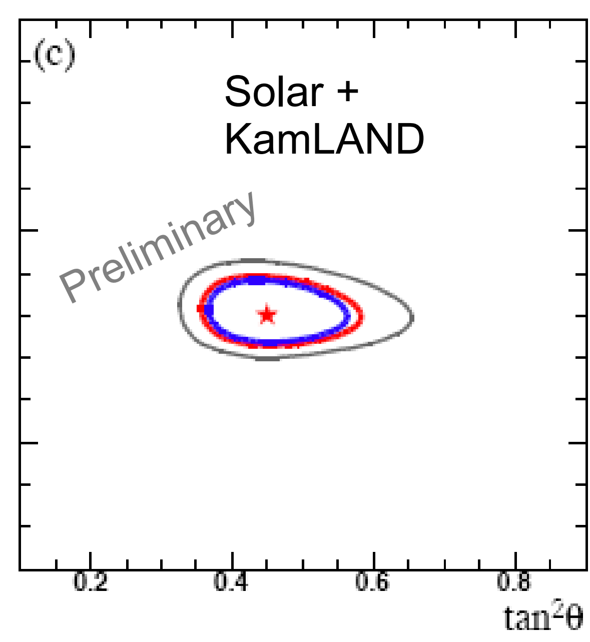
$$\theta = 33.8^{+1.4}_{-1.3}\ \text{degrees}$$

$$f_{8B} = 0.873\, f_{8B(BSB05-OP)}$$









Cl-Ar
Super-K
SAGE
Gallex
GNO
SNO
Borexino

766 t-y KamLAND

SNO Collaboration

SNO gratefully acknowledges…

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- Canada Research Chairs
- Westgrid

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- Department of Energy
- NERSC PDSF

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Portugal:

- FCT

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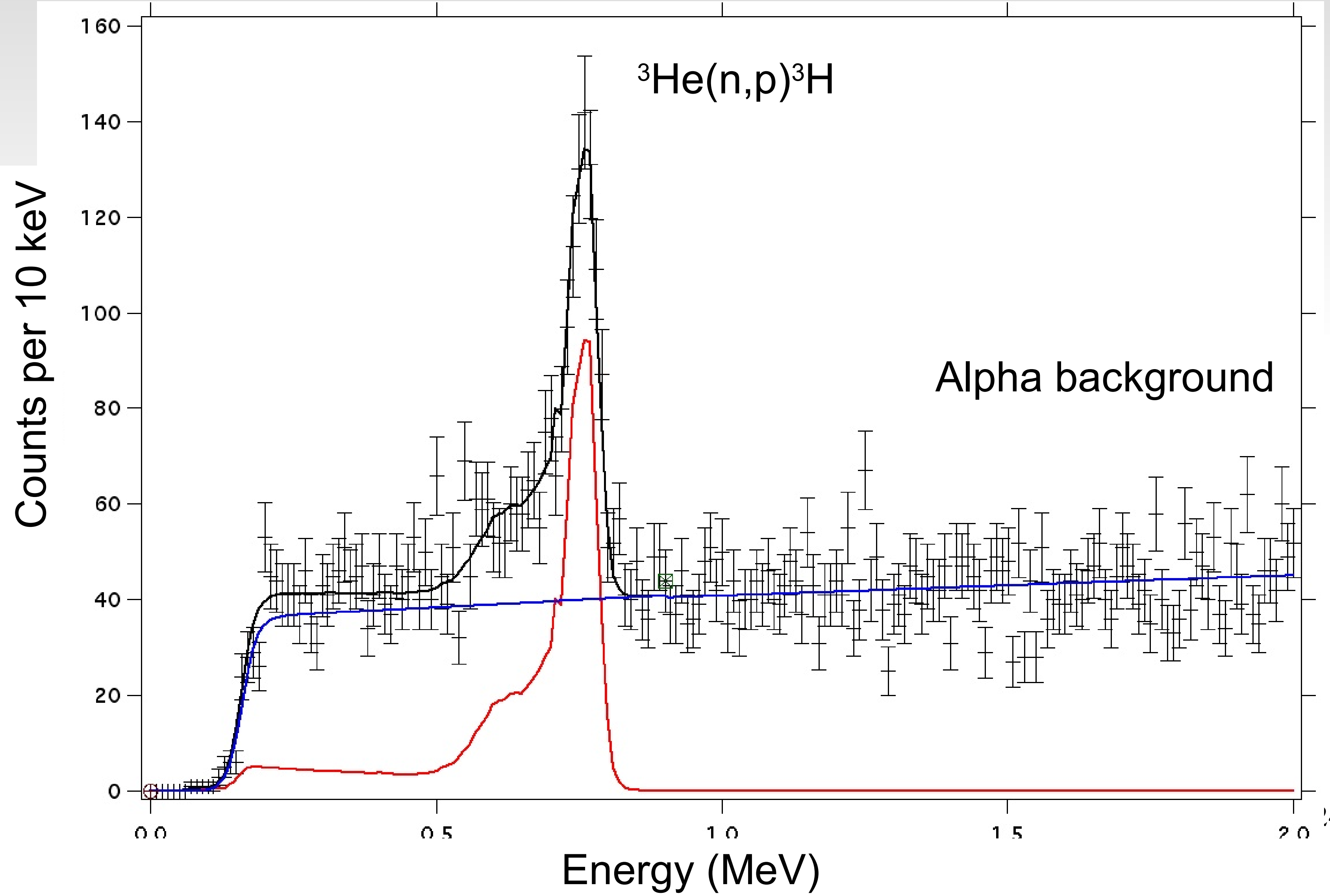
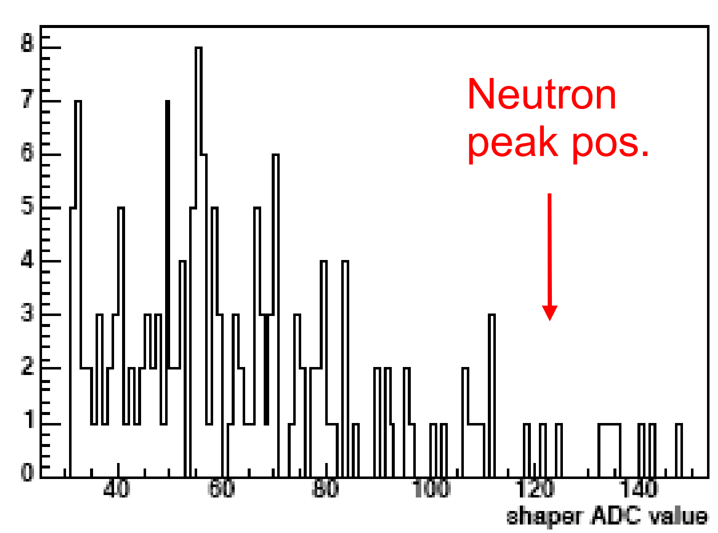
Neutron-capture spectrum (blind data)



Instrumental Events

Energy spectra of 2 strings showed instrumental events that could not be completely cut from neutron/alpha events.



These strings were dropped and PDFs were added in the analysis to allow for such events to be present on other strings.

391- day salt results

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

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

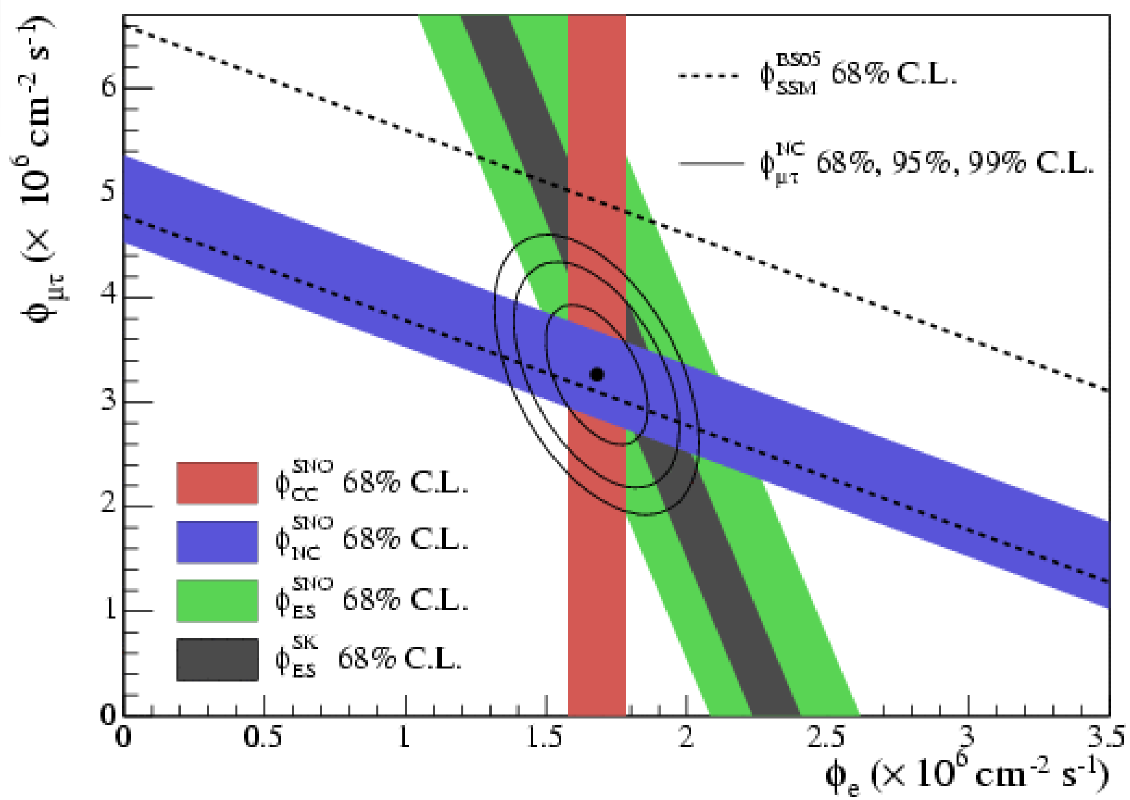
$$\varphi_{ES}=2.35\ ^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

$$\frac{\varphi_{CC}}{\varphi_{NC}}=\text{٠.٣٤٠}\pm\text{٠.٠٢٣}(\text{stat.})^{+\text{٠.٠٢٩}}_{-\text{٠.٠٣١}}$$

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

$$\Delta m^2=8.0^{+0.4}_{-0.3}\times10^{-5}\ \text{eV}^2$$

$$\theta\ =\ 33.9^{+1.6}_{-1.6}\ \text{deg}$$



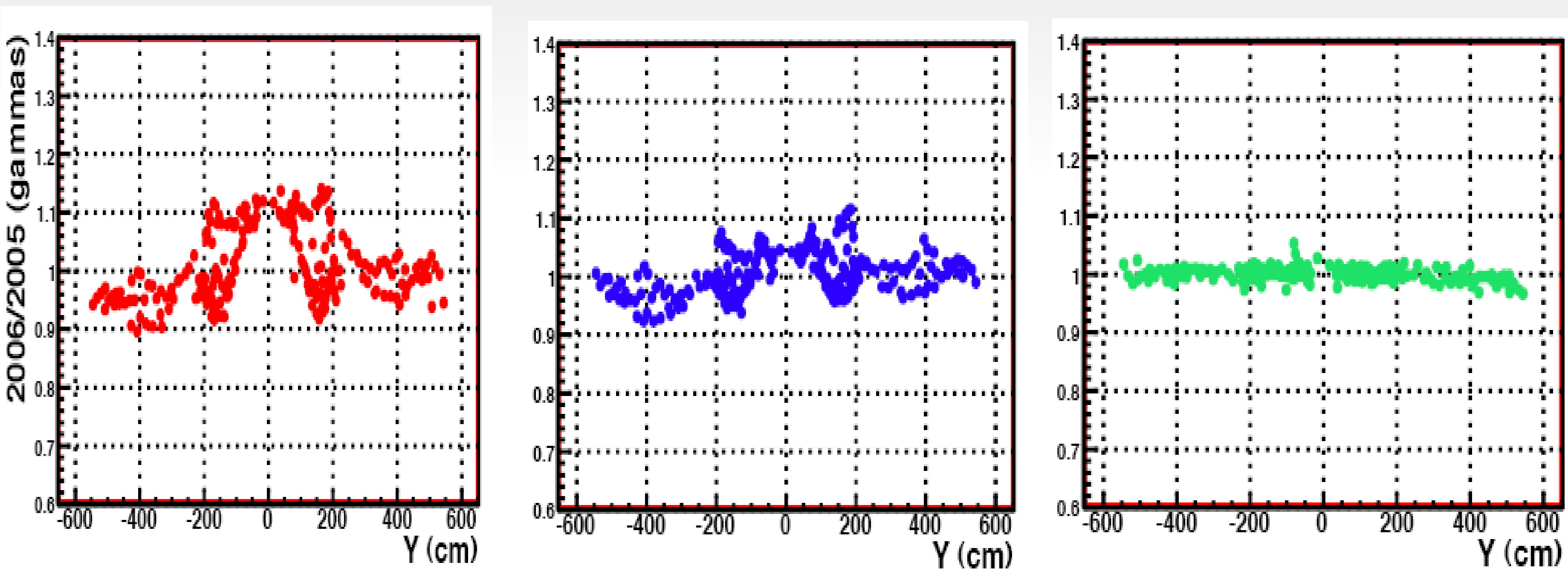
PRC **72**, 055502 (2005)

Calibrating the Neutron Efficiency

- Mixing ^{24}NaCl with the D_2O.

Normalized ratio of Cherenkov light at many points in vessel: 2006 data/ 2005 data. Different brine injection methods. Equalized ratio indicates uniform mixing.

First day after injection | During mixing | Steady state



Neutron efficiency: 0.211(7) for NC signal.
Excellent agreement with Monte Carlo: 0.210(3)

Signal Extraction - Extended Maximum Likelihood Fit for Fluxes

- maximize likelihood, N event measurmnts (x_1,...,x_n), pars (a_1,...,a_k):

$$L(\vec{x}|\vec{a}) = \frac{e^{-\nu}\nu^N}{N!}\prod_{i=1}^{N} P(\vec{x}_i|\vec{a})\prod_{k=1}^{K} Gaus(a_k, \mu_k, \sigma_k)$$

Poisson probability of observing N events

Standard maximum likelihood

Constraints on systematics from calibration data

- minimize -logL: $logL(\vec{x}|\vec{a}) = -\nu(\vec{a}) + \sum_{i=1}^{N} \log \nu(\vec{a}) P(\vec{x}_i|\vec{a}) - 0.5\sum_{k=1}^{K}[(a_k-\mu_k)/\sigma_k]^2$
- ν = predicted # of event, P = probability density function (PDF)
- In SNO we have M event types (j=CC,ES,NC,...) so:
- $$logL(\vec{x}|\vec{a}) = -\sum_{j=1}^{M} f_j(\vec{a})\phi_j(\vec{a}) + \sum_{i=1}^{M} \log\sum_{j=1}^{N} f_j(\vec{a})\phi_j(\vec{a})P_j(\vec{x}_i|\vec{a}) + constraints$$
- where ϕ is a flux and f is a conversion factor from flux to events

Joint PMT + NCD fit

- For the NCD phase, NCD and PMT NC flux is common, as are neutron backgrounds
- Just add -logL from the two measurements, using common flux parameter:

$$logL(\vec{x}|\vec{a}) = -\sum_{j=1}^{M^{PMT}} f_j^{PMT}(\vec{a})\phi_j(\vec{a}) + \sum_{i=1}^{M^{PMT}} \log \sum_{j=1}^{N^{PMT}} f_j^{PMT}(\vec{a})\phi_j(\vec{a}) P_j(\vec{x}_i^{PMT}|\vec{a})$$

$$-\sum_{j=1}^{M^{NCD}} f_j^{NCD}(\vec{a})\phi_j(\vec{a}) + \sum_{i=1}^{M^{NCD}} \log \sum_{j=1}^{N^{NCD}} f_j^{NCD}(\vec{a})\phi_j(\vec{a}) Q_j(\vec{x}_i^{NCD}|\vec{a})$$

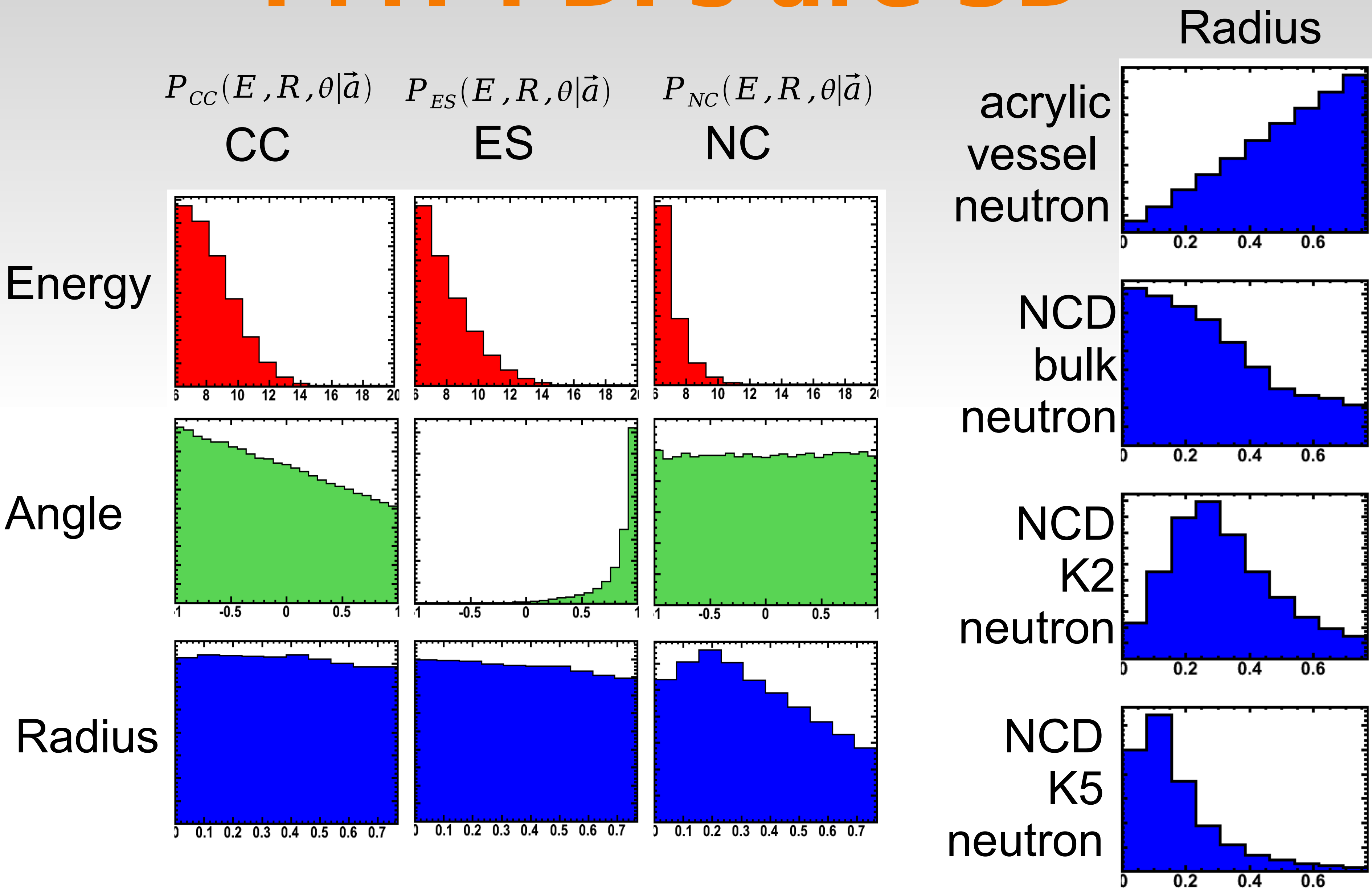
- f are conversion from flux to number of events, and ϕ are fluxes

Systematic Uncertainties

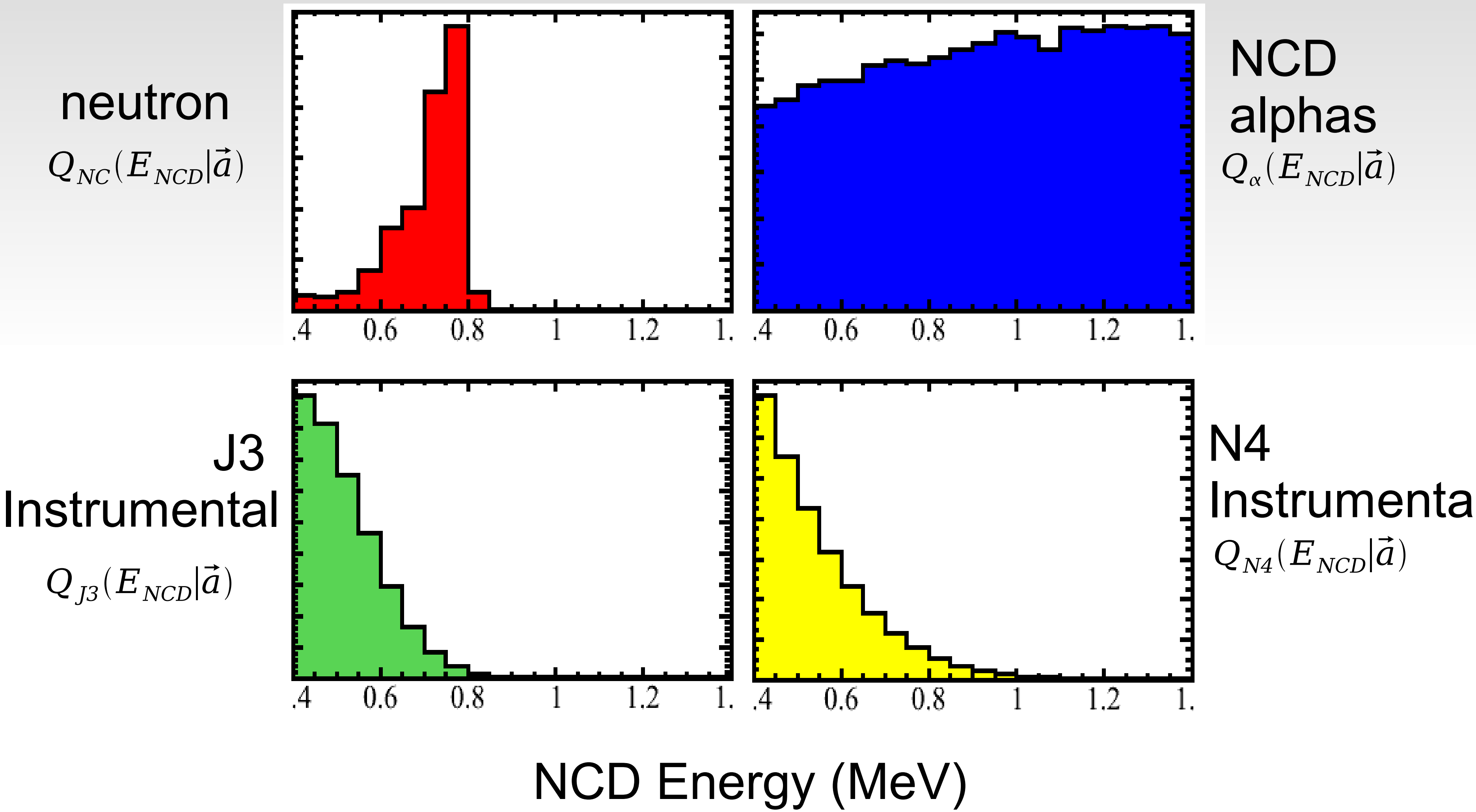
TABLE II: Sources of systematic uncertainties on NC, CC, and ES fluxes. The total error differs from the individual errors added in quadrature due to correlations.

Nuisance Parameter	NC uncert. (%)	CC uncert. (%)	ES uncert. (%)
PMT energy scale	±0.6	±2.7	±3.6
PMT energy resolution	±0.1	±0.1	±0.3
PMT radial scaling	±0.1	±2.7	±2.7
PMT angular resolution	±0.0	±0.2	±2.2
PMT radial energy dep.	±0.0	±0.9	±0.9
Background neutrons	±2.3	±0.6	±0.7
Neutron capture	±3.3	±0.4	±0.5
Cherenkov/AV backgrounds	±0.0	±0.3	±0.3
NCD instrumentals	±1.6	±0.2	±0.2
NCD energy scale	±0.5	±0.1	±0.1
NCD energy resolution	±2.7	±0.3	±0.3
NCD alpha systematics	±2.7	±0.3	±0.4
PMT data cleaning	±0.0	±0.3	±0.3
Total experimental uncertainty	±6.5	±4.0	±4.9
Cross section [16]	±1.1	±1.2	±0.5

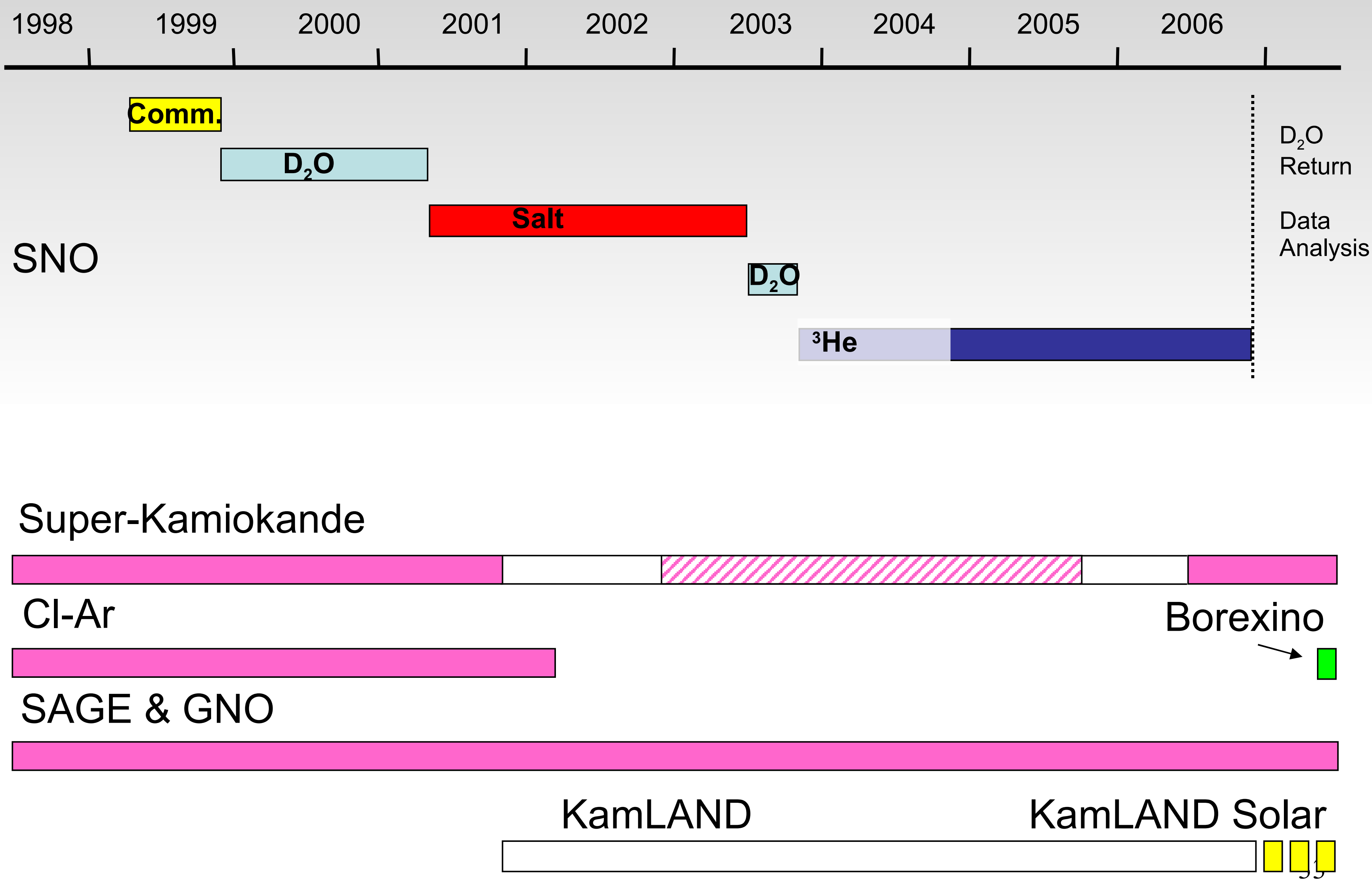
PMT PDFs are 3D



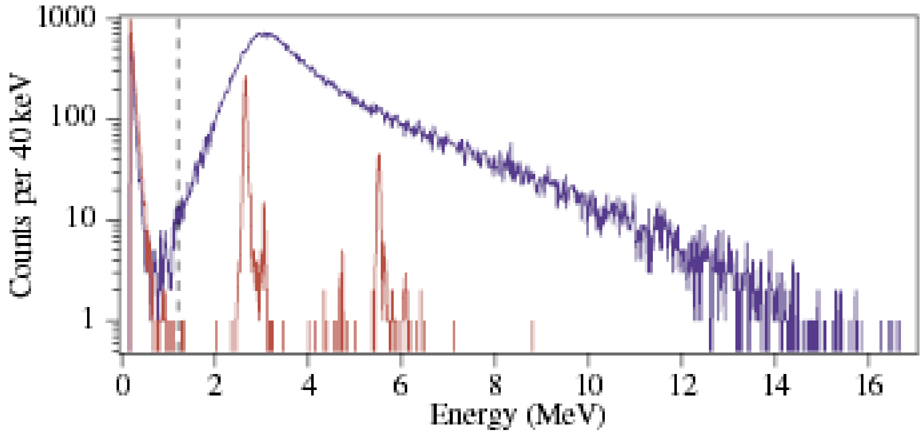
NCD PDFs are 1D



Recent Solar Neutrino Program

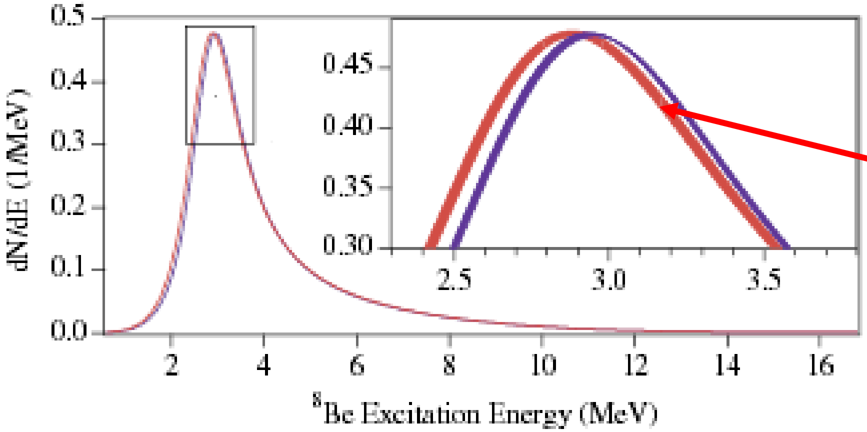


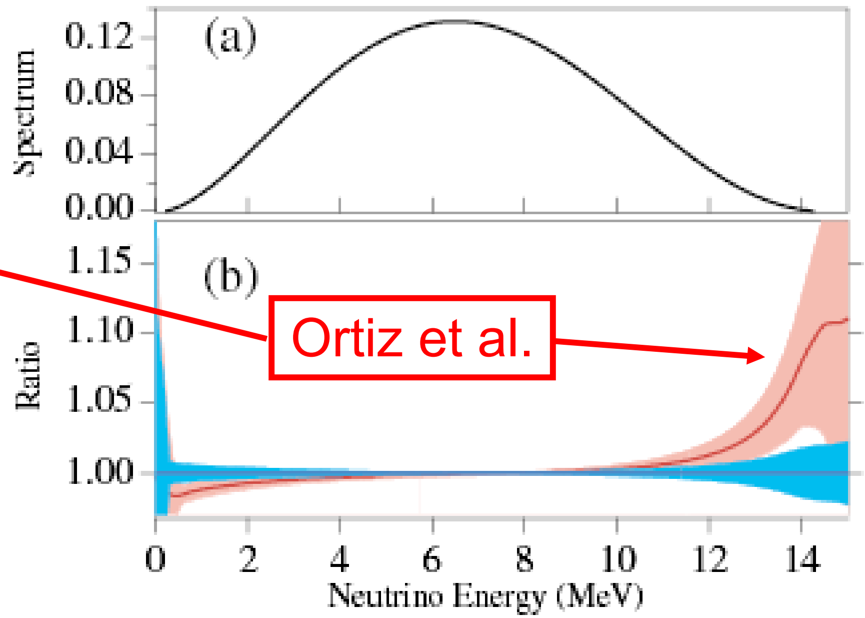
New Measurements of ^{8}B ν Spectrum



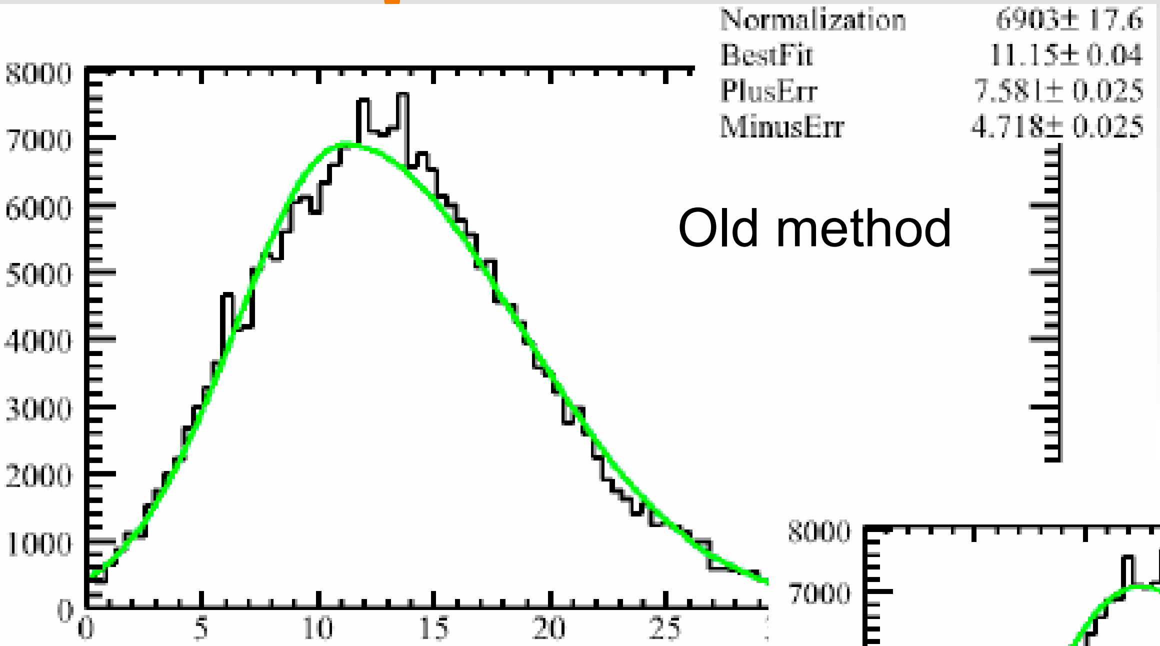
Winter, Freedman, et al. PRL **91** 252501, NP A746, 311 (2004).

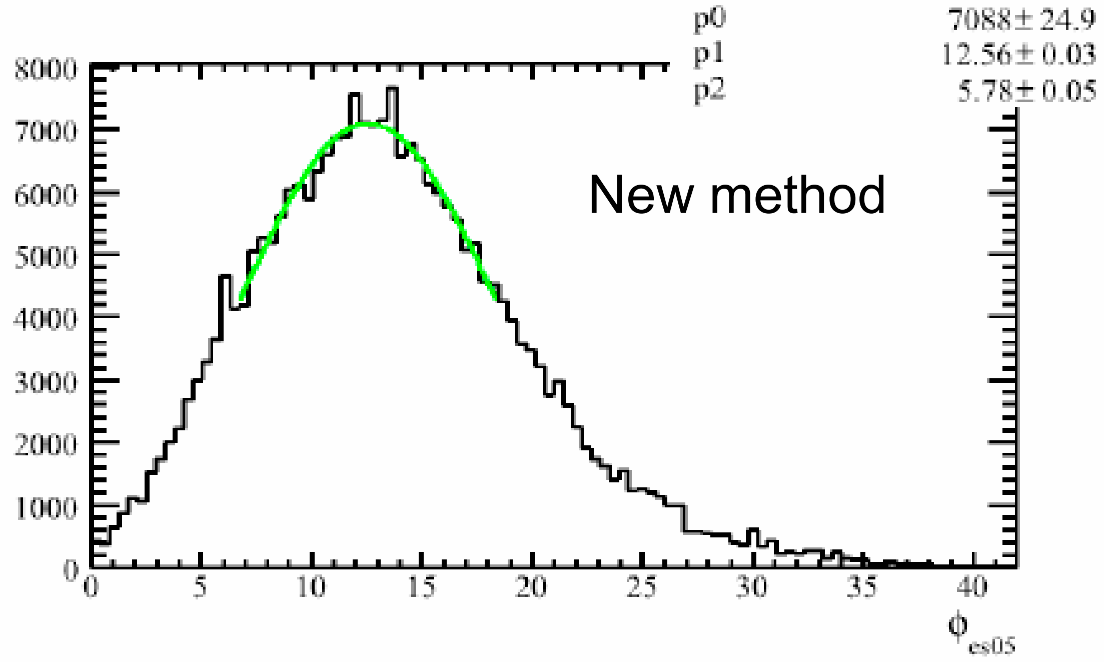
Bhattacharya et al. PRC **73**:055802,2006



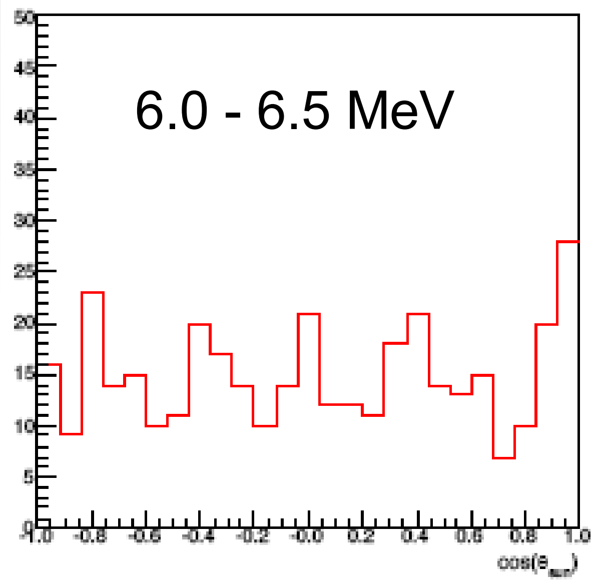


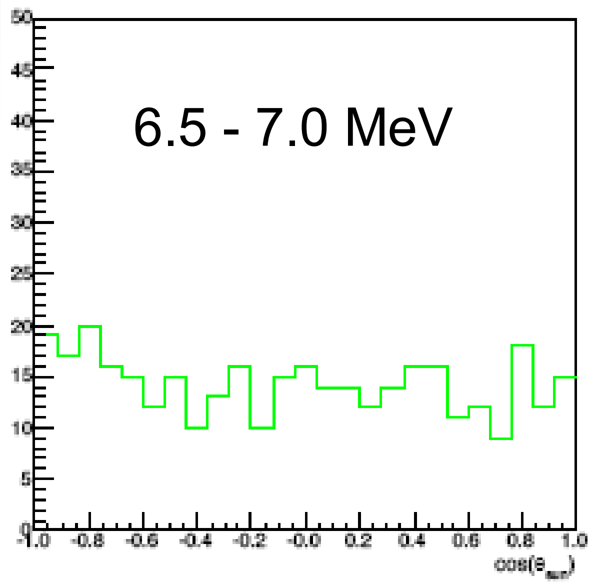
Change in estimate of best-fit to posterior distributions

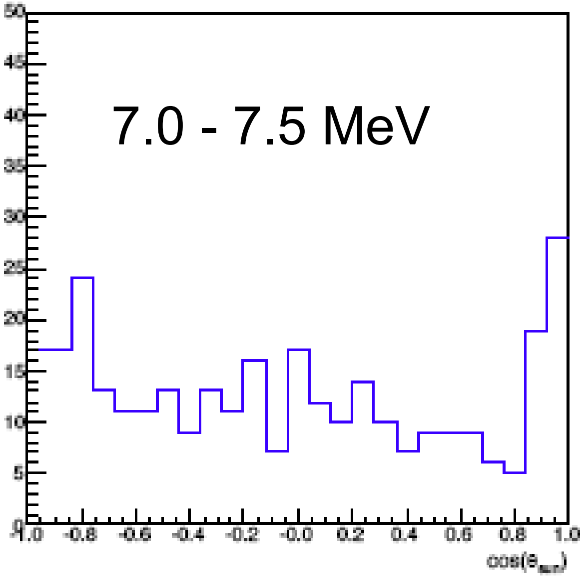


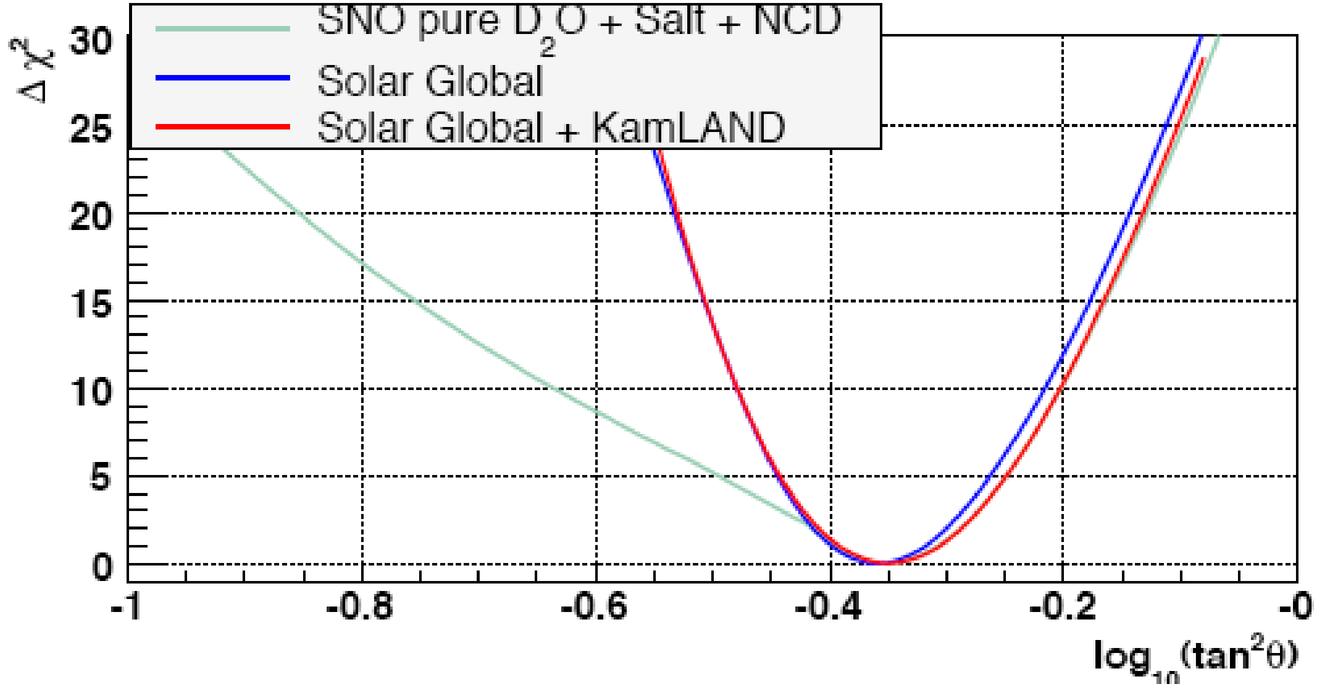


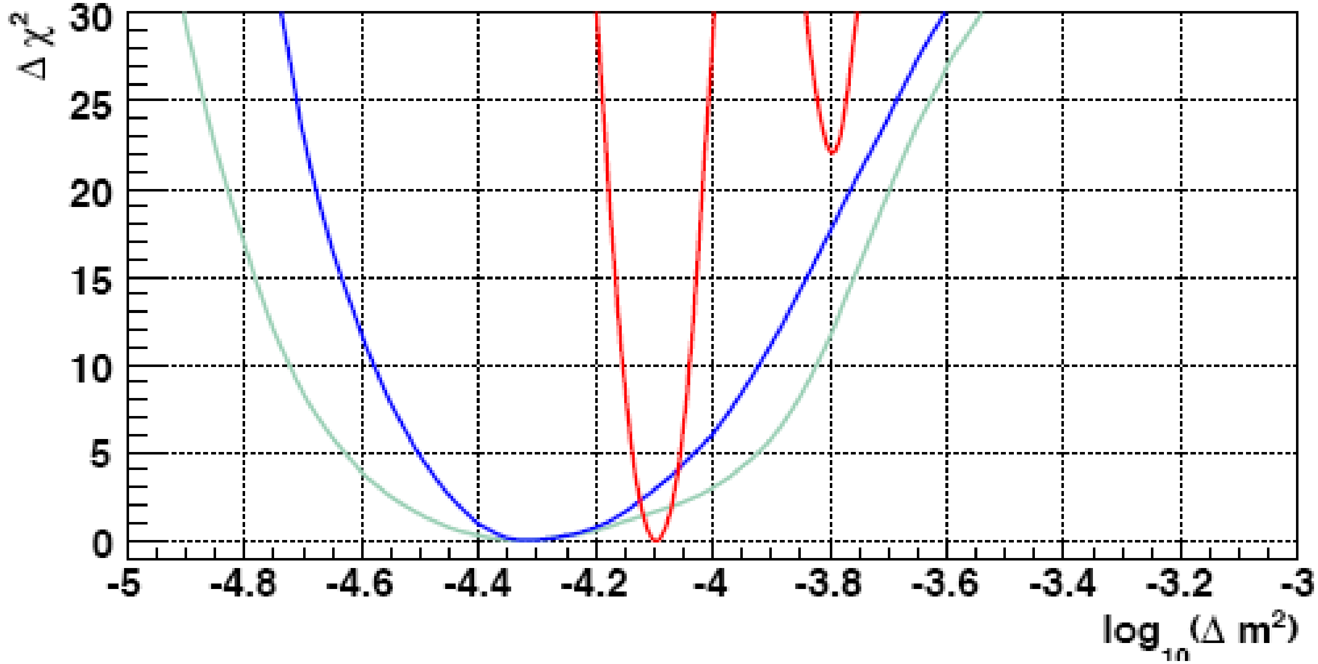
Angular distributions for ES in 3 Energy bins



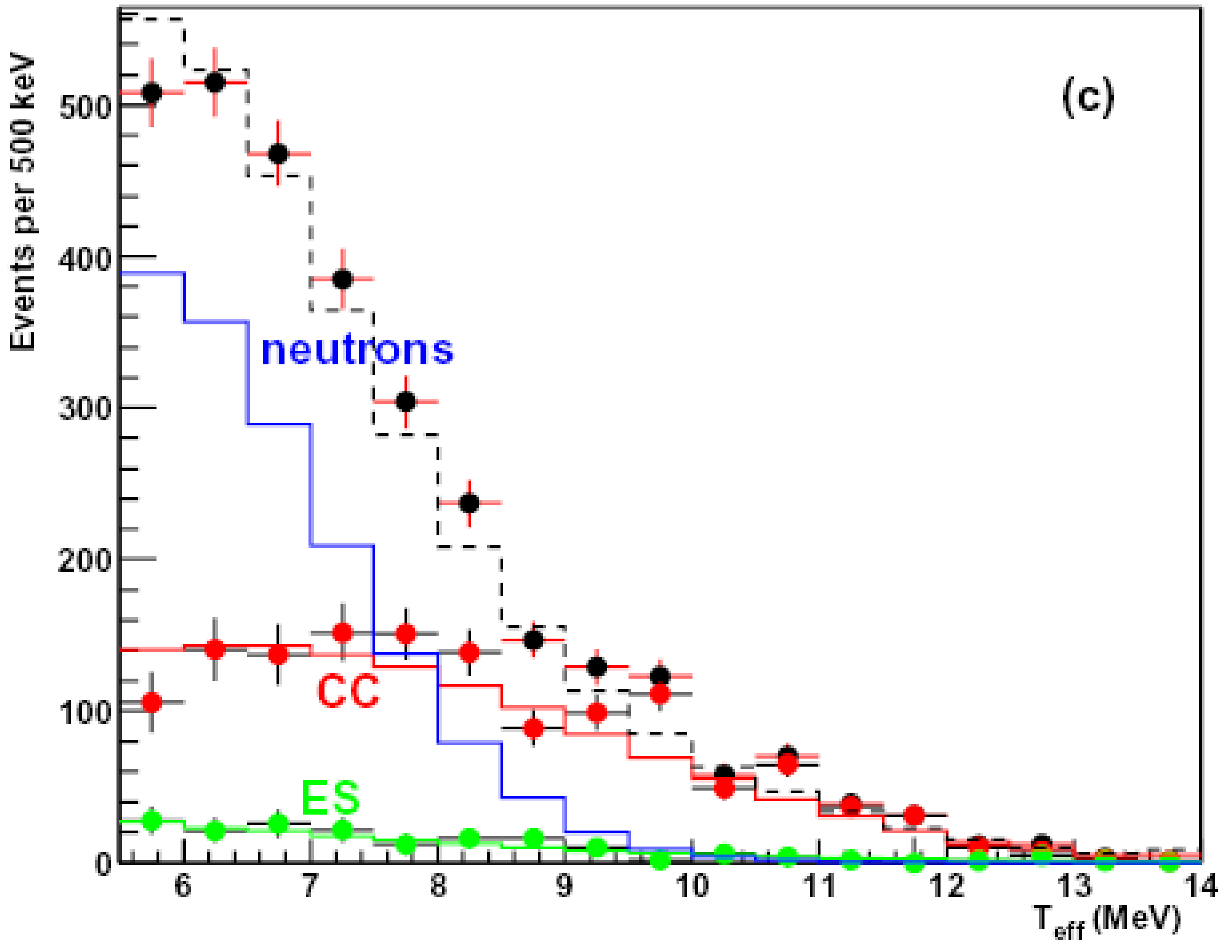





SNO pure D_2O + Salt + NCD
Solar Global
Solar Global + KamLAND
$\Delta\chi^2$
30
25
20
15
10
5
0
-1
-0.8
-0.6
-0.4
-0.2
-0
$\log_{10}(\tan^2\theta)$

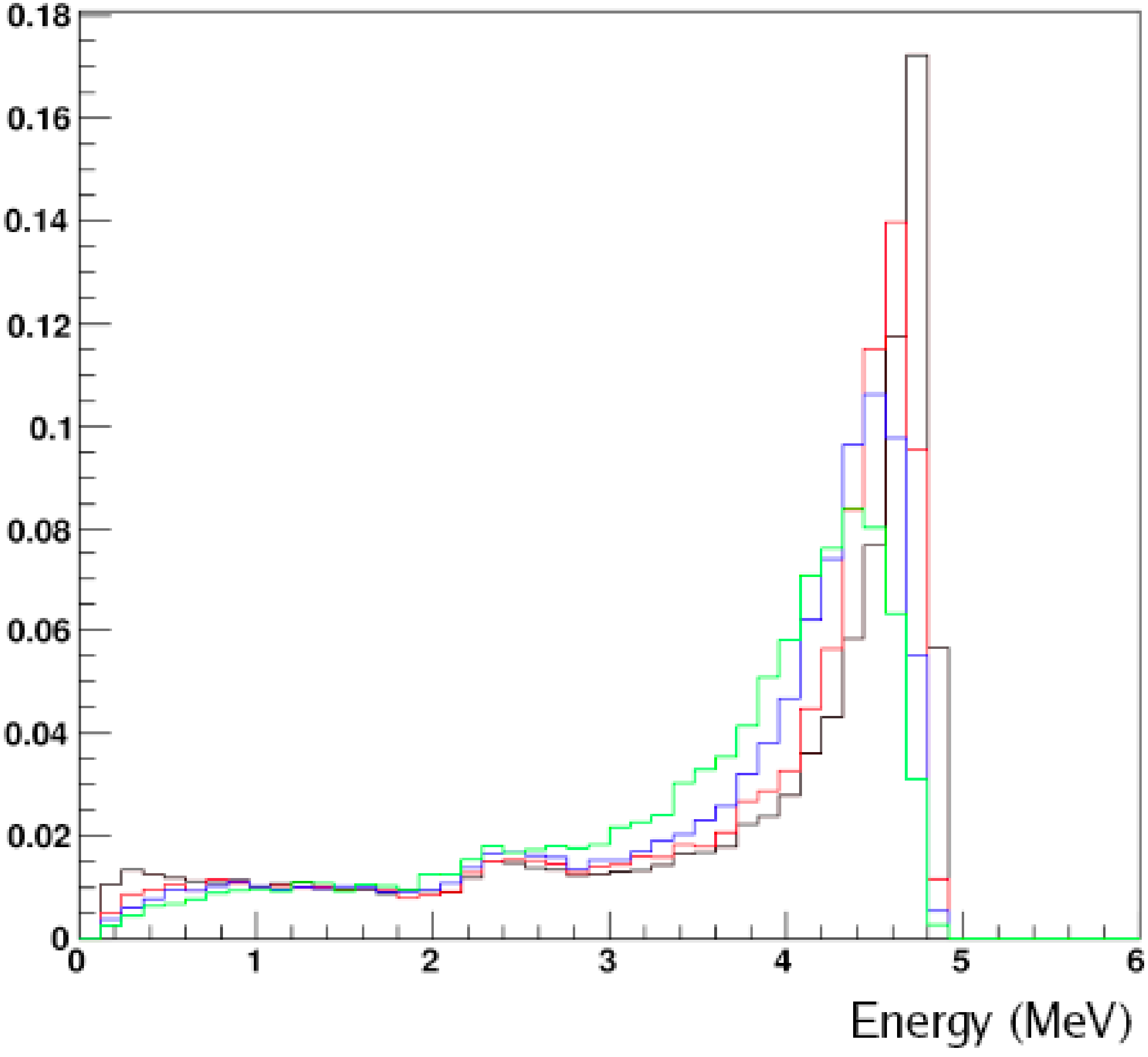

$\Delta\chi^2$
30
25
20
15
10
5
0
-5
-4.8
-4.6
-4.4
-4.2
-4
-3.8
-3.6
-3.4
-3.2
-3
$\log_{10}(\Delta m^2)$

Energy spectra, salt phase



Electron kinetic energy

Energy distribution assuming an embedded Po profile



Assume exponentially decreasing 210Po concentration inside nickel

Black: Surface Po
Red: 0.1 microns
Blue: 0.25 microns
Green: 0.5 microns

Cutting instrumental events