Results from SNO and New Directions in Solar Neutrino Experiments

Introduction

Recent SNO Results

NCD phase

Future Solar ν experiments

Keith Rielage on behalf of the
SNO Collaboration
INFO '05

CENPA
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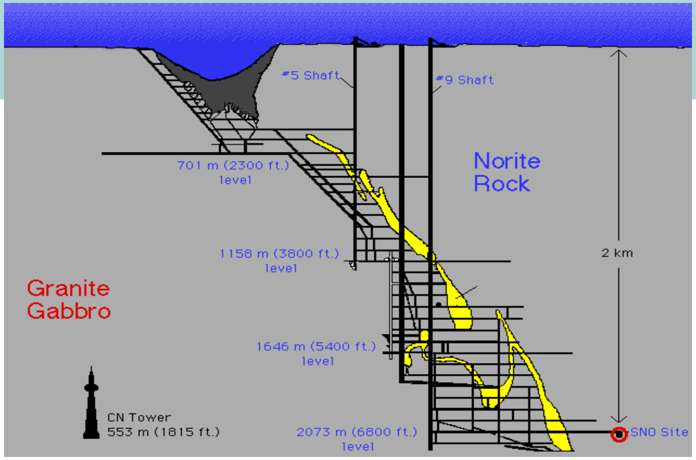
University of Washington

Sudbury Neutrino Observatory



1000 tonnes D_2O

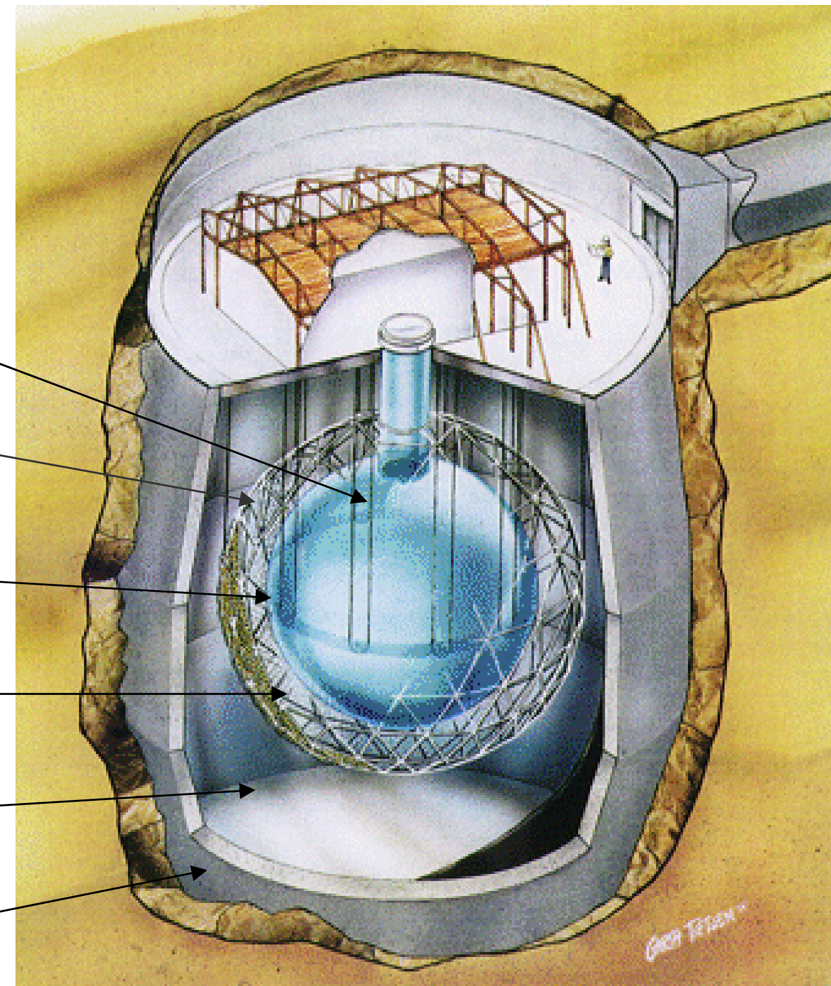
Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

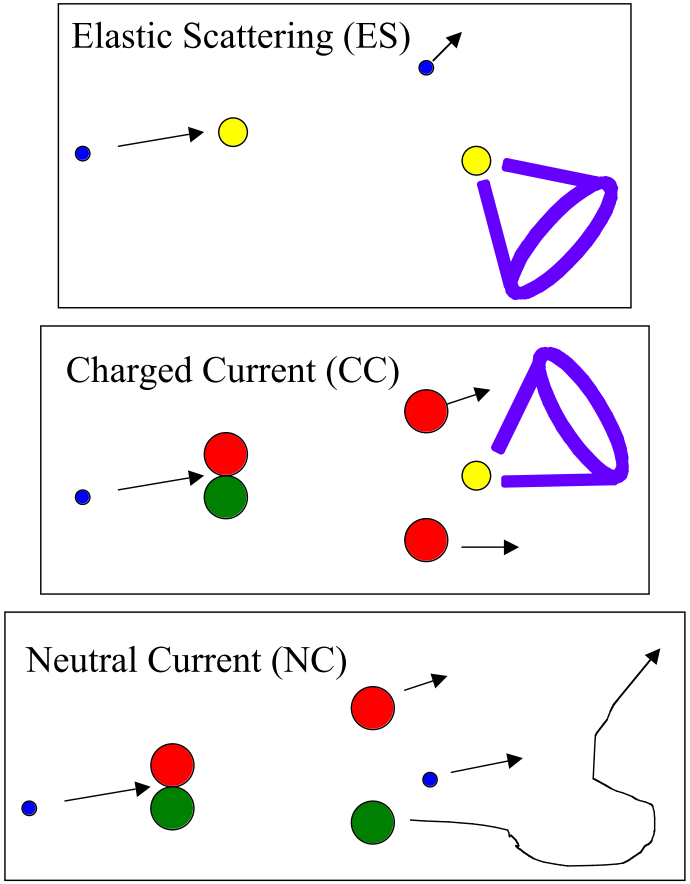
Urylon Liner and Radon Seal



Why SNO is Unique?

Neutrino interactions in heavy water:

- Elastic Scattering: $e^- + \nu_x \rightarrow e^- + \nu_x$
  - Mostly sensitive to ν_e.
  - Strong directional sensitivity.
- Charged Current: $d + \nu_e \rightarrow p + p + e^-$
  - Sensitive to ν_e only.
  - Can measure ν_e energy spectrum.
- Neutral Current: $d + \nu_x \rightarrow p + n + \nu_x$
  - Equally sensitive to all three flavors.
  - SNO is the only experiment that can measure this reaction.
- CC/NC ratio < 1 → definitive evidence of neutrino flavor change.



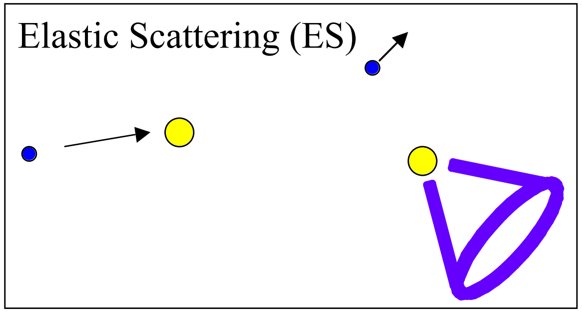
Why SNO is Unique?

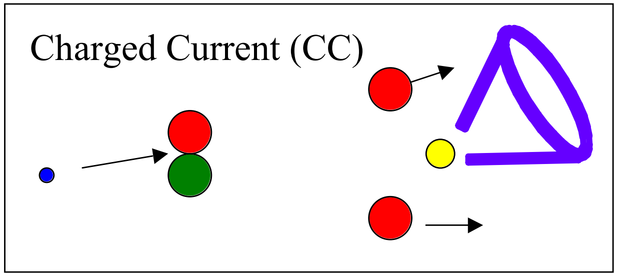
Key physics signatures

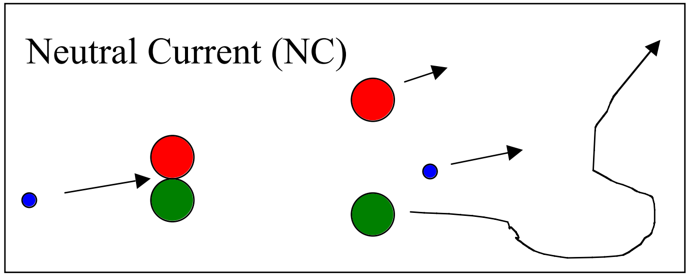
$$\frac{\Phi_{cc}}{\Phi_{nc}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

$$\frac{\Phi_{cc}}{\Phi_{es}} = \frac{\nu_e}{\nu_e + 0.154(\nu_\mu + \nu_\tau)}$$

$$\Phi_{day} \quad \text{vs} \quad \Phi_{night}$$



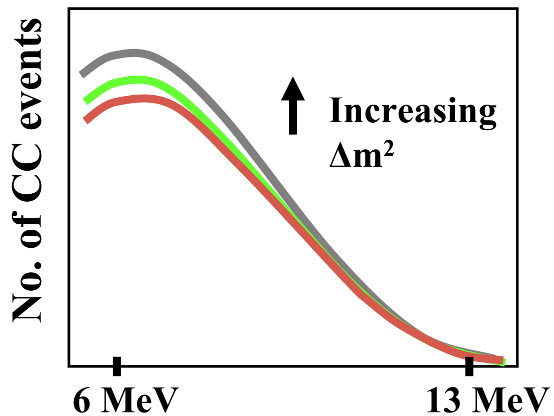




Solar Neutrino Physics with SNO

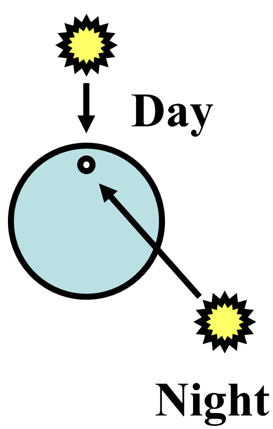
MSW Signatures	MSW Parameter Constraints

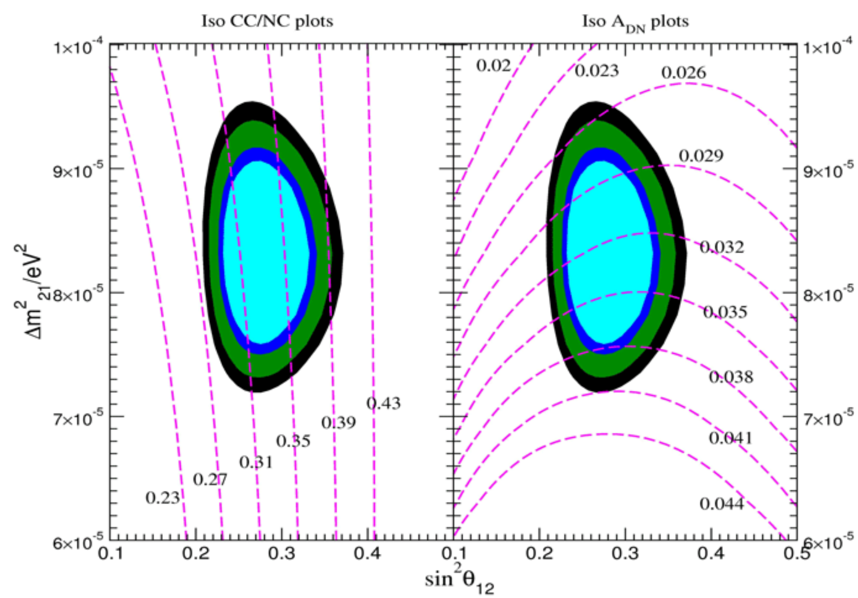
Spectrum



Day-Night Asymmetry:

$$A_e \equiv \frac{2(N_e - D_e)}{N_e + D_e}$$





hep-ph/0406328 July 21 2004 Bandyopadhyay, Choubey, Goswami, Petcov, and Roy

Global analysis of solar neutrino and KamLAND data from 2004

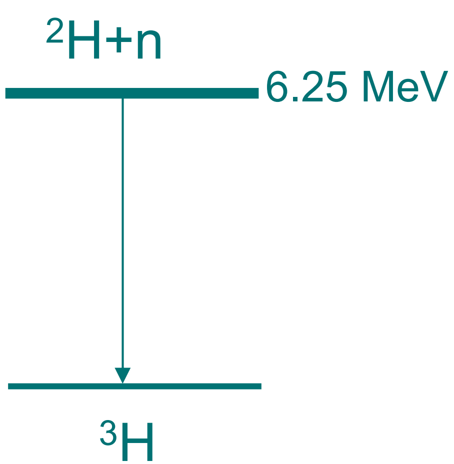
SNO measurements of CC/NC, spectrum, and day-night asymmetry contribute to MSW constraints

SNO - 3 neutron detection methods

Phase I (D_2O)

Nov. 99 - May 01

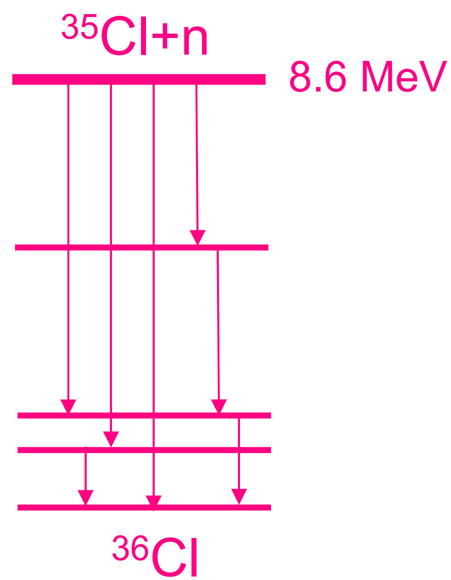
n captures on
$^2H(n, \gamma)^3H$
σ = 0.0005 b
Observe 6.25 MeV γ
PMT array readout
Good CC



Phase II (salt)

July 01 - Sep. 03

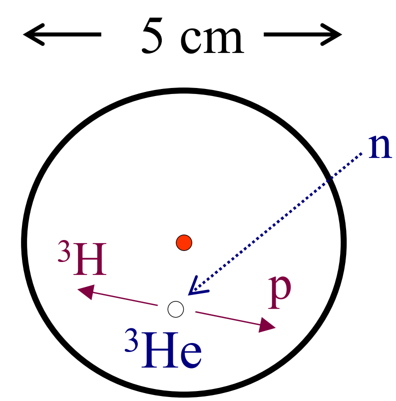
2 t NaCl. n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
σ = 44 b
Observe multiple γ's
PMT array readout
Enhanced NC



Phase III (^3He)

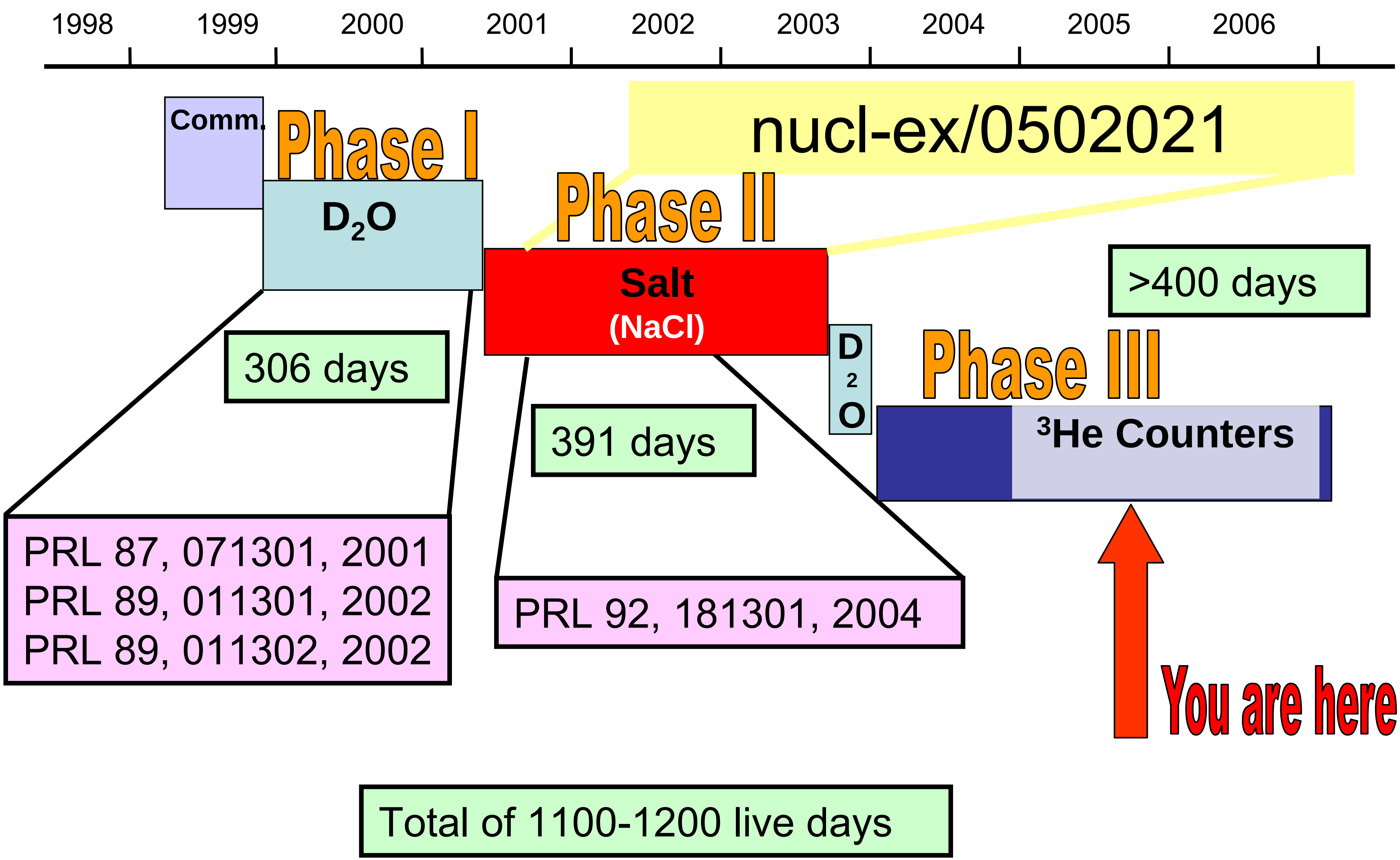
Nov. 04 - Dec. 06

40 proportional counters
$^3He(n, p)^3H$
σ = 5330 b
Observe p and ^3H
PC independent readout
Event by Event Det.



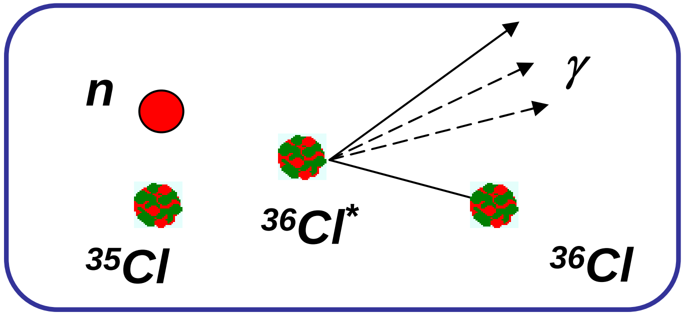
$$n + {}^3He \rightarrow p + {}^3H$$

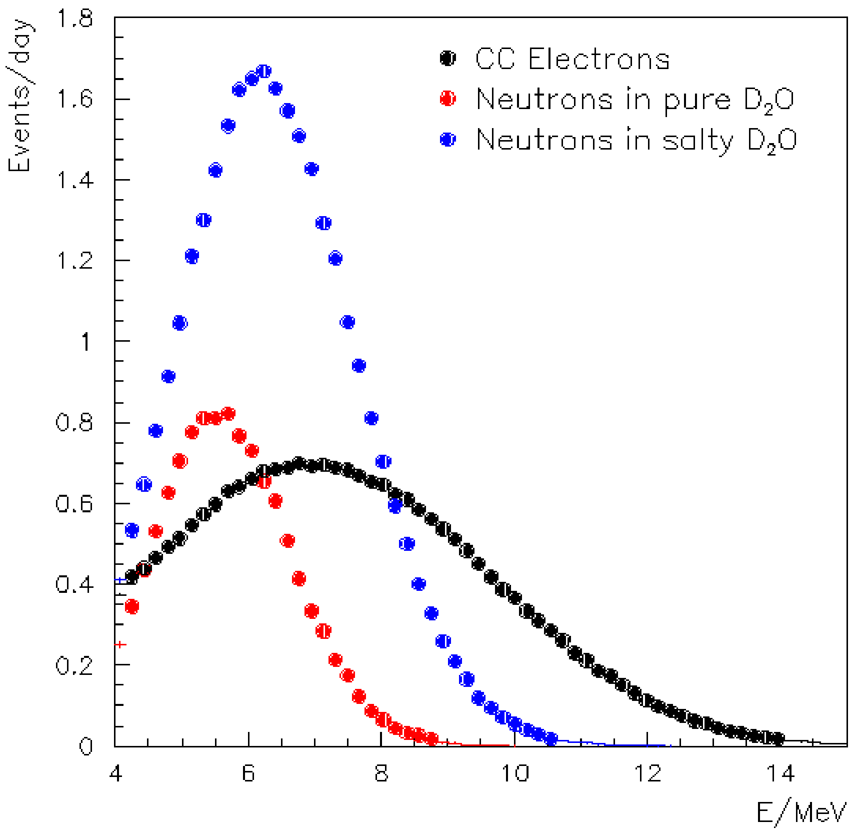
SNO Measurement Phases



Advantages of Salt

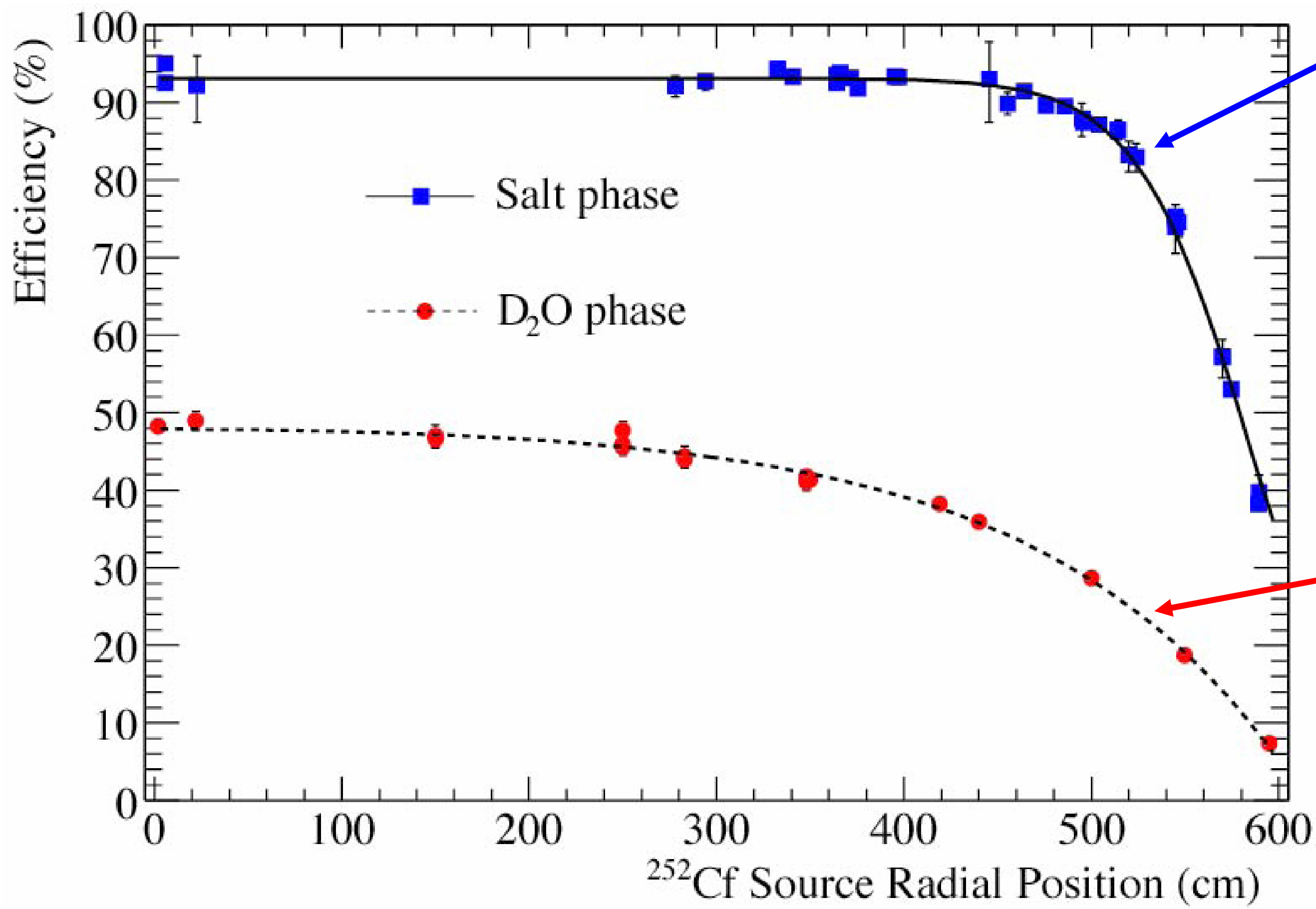
- Neutrons capturing on ^{35}Cl provide higher neutron energy above threshold.
- Higher capture efficiency
- Gamma cascade changes the angular profile.





Neutron Capture Efficiency in SNO

Salt Phase



$^{35}Cl(n,\gamma)^{36}Cl$

Net Average Efficiency 39.9%

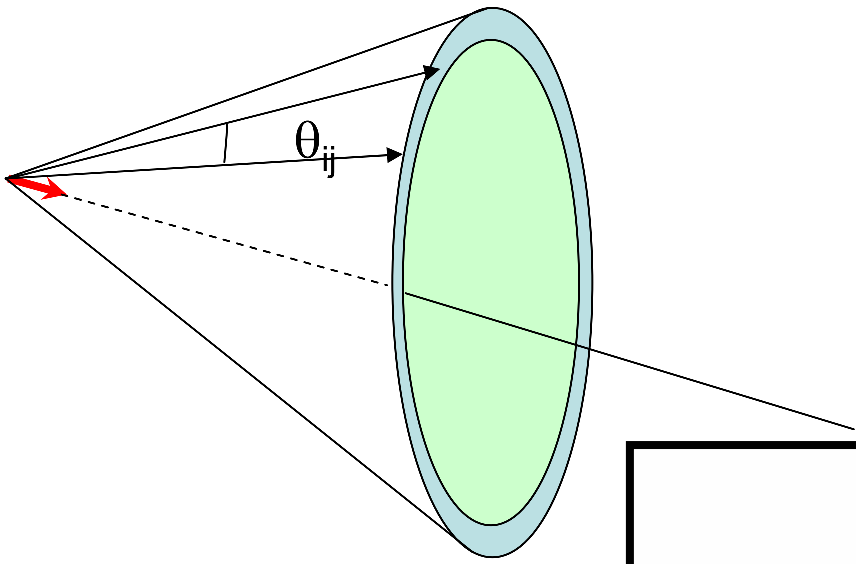
$T_e \geq 5.5$ MeV and $R_\gamma \leq 550$ cm

$^{2}H(n,\gamma)^{3}H$

Net Average Efficiency 14.4%

$T_e \geq 5.0$ MeV and $R_\gamma \leq 550$ cm

Cherenkov light and β_{14}



Charged particle light cone

↓

Legendre expansion of angular distribution

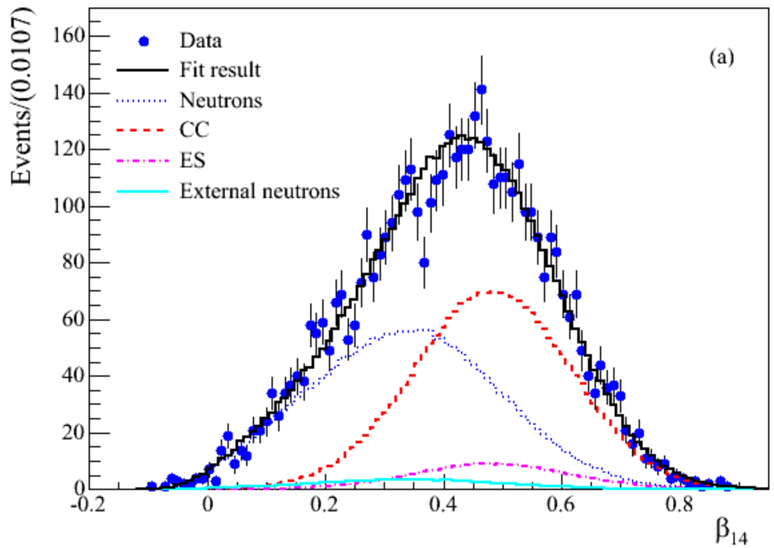
$$\beta_1 = \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} cos\theta_{ij}$$

$$\beta_4 = \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{1}{64}(9 + 20cos2\theta_{ij} + 35cos4\theta_{ij})$$

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

391 Day Salt Results

Salt Phase



Extracted Events:

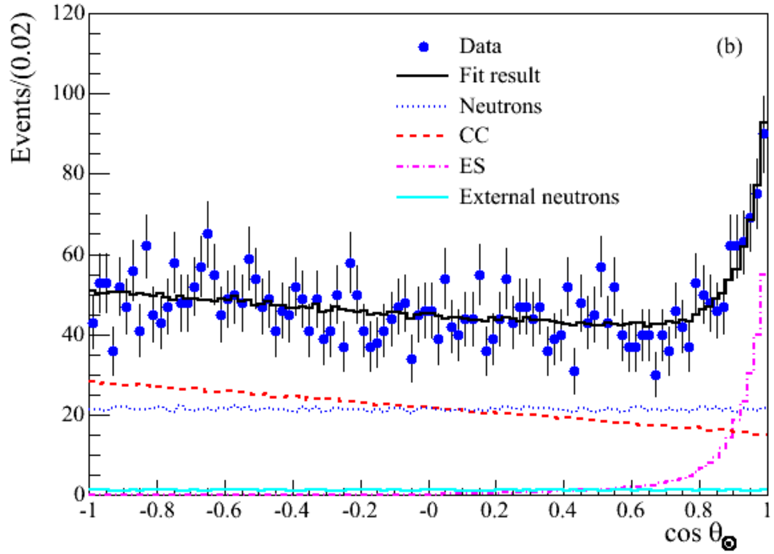
CC: 2176 ± 78

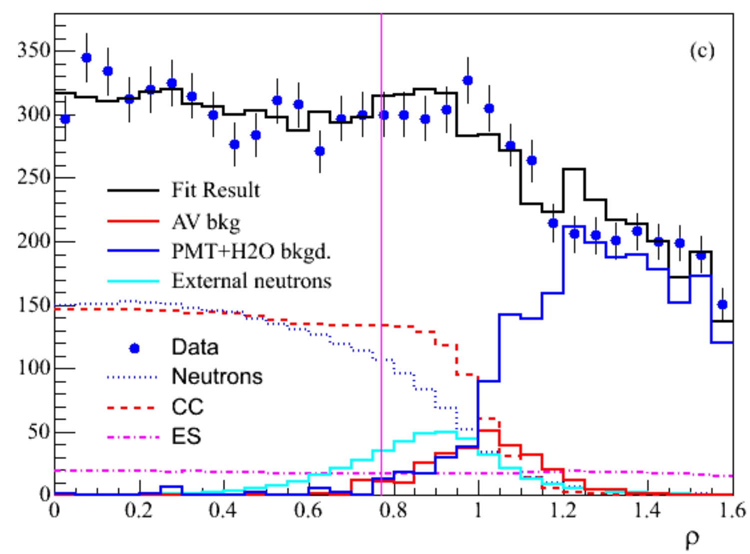
NC: 2010 ± 85

ES: 279 ± 26

External neutrons: 128 ± 42

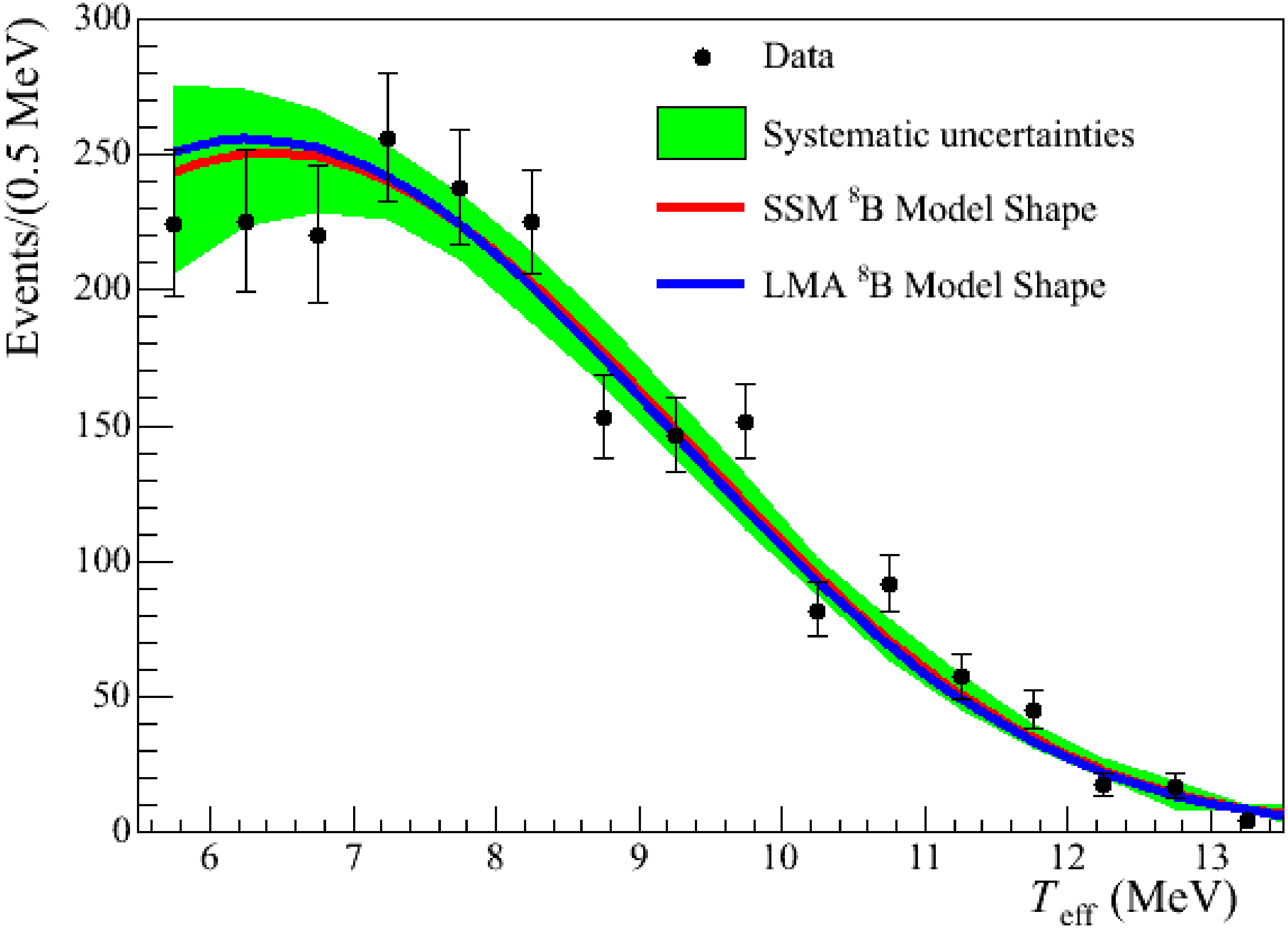
Backgrounds fixed in fit: 128





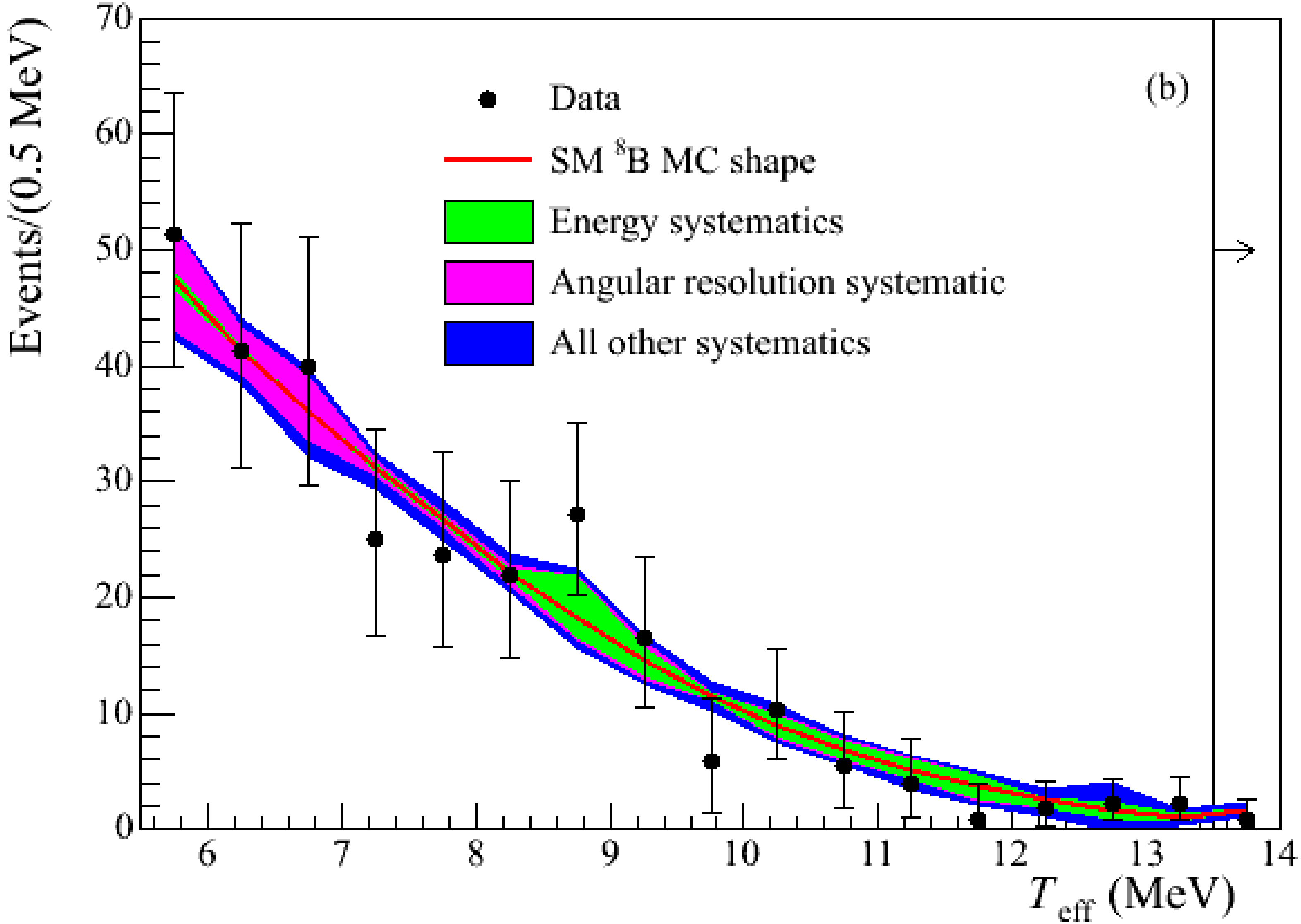
Predicted LMA CC spectral distortion

Salt Phase



Elastic Scattering Spectrum

Salt Phase



Energy-Unconstrained Fluxes

Salt Phase

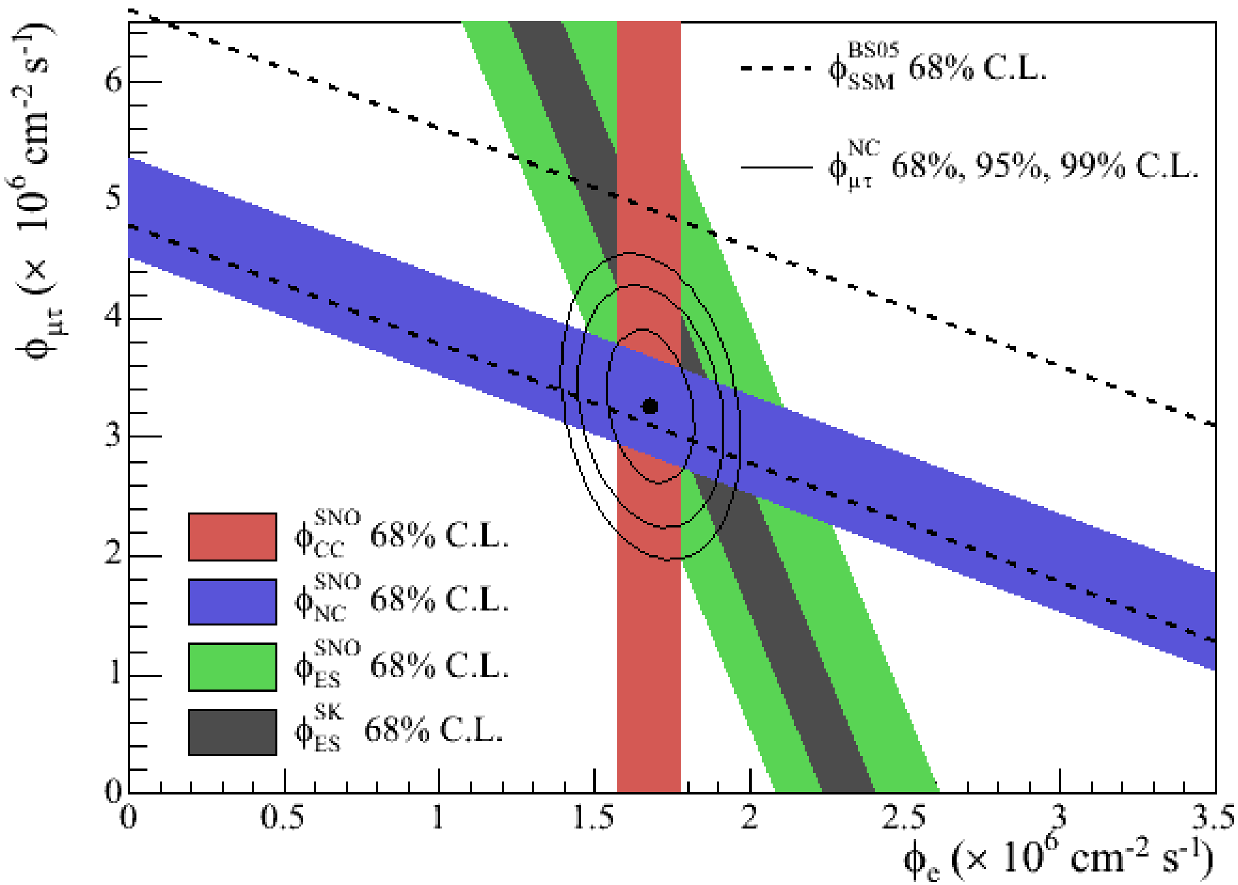
$$\phi_{CC} = 1.68\ ^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

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

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

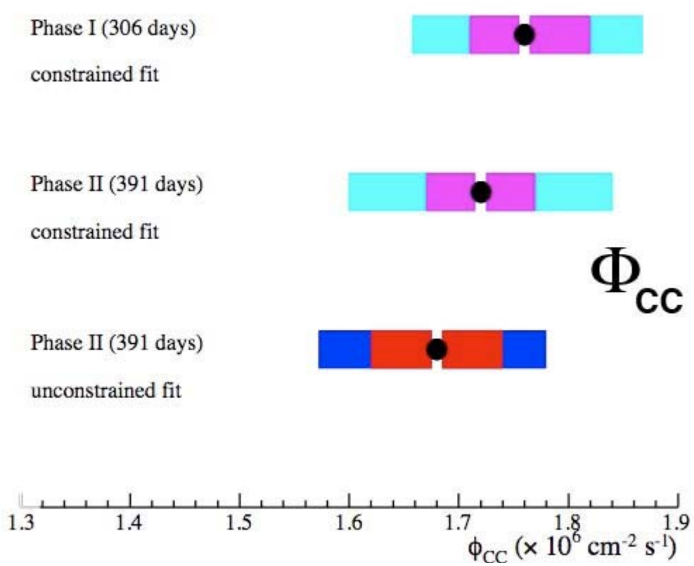
(In units of $10^6\,\text{cm}^{-2}\text{s}^{-1}$)

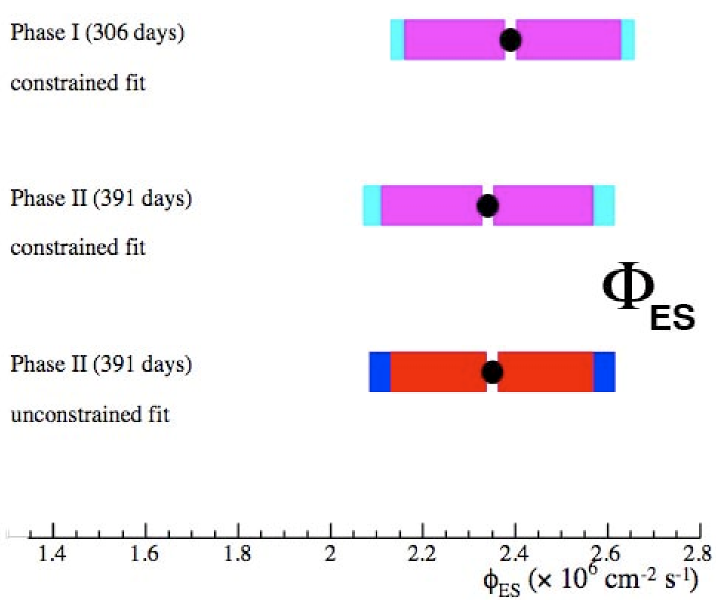
$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}$$

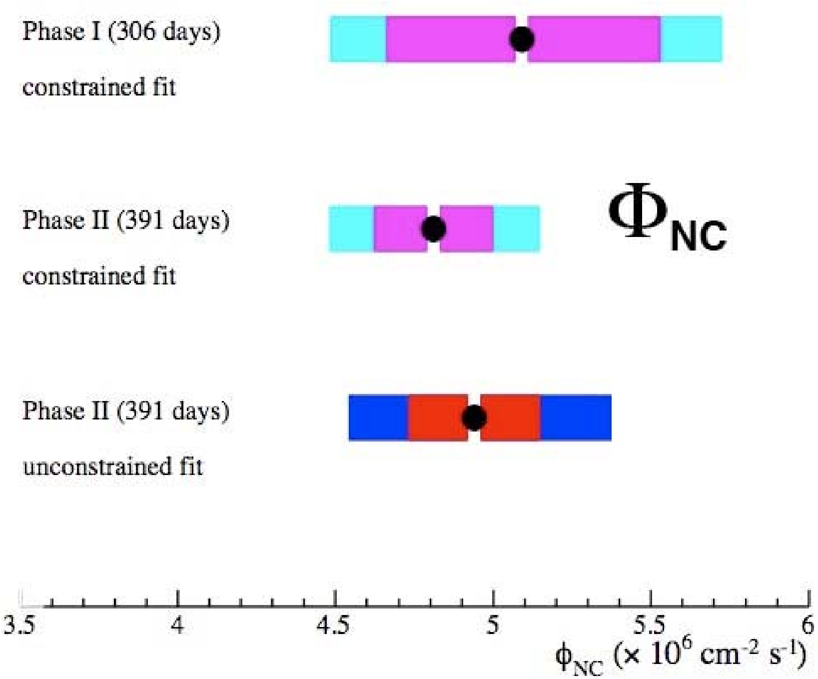


SNO flux results - Summary

Salt Phase







Day Night Asymmetries

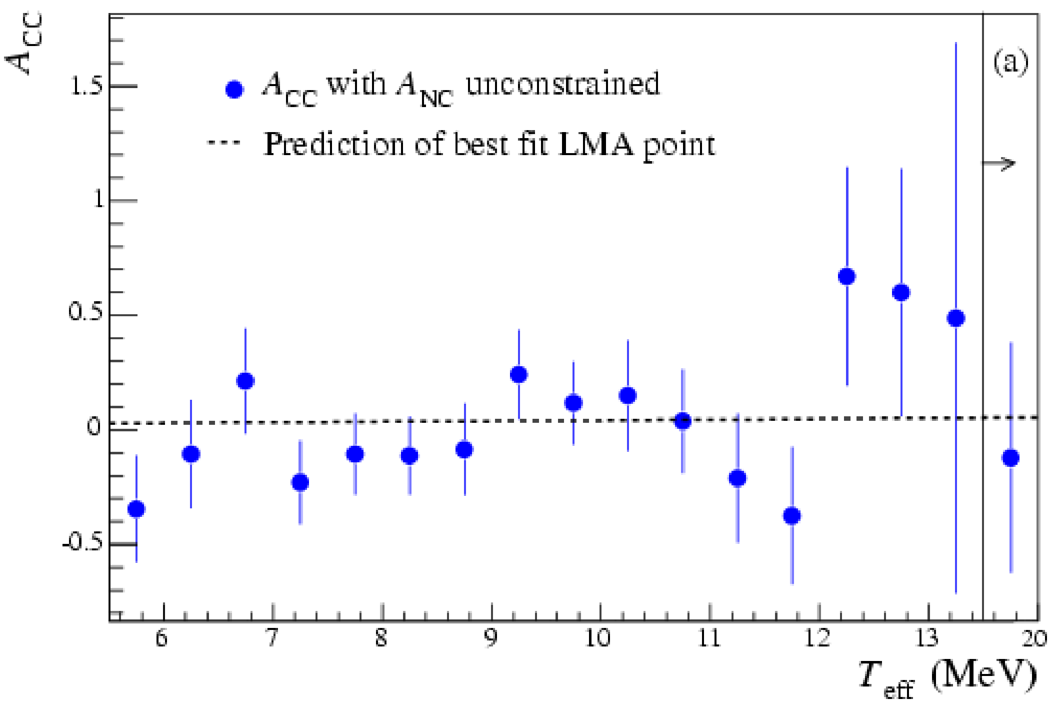
Salt Phase

A_{CC}= -0.056 ± 0.074 (stat.) ± 0.051 (syst.)

A_{NC}= 0.042 ± 0.086(stat.) ± 0.067 (syst.)

A_{ES}= 0.146 ± 0.198(stat.) ± 0.032 (syst.)

$$\left(A \equiv \frac{2(N-D)}{N+D} \right)$$

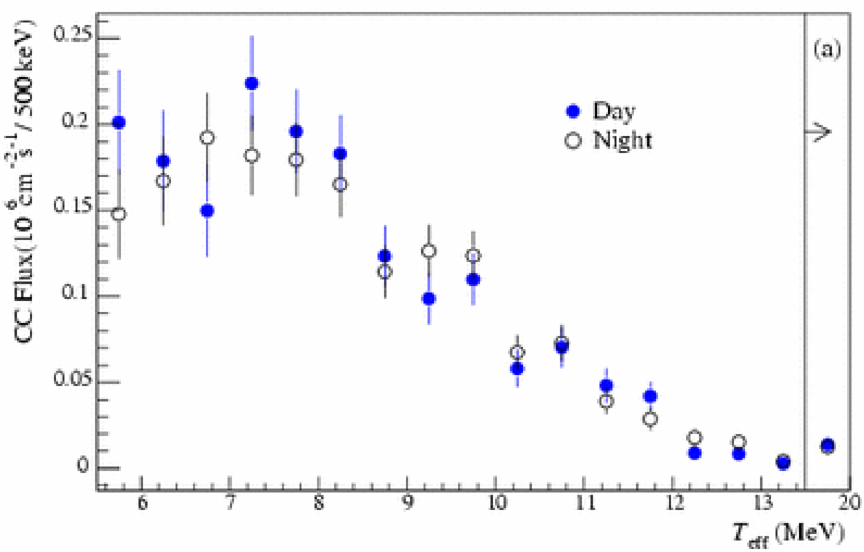


A_{CC} and A_{NC} are correlated (ρ = -0.532)

In standard neutrino oscillations, A_{NC} should be zero…

Day Night Asymmetries

Salt Phase



$$\left(A \equiv \frac{2(N-D)}{N+D} \right)$$

Constraining A_{NC} to be zero:

A_{CC}= -0.037 ± 0.063(stat.) ±0.032(syst.)

A_{ES}= 0.153 ± 0.198(stat.) ±0.030(syst.)

In the pure-D2O phase,

$$A_e = 0.070 \pm 0.049 \; {}^{+0.013}_{-0.012}$$

(shape constrained, A_{NC} constrained)

Combine with analogous A_{CC} from the salt phase:

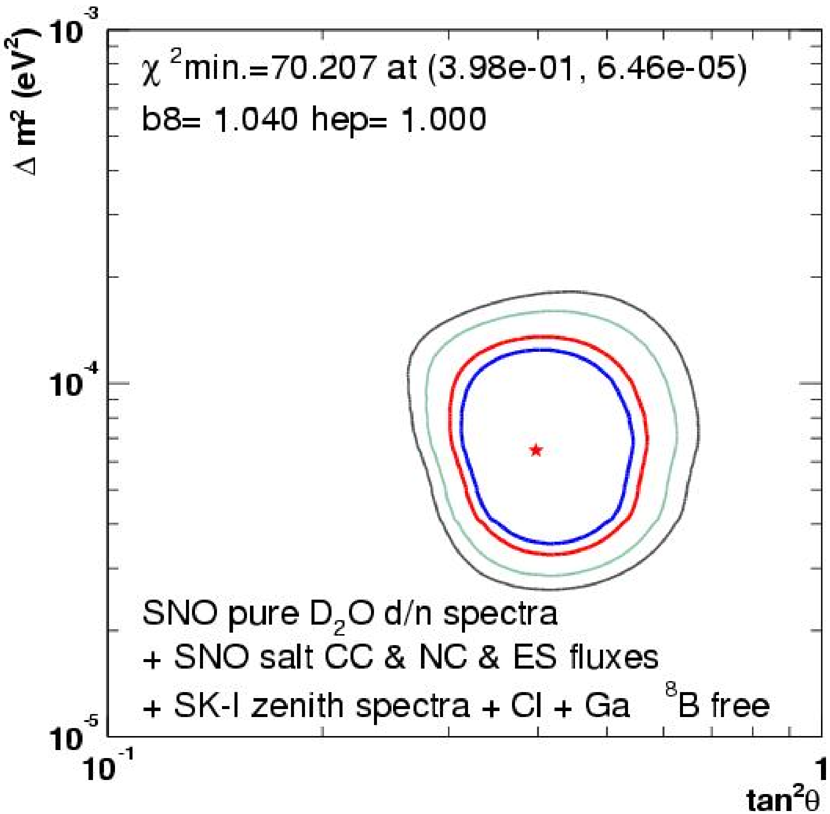
$$A_{salt + D_2O} = 0.037 \pm 0.040$$

Convert Super-Kamiokande A_{ES} to A_e, and combine with SNO:

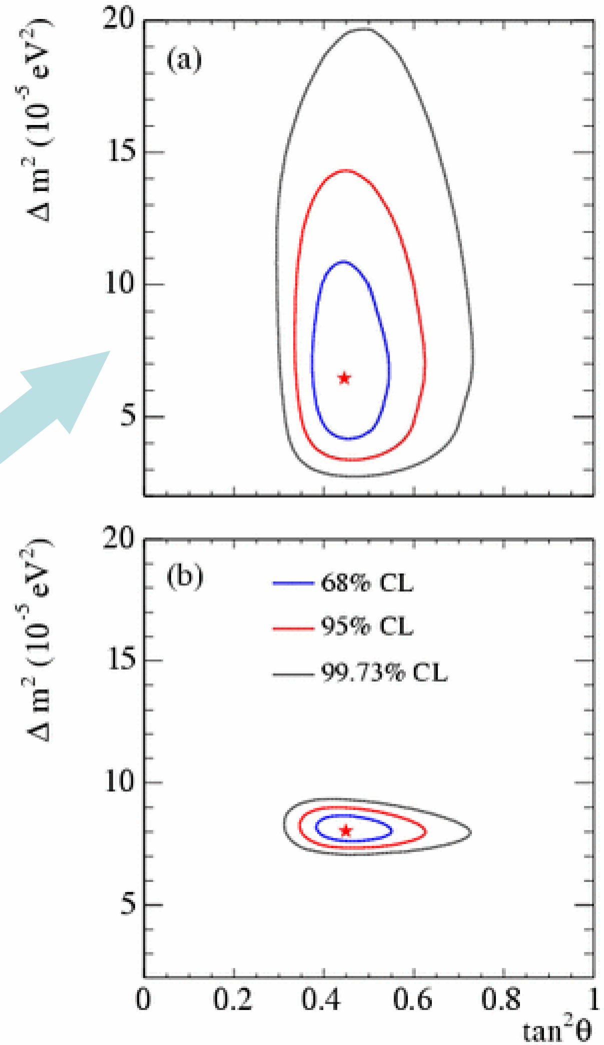
$$A_{SNO + SK} = 0.035 \pm 0.027$$

MSW Constraints

Salt Phase



Previous global analysis of solar neutrino data



Global Solar, with new salt results

Global Solar + KamLAND 766 ton-year data

$$\text{a) } \Delta m^2 = 6.5^{+4.4}_{-2.3} \times 10^{-5}\,\text{eV}^2, \quad \tan^2\theta = 0.45^{+0.09}_{-0.08}$$

$$\text{b) } \Delta m^2 = 8.0^{+0.6}_{-0.4} \times 10^{-5}\,\text{eV}^2, \quad \tan^2\theta = 0.45^{+0.09}_{-0.07}$$

What is next?

- Lower energy threshold for combined analysis of the full salt and D_2O data sets
- Looking at hep
- NCD phase ....

The SNO Neutral Current Detectors

^{3}He Phase

- First two phases of SNO relied on statistical separation of NC, CC, and ES signals using energy, radial distribution, angle with respect to the sun, and isotropy (salt phase only).
- Third phase has separate system to detect neutrons from NC interactions, so no statistical separation necessary.
- NCD Phase - Nov. 2004 through end of 2006:
  - Salt removed.
  - Array of ^{3}He proportional counters (Neutral Current Detectors) deployed into heavy water.
  - Neutron capture on ^{3}He in NCDs (σ = 5330 b):

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

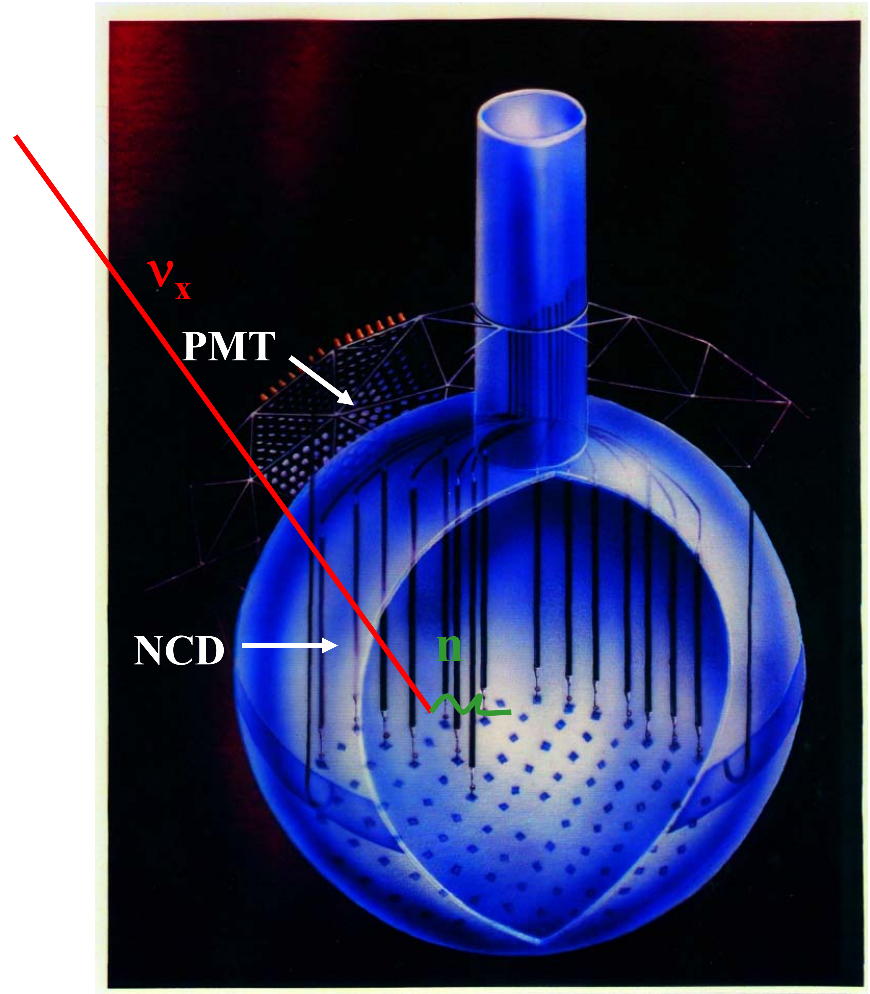
Benefits of the NCDs

Physics Motivation

Event-by-event separation. Measure NC and CC in separate data streams.

Different systematic uncertainties than neutron capture on NaCl.

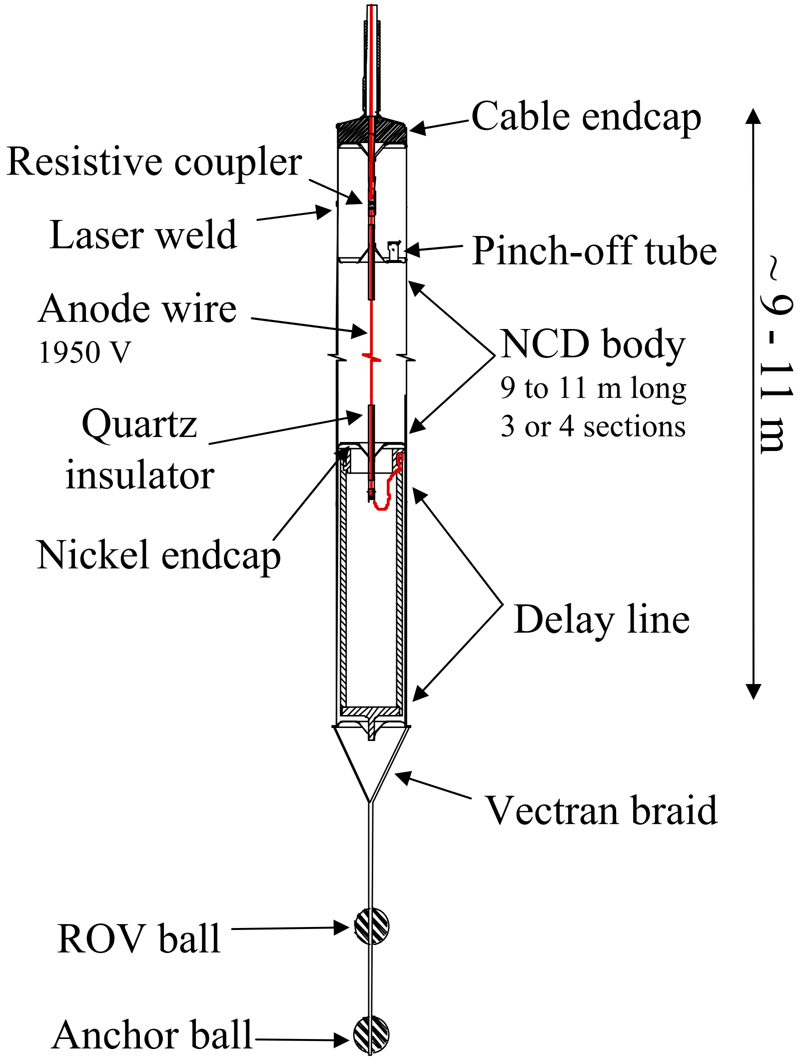
^{3}He array removes neutrons from CC, calibrates remainder. CC spectral shape.



The SNO Neutral Current Detectors

^3He Phase

- Proportional counters detect neutrons via: $n + {}^3He \rightarrow p + {}^3H$.
- Low radioactivity CVD nickel, 5 cm diameter, 0.36 mm thick.
- Gas is 85% ^3He and 15% CF_4, at ~ 2.5 atm.
- Anchored to the bottom of SNO on a 1-meter square grid.
- 40 strings, each 9 to 11 meters long, 398 meters total length.
- 50 µm copper anode wire at 1950 V.

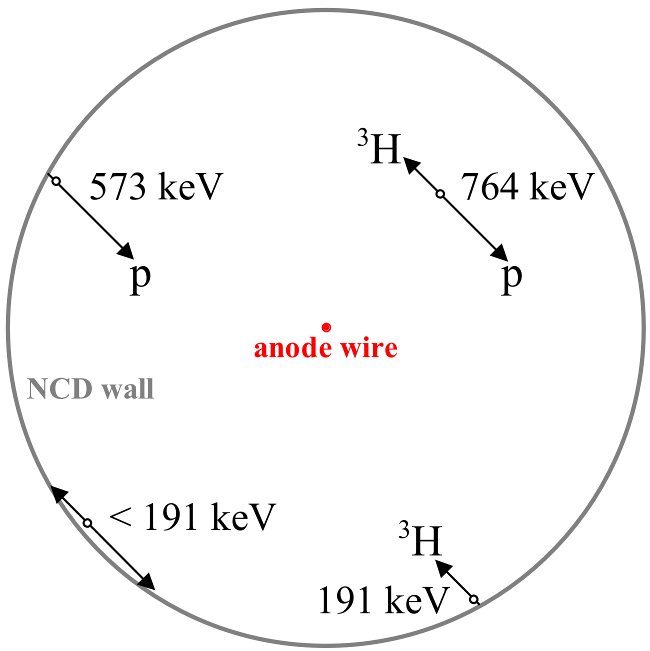


Neutron Capture in the NCDs

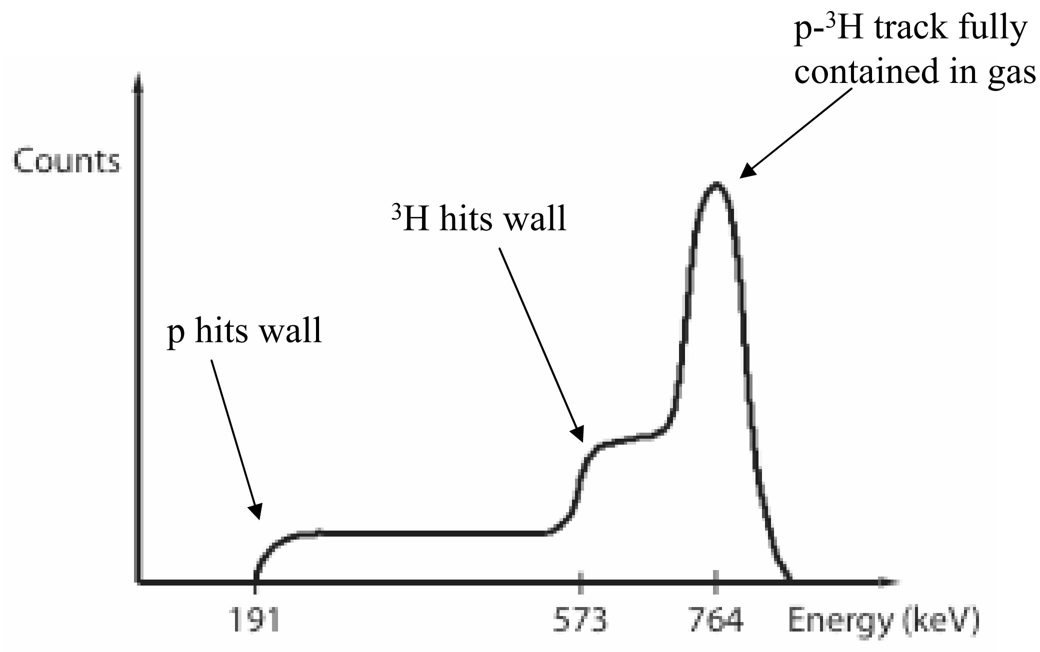
^{3}He Phase

~ 1200 n captures per year in NCDs from solar ν

$$n + {}^3\text{He} \rightarrow p + {}^3\text{H} \quad (Q = 764\ \text{keV})$$



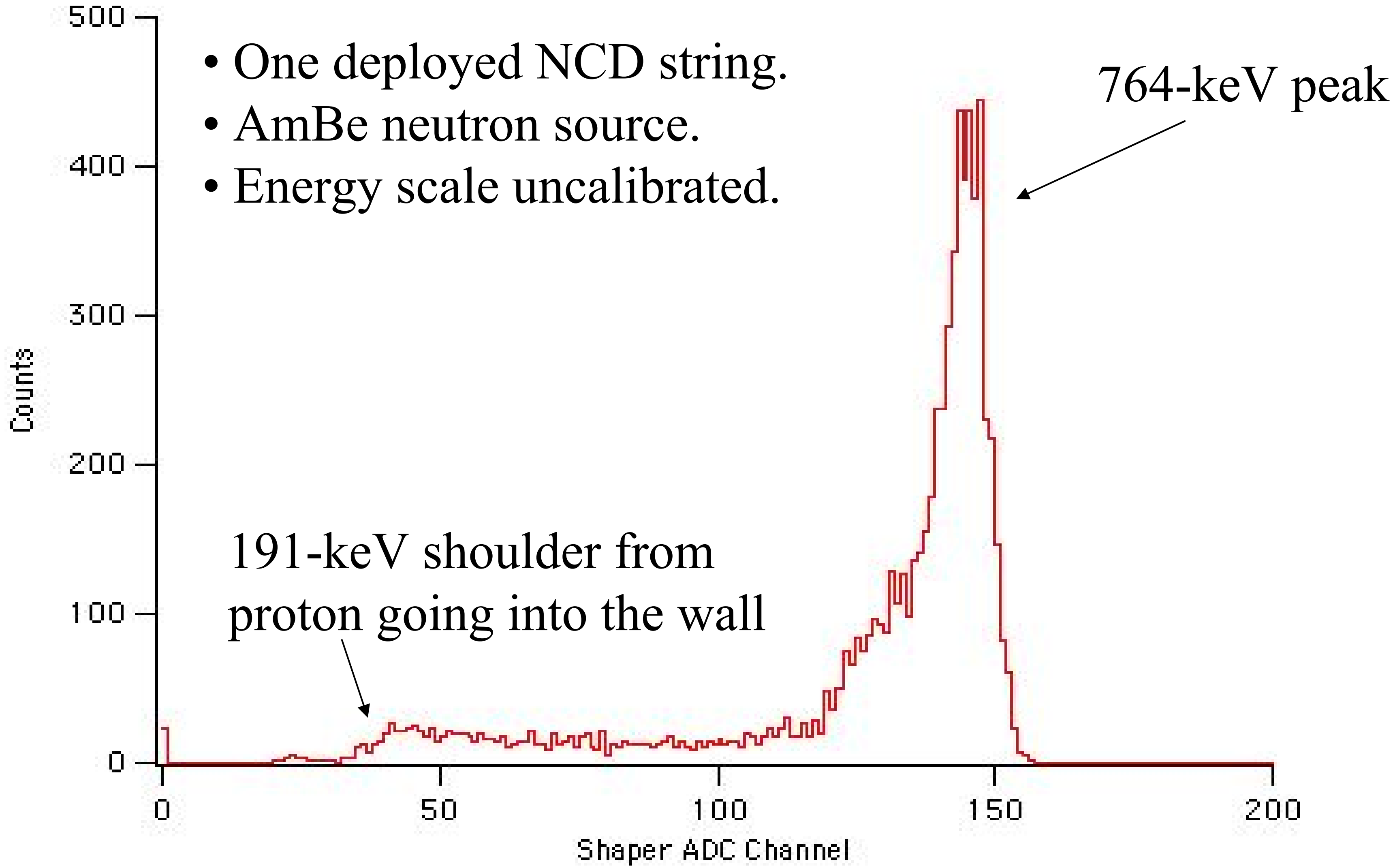
End view of an NCD with representative ionization tracks.



Idealized energy spectrum in a ^{3}He proportional counter.

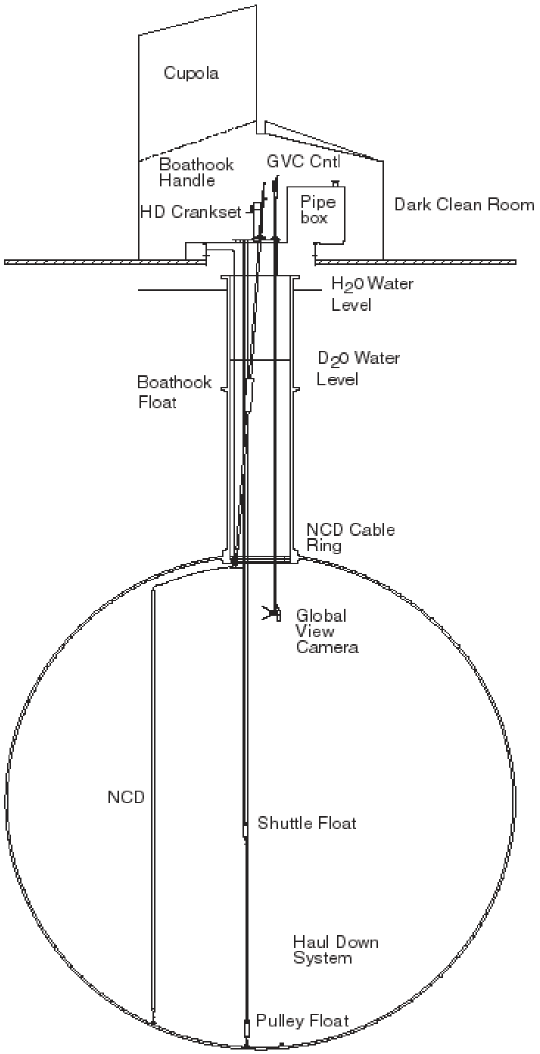
Neutron Energy Spectrum

^{3}He Phase

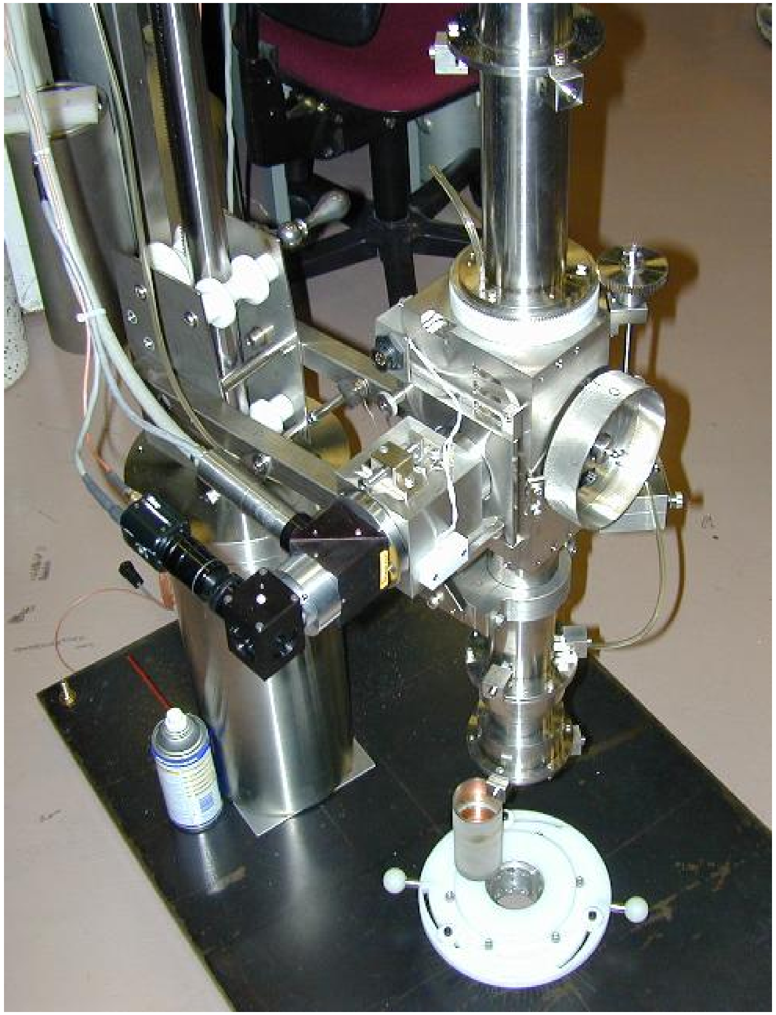


Deployment Constraints

- Desired NCD string length = 9 - 11 meters.
- Elevator size = 3 meters.
- Detector sections ≤ 3 meters long.
- Sections had to be electrically connected and welded together underground.
- Roof height = 5.5 meters.
- Many of the welds were done above the open detector, where cleanliness is most critical.
- No data taken during NCD deployment.



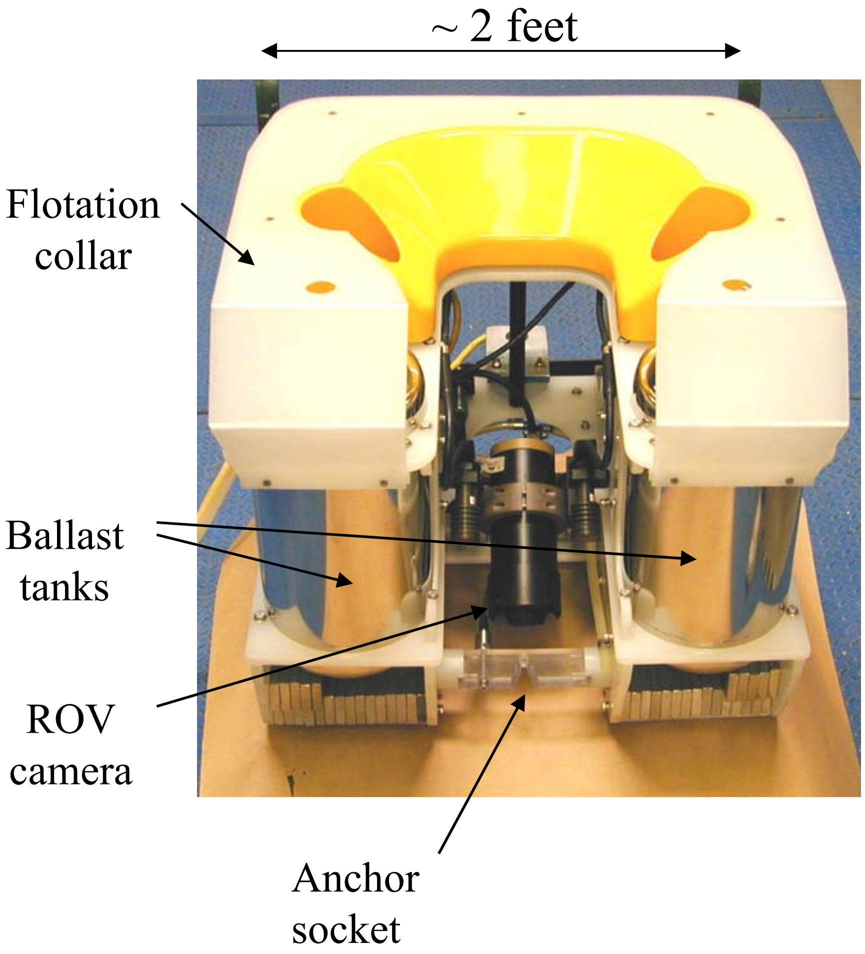
The Laser Welder

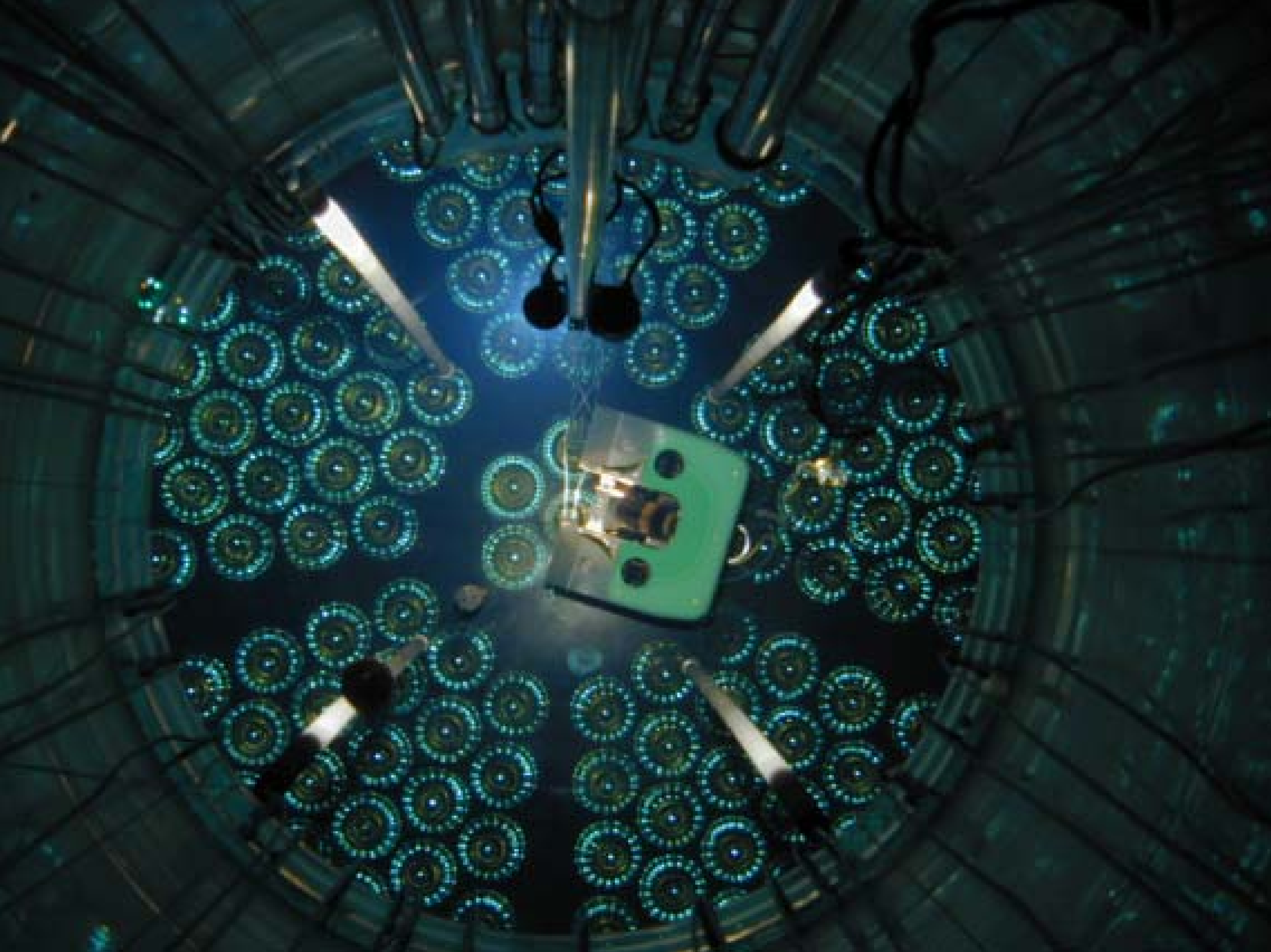


- Very clean laser welding process.
- 1024-nm pulsed Nd-YAG laser melted craters in the nickel, fusing two overlapping pieces together.
- Operated with horizontal tubes on a welding bench or with vertical tubes over the neck of the acrylic vessel.
- Prior to each weld, injected ^{4}He into weld joint for leak testing.

The Remotely Operated Vehicle

- Welded NCD string lowered into the D_2O with pulley system.
- ROV in heavy water during NCD deployment:
  - Two ballast tanks to control buoyancy and six joystick-controlled thrusters.
  - Umbilicals provide purge gas, electrical power, and video feed.
- ROV pilot lifted the NCD off the pulley, flew it to its designated anchor point, and anchored it.

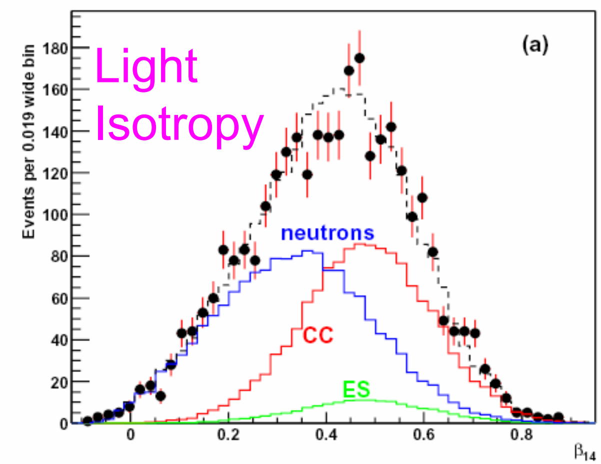


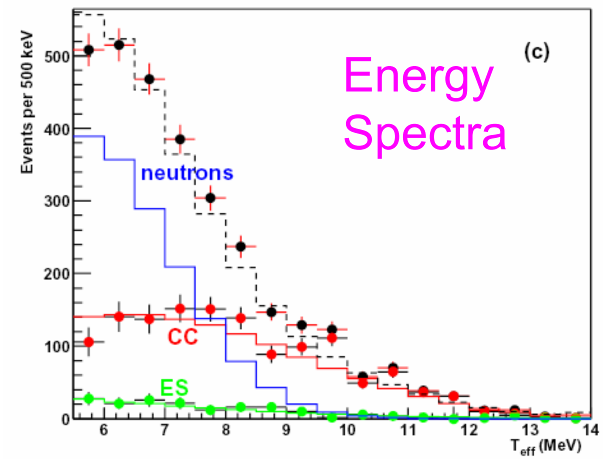


Correlation Coefficients

^{3}He Phase

Recall salt analysis





	D_2O unconstrained	D_2O constrained	Salt unconstrained	^{3}He
NC,CC	-0.950	-0.520	-0.521	~0
CC,ES	-0.208	-0.162	-0.156	~-0.2
ES,NC	-0.297	-0.105	-0.064	~0

Estimated Sensitivity with NCDs

^{3}He Phase

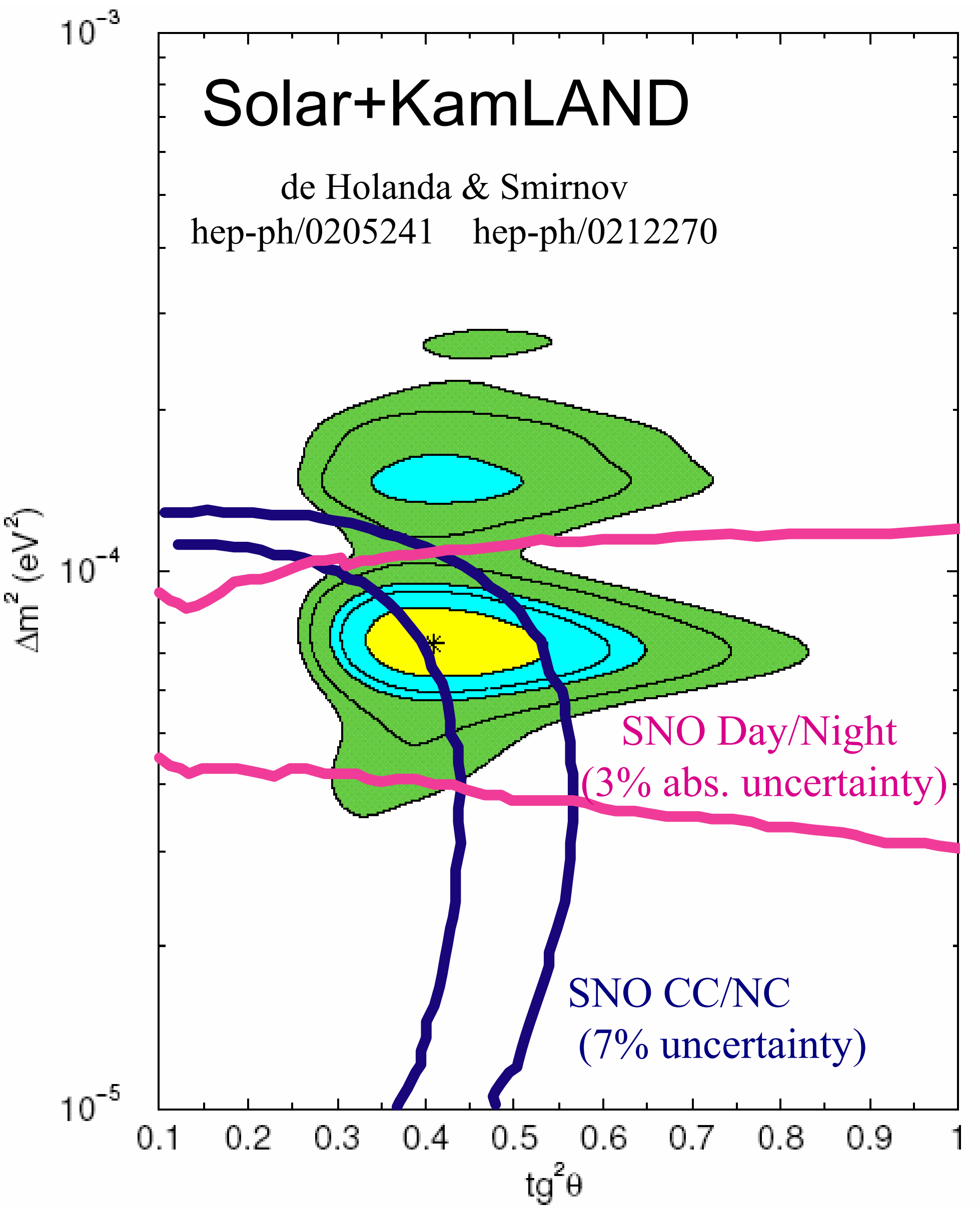
- Neutron capture efficiency:
  - D_2O: 29% → 14% after analysis cuts.
  - Salt: 87% → 40% after analysis cuts.
  - NCD: 28% → 14% after analysis cuts (estimated).
- Statistical separation unnecessary - simply count neutrons.
- Increased supernova sensitivity due to CC/NC separation.

	D_2O	Salt	NCD (estimated)
NC Error	13%	8%	4%
CC Error	6%	6%	6%
Day/Night Error	5%	7%	4%

Precision ν measurements with SNO

^{3}He Phase

- Improved (~2x precision) SNO NC/CC measurement would yield an improved θ_{12} value
- Similar improvement of SNO Day/Night asymmetry would help with Δm_{12}
- Consistency tests
- In 3 ν mixing, also helps constrain θ_{13}
  (Maltoni et al. hep-ph/0309130)



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S.N. Ahmed, M. Chen, F.A. Duncan, E.D. Earle, H.C. Evans, G.T. Ewan, B.G. Fulsom, K. Graham, A.L. Hallin, W.B. Handler, P.J. Harvey, C. Howard, L.L. Kormos, C. Kraus, C.B. Krauss, A.V. Krumins, J.R. Leslie, R. MacLellan, H.B. Mak, J. Maneira, A.B. McDonald, B.A. Moffat, A.J. Noble, C.V. Ouellet, B.C. Robertson, P. Skensved, Y.Takeuchi, M. Thomas, A. Wright
Queen's University

D.L. Wark
Rutherford Laboratory and University of Sussex

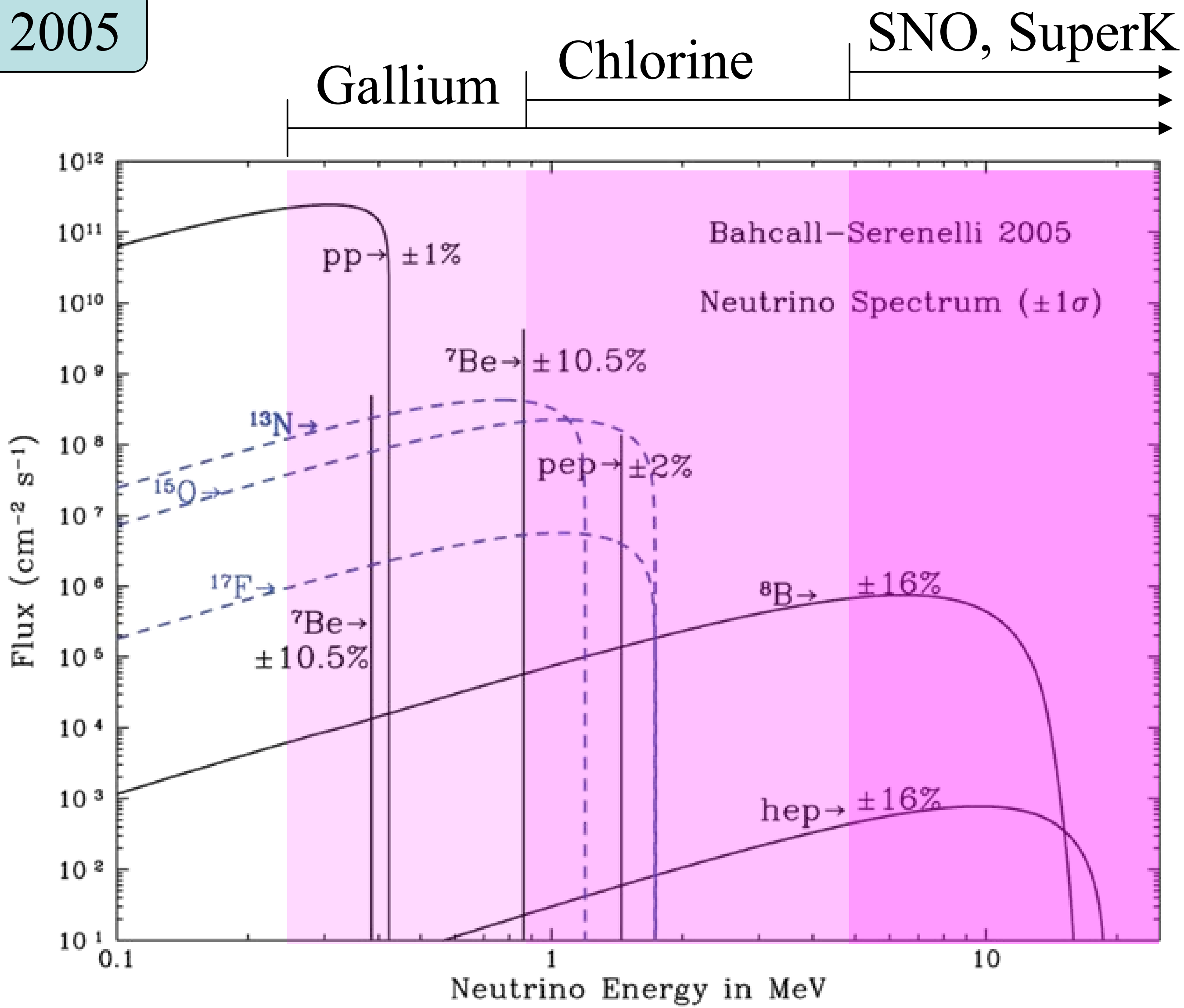
A.E. Anthony, J.C. Hall, M. Huang, J.R. Klein, S.R. Seibert
University of Texas at Austin

R.L. Helmer
TRIUMF

T.V. Bullard, G.A. Cox, P.J. Doe, J. Detwiler, C.A. Duba, J.A. Formaggio, N. Gagnon, R. Hazama, M.A. Howe, S. McGee, K.K.S. Miknaitis, N.S. Oblath, J.L. Orrell, K. Rielage, R.G.H. Robertson, M.W.E. Smith, L.C. Stonehill, B.L. Wall, J.F. Wilkerson
University of Washington

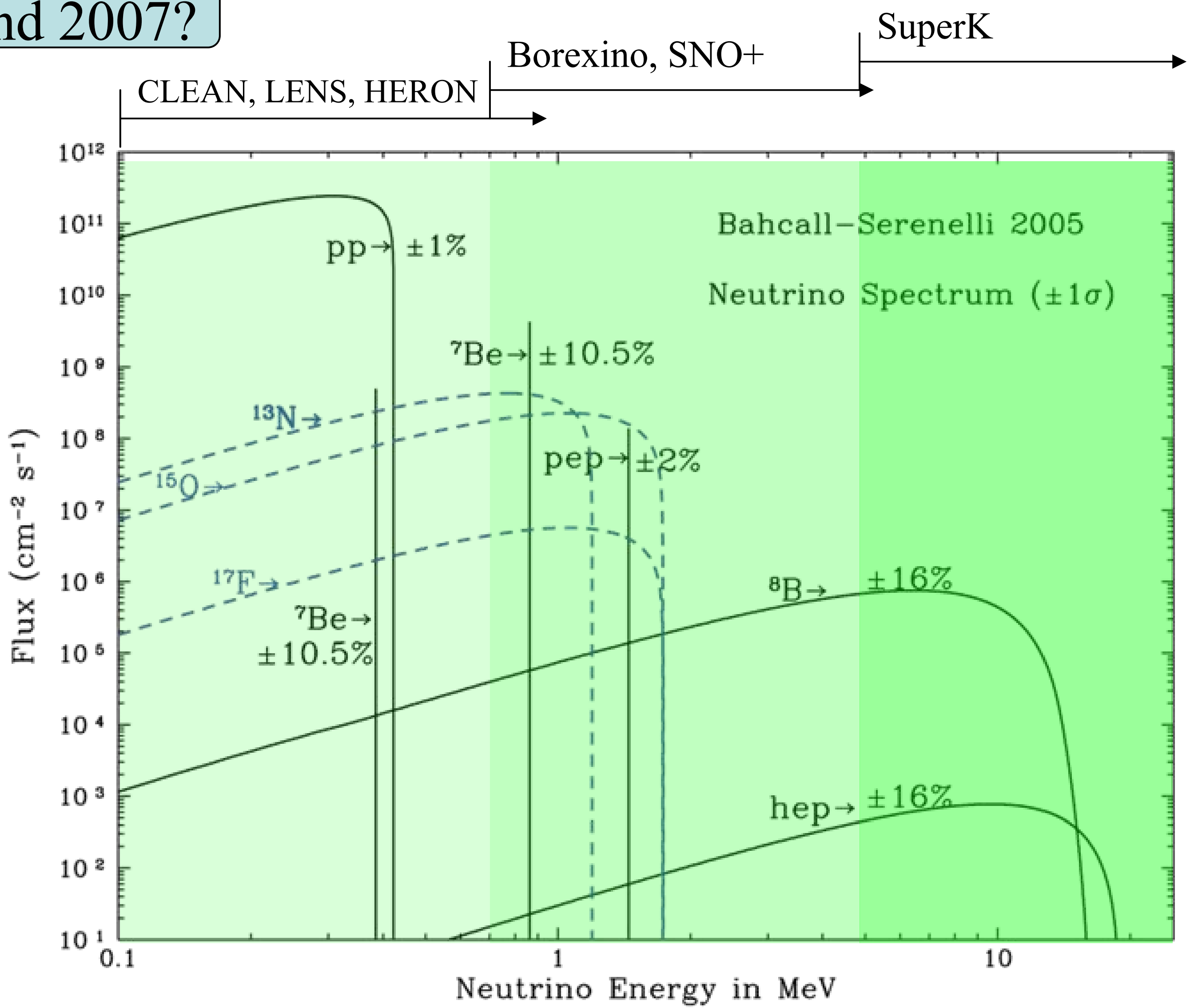
What does the Future Hold?

Up to 2005



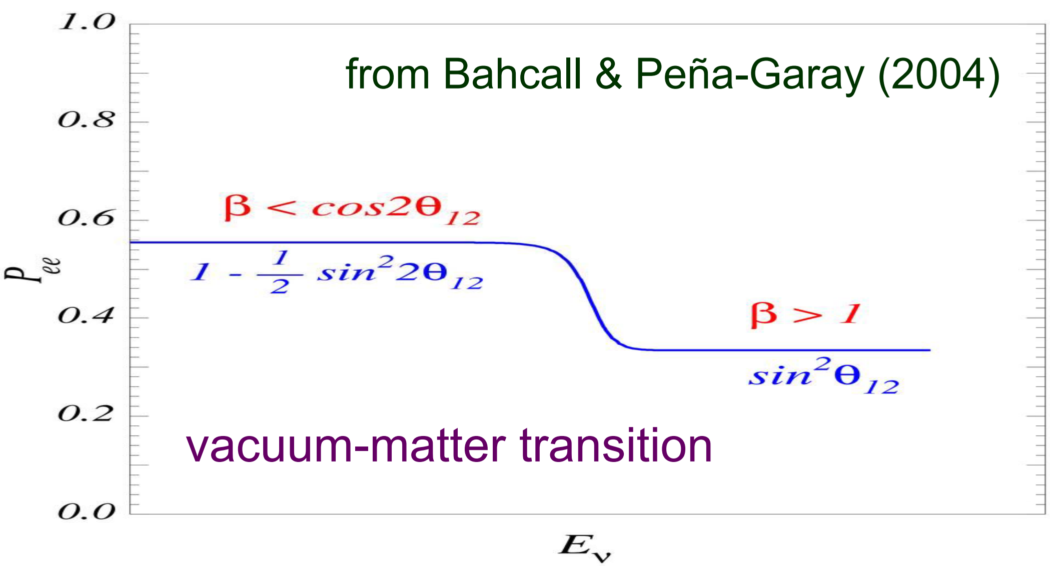
What does the Future Hold?

Beyond 2007?



Low Energy Solar Neutrinos

- precision survival probability measurement: *pep*, *pp*
- precision measurement of total solar neutrinos
  - *91% from pp*
- observe rise in survival probability at lower energies: lower energy ^{8}B, ^{7}Be, *pep*
- testing the vacuum-matter transition is sensitive to new physics
- Observe CNO neutrinos



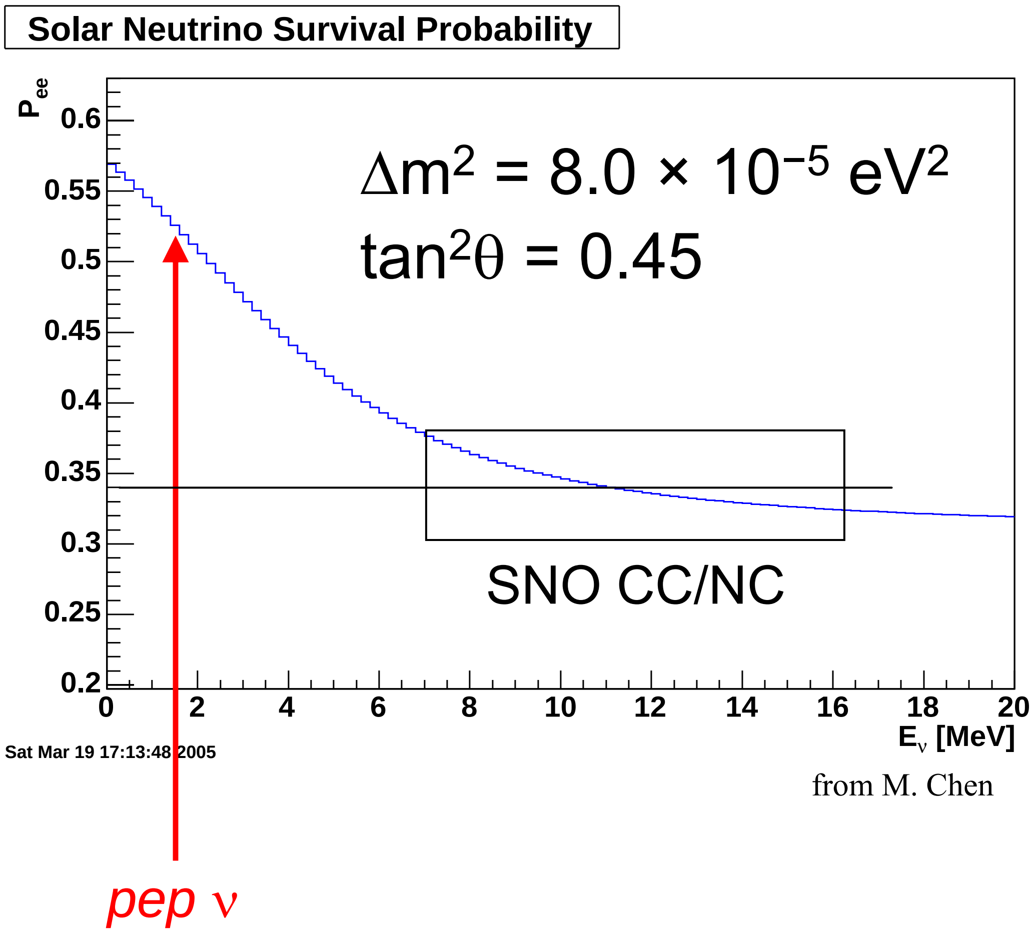
Survival Probability Rise

SSM pep flux:

uncertainty ±1.5%

allows precision test

transition from matter to vacuum dominance…test the extrapolation of the "simplest neutrino oscillation model" coupled with solar models

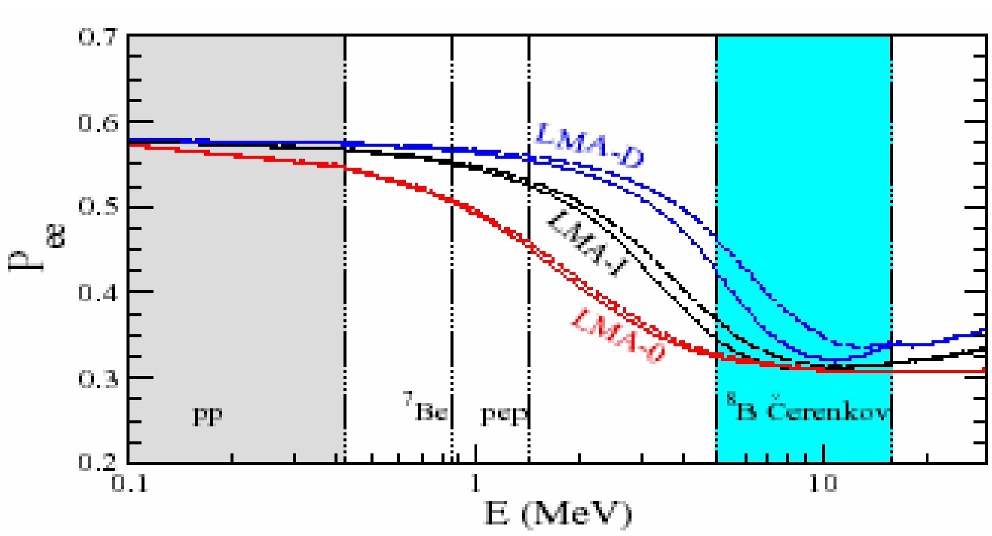


from M. Chen

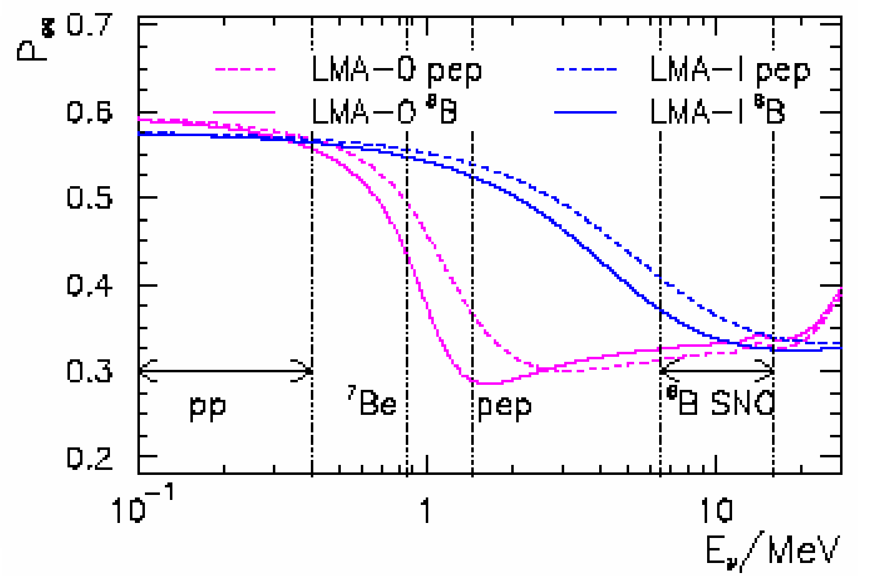
Sensitive to new physics:

- non-standard interactions
- mass-varying neutrinos
- CPT violation
- large θ_{13}
- sterile neutrino admixture

Non-Standard Interactions



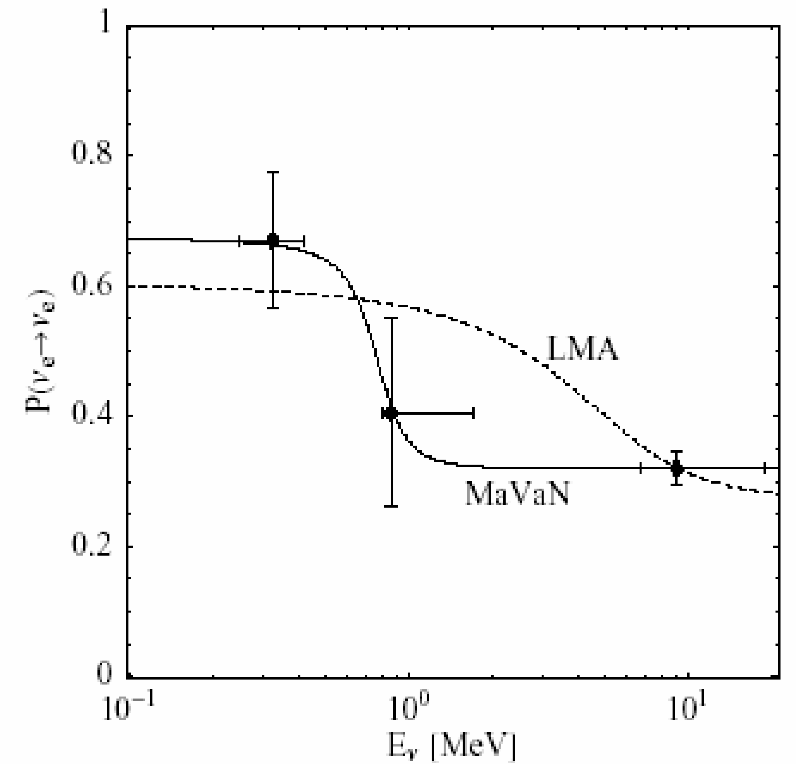
Miranda, Tórtola, Valle (2005)



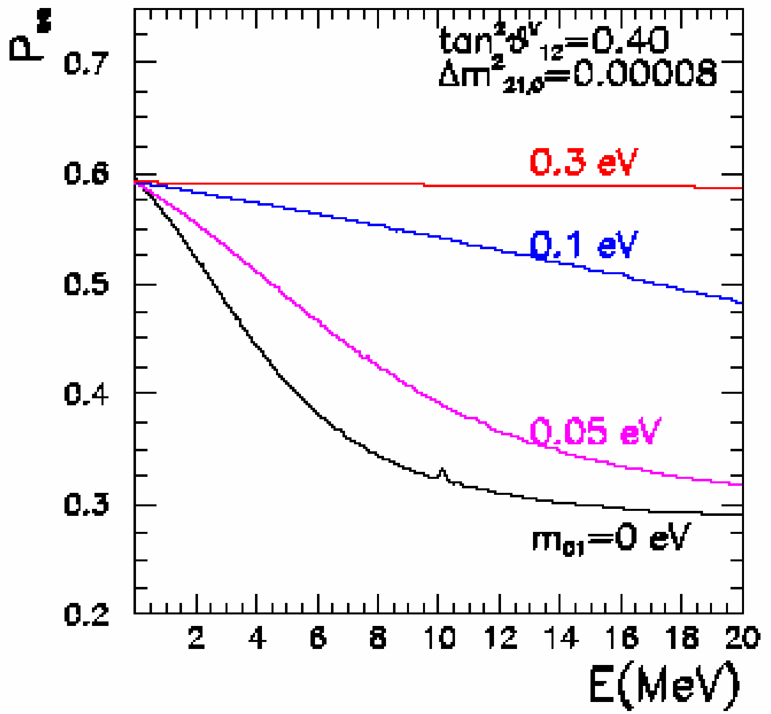
Friedland, Lunardini, Peña-Garay (2004)

- Drastically different predictions from models for pep and ^{7}Be

Mass-Varying Neutrinos



Barger, Huber, & Marfatia (2005)

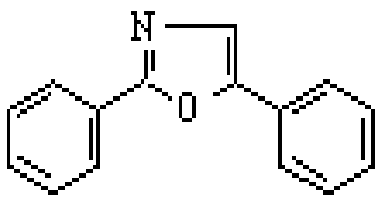


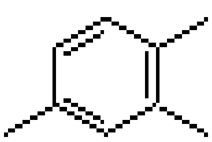
Cirelli, Gonzalez-Garcia, Peña-Garay (2005)

- Again, different predictions for low energy solar neutrinos

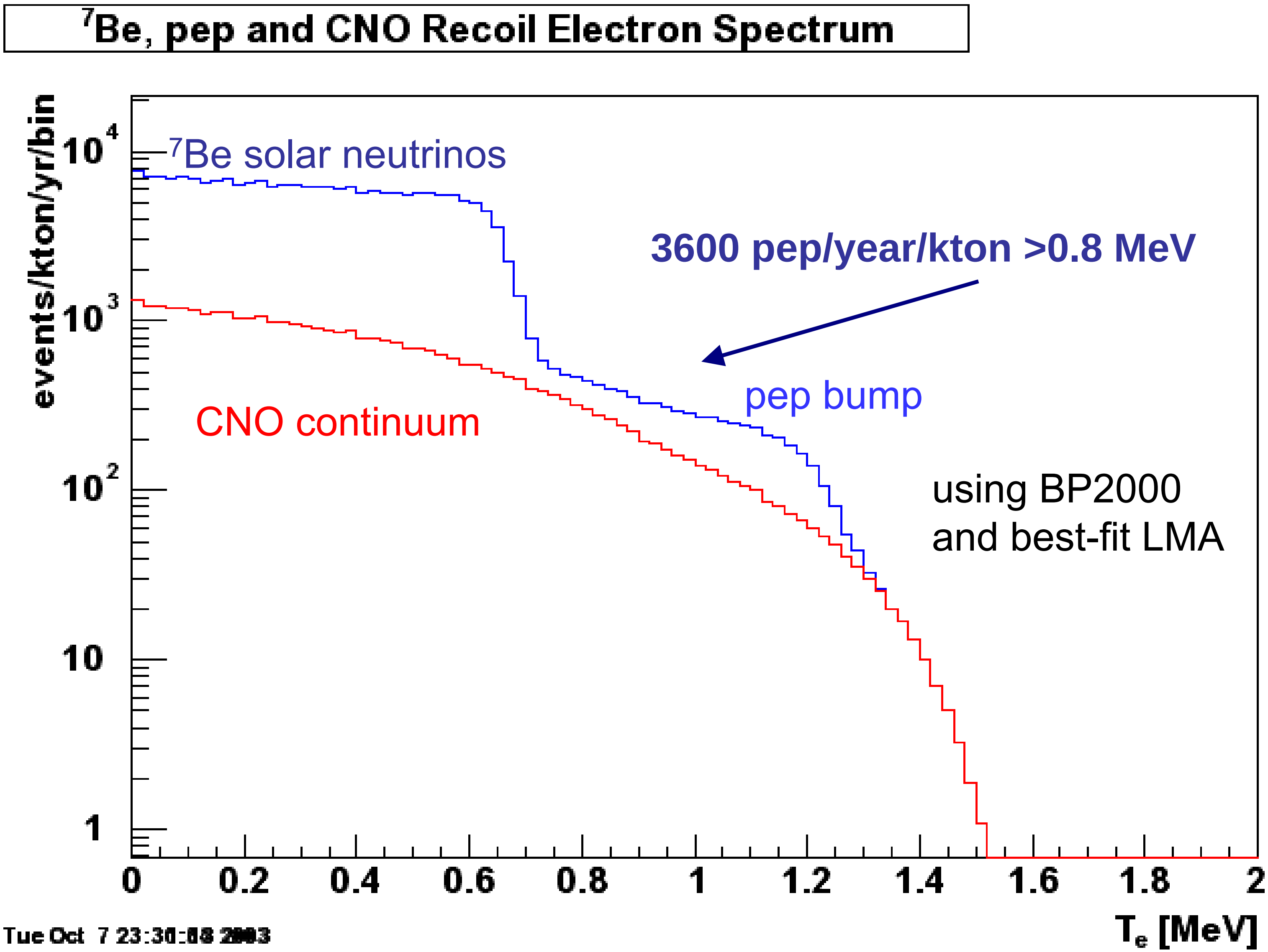
SNO+

- Current discussions of what to do with SNO cavity once SNO ends in 2007 after returning the D2O
- Main proposal is to replace D2O with liquid scintillator
- Backgrounds are lower than KamLand due to depth
  - Must improve purification of scintillator
  - Must choose scintillator that will not harm acrylic
- Physics program:
  - pep, CNO, 7Be, low 8B solar neutrinos
  - Geo neutrinos
  - 240 km baseline reactor oscillation confirmation
  - Supernova neutrinos
  - Double beta decay?



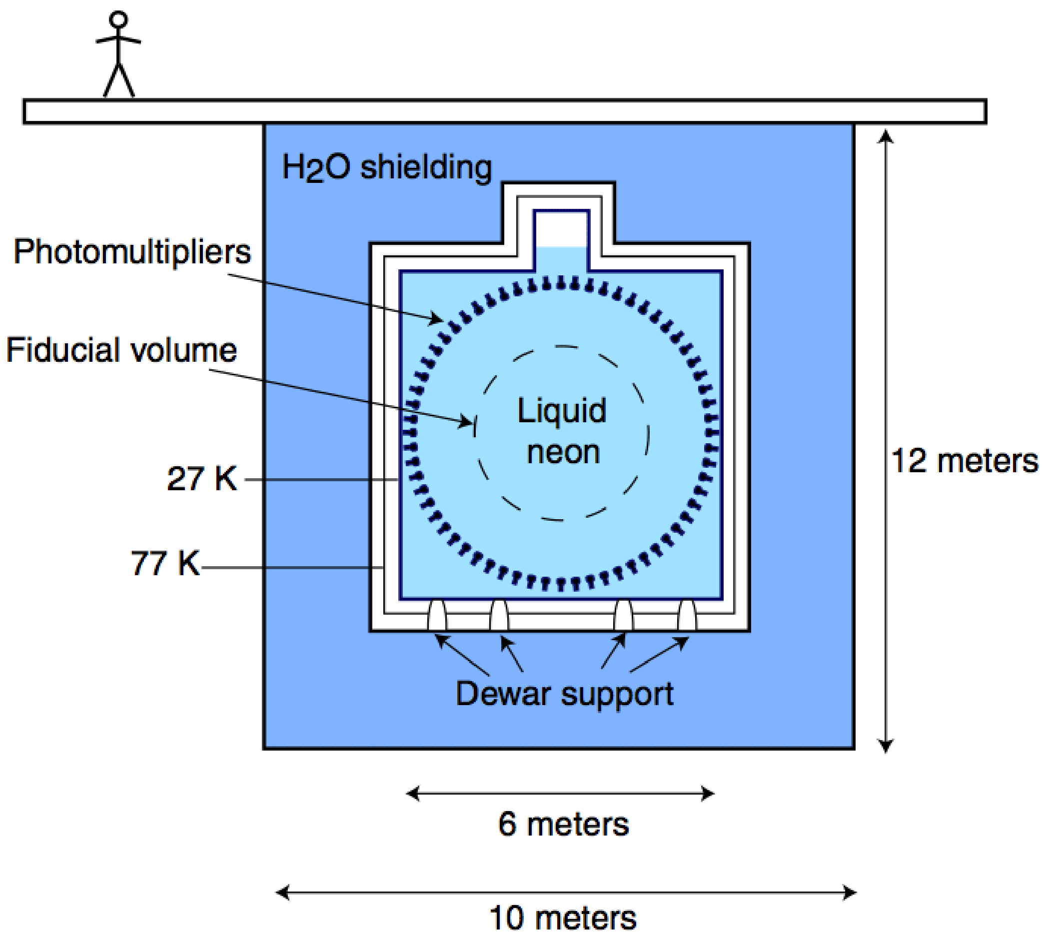


SNO+ Event Rates (Oscillated)



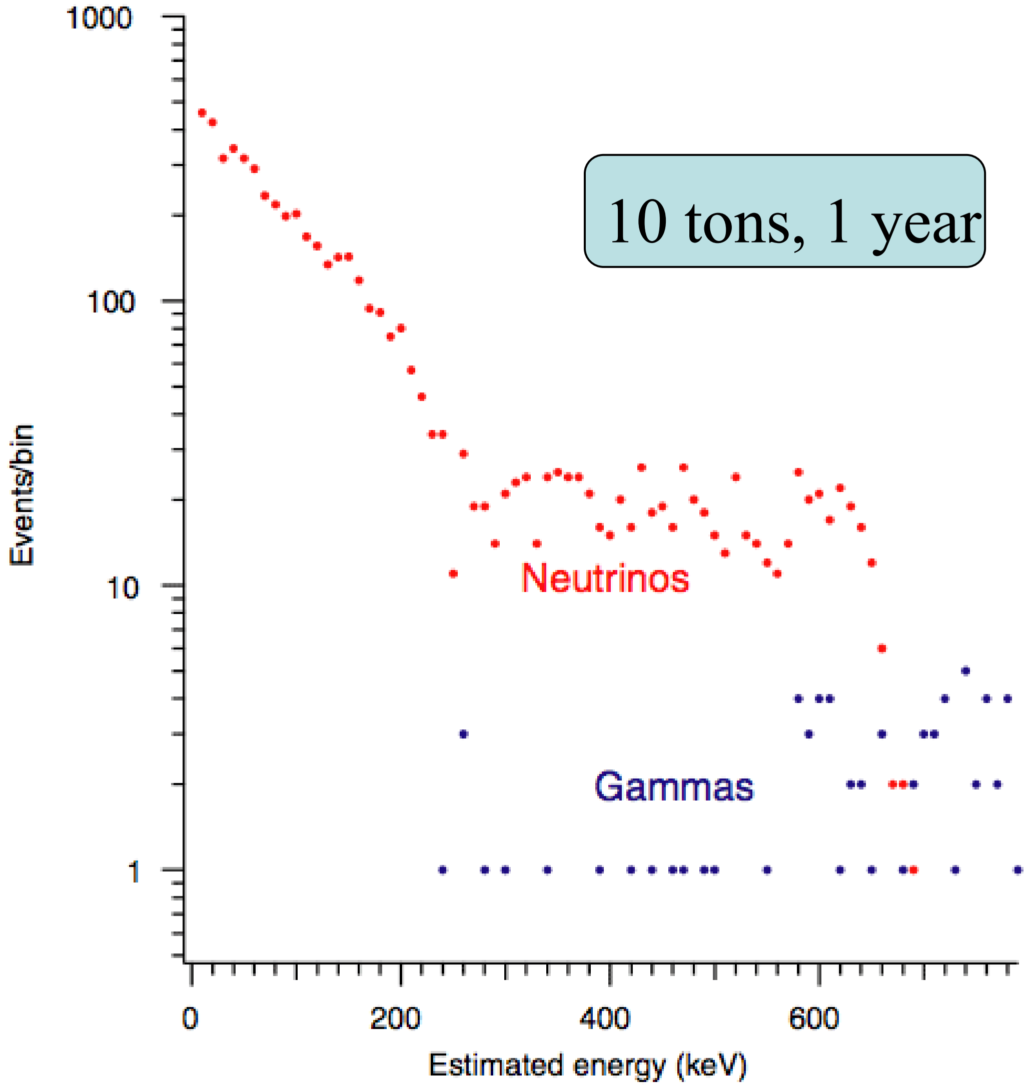
CLEAN

- **C**ryogenic **L**ow **E**nergy **A**strophysics with **N**oble gases
- Scintillation in liquid neon
- Physics program
  - pp, CNO solar neutrinos
  - Supernova neutrinos
  - Neutrino magnetic moment
- Needs large depth to shield backgrounds



130 ton version of CLEAN

CLEAN Event Rates



New Directions Summary

- Direction seems to be in lower energy solar neutrinos with precision spectral measurements
- New and old technology approaches proposed
- Must go deep (SNOLab or DUSEL)
- Possible measurements in the next 10 years
- Vacuum-matter transition seems like area to test theories/new physics