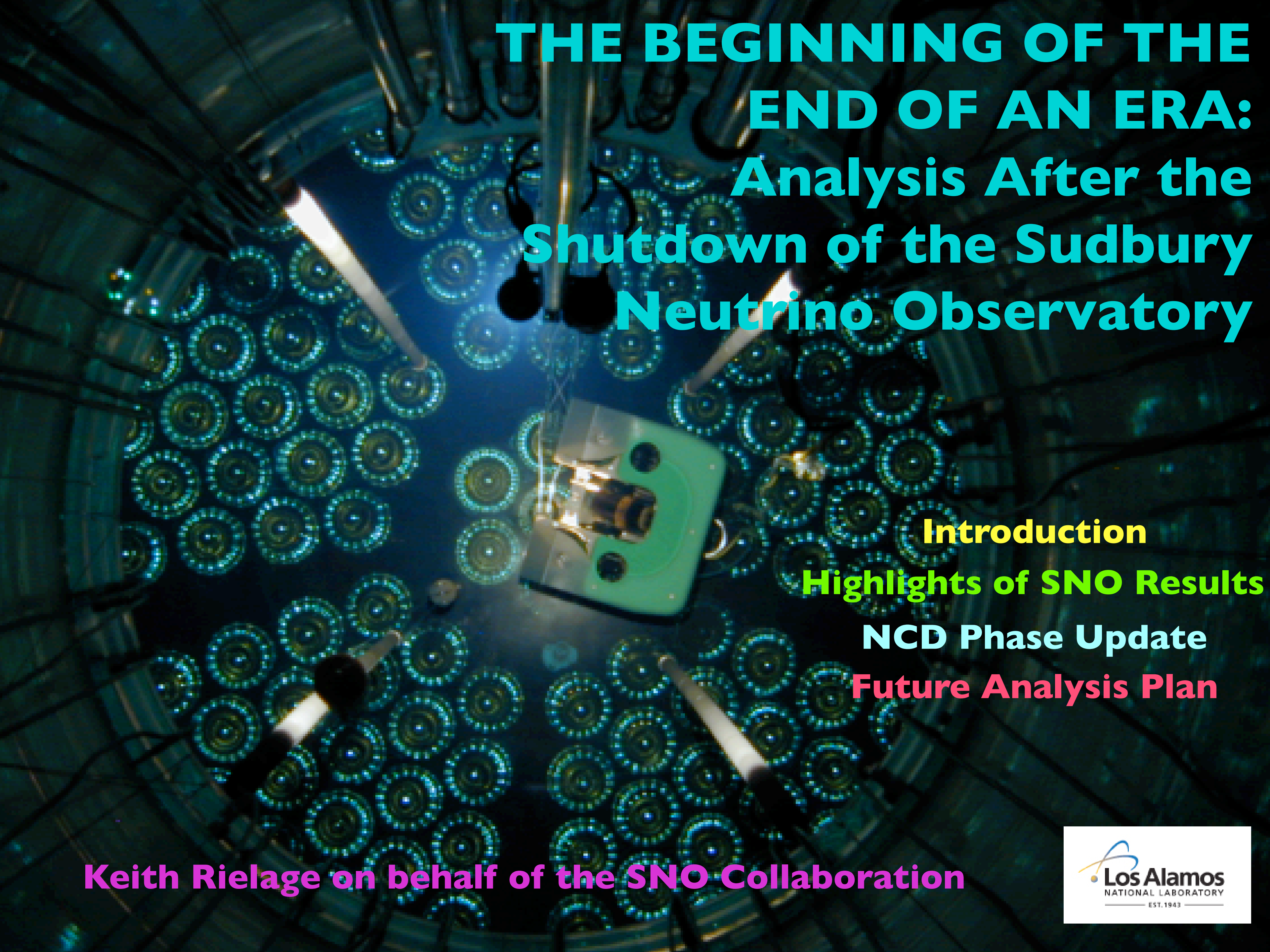


THE BEGINNING OF THE END OF AN ERA: Analysis After the Shutdown of the Sudbury Neutrino Observatory

Introduction

Highlights of SNO Results

NCD Phase Update

Future Analysis Plan

Keith Rielage on behalf of the SNO Collaboration

Los Alamos NATIONAL LABORATORY EST. 1943

The Beginning: The Solar Neutrino Problem

1967: Ray Davis begins solar neutrino experiment, the flux measurement is less than expected

1970's-1980's: Experiments utilizing chlorine, gallium, water continue to report flux below the Standard Solar Model

Where did the solar neutrinos go?

The Beginning: The Solar Neutrino Problem

SSM Energy Generation

$p + p \rightarrow {}^2H + e^+ + \nu_e$ $\quad$ $p + e^- + p \rightarrow {}^2H + \nu_e$

$\downarrow$

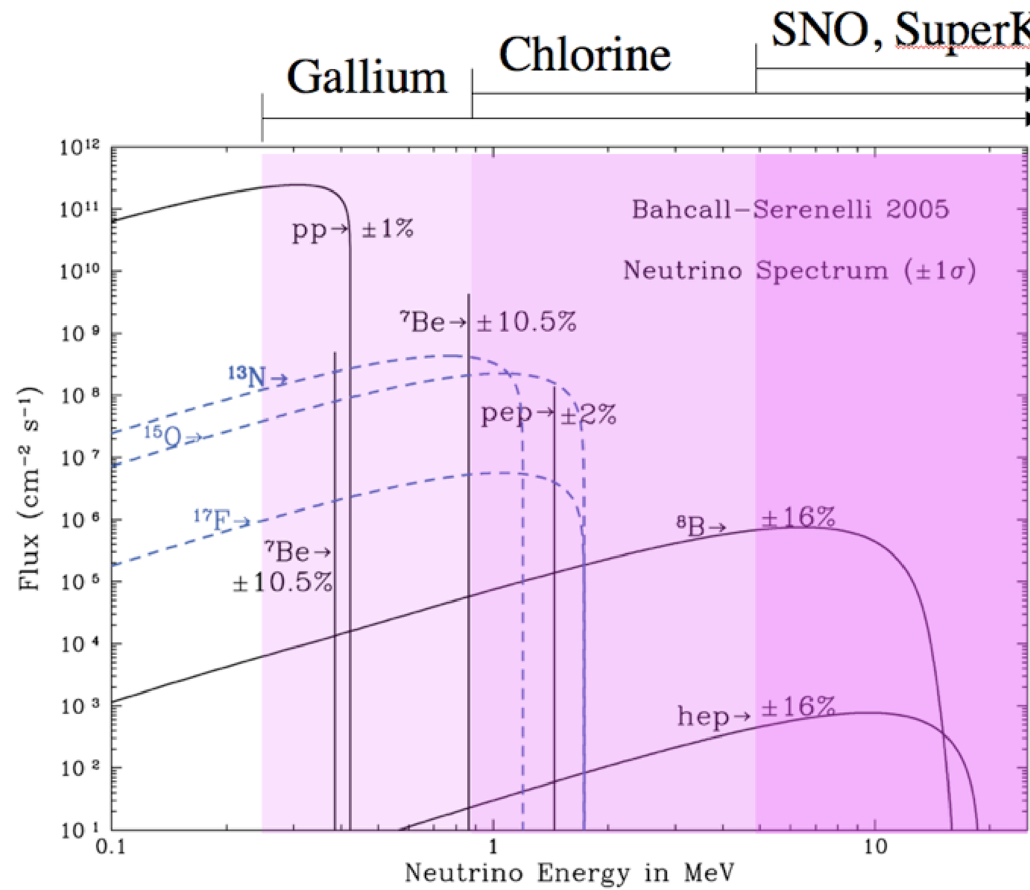
${}^2H + p \rightarrow {}^3He + \gamma$

${}^3He + {}^3He \rightarrow {}^4He + 2p$ $\quad$ ${}^3He + p \rightarrow \alpha + e^+ + \nu_e$

${}^3He + \alpha \rightarrow {}^7Be + \gamma$

${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$ $\quad$ ${}^7Be + p \rightarrow {}^8B + \gamma$

${}^7Li + p \rightarrow \alpha + \alpha$ $\quad$ ${}^8B \rightarrow 2\,\alpha + e^+ + \nu_e$



The Beginning: The Solar Neutrino Problem

1967: Ray Davis detects solar neutrinos, flux is less than expected

1970's-1980's: Experiments utilizing chlorine, gallium, water continue to report flux below the Standard Solar Model

Where did the solar neutrinos go? Do they oscillate between mass eigenstates as they pass through matter?

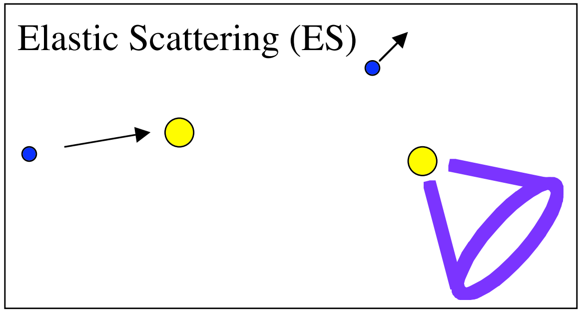
1984: Herb Chen proposes the use of heavy water in a solar neutrino detector to check for all active 'flavors'

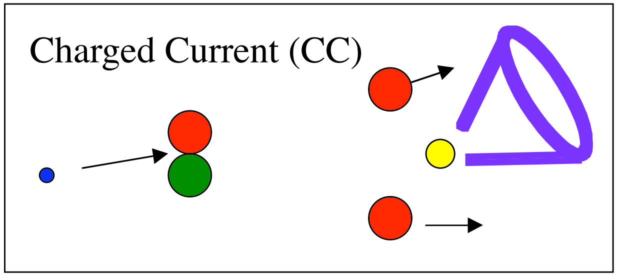
The Sudbury Neutrino Observatory (SNO) is born!

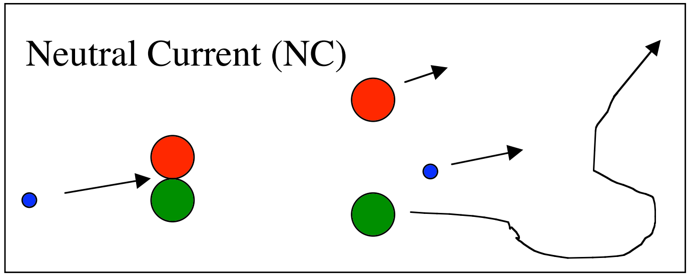
Why SNO is Unique?

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 $< 1 \rightarrow$ definitive evidence of neutrino flavor change







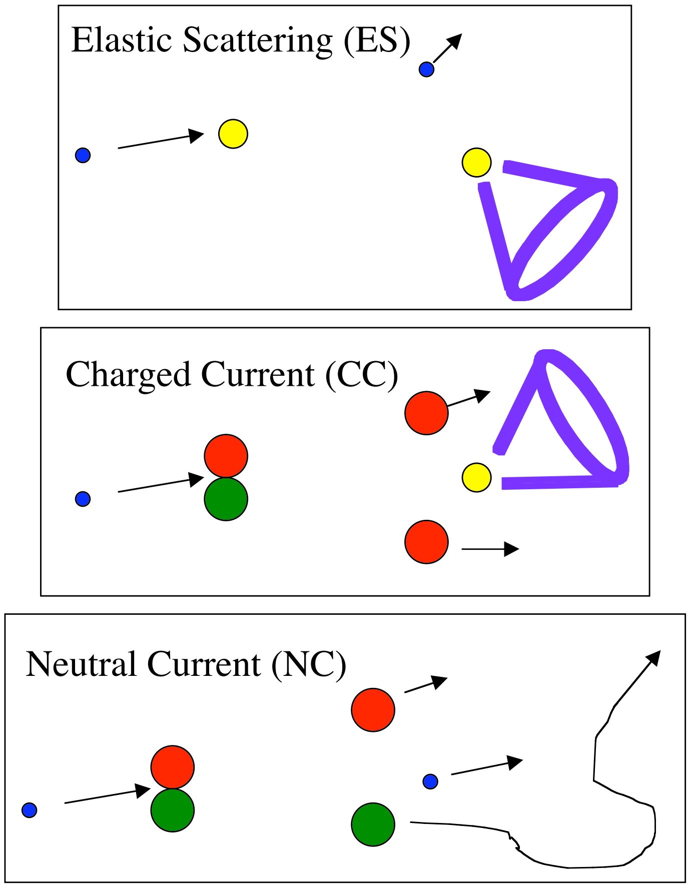
Why SNO is Unique?

Key physics signatures

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

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

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

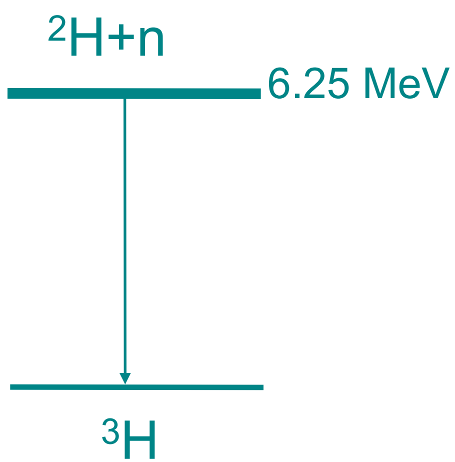


SNO - Three Neutron Detection Methods

Phase I (D_2O)

Nov. 99 - May 01

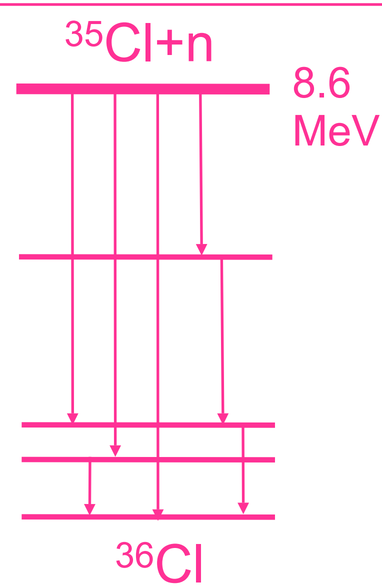
n captures on
$^2H(n, \gamma)^3H$
σ = 0.0005 b
Observe 6.25 MeV γ
PMT array readout
Good CC



Phase II (salt)

July 01 - Sep. 03

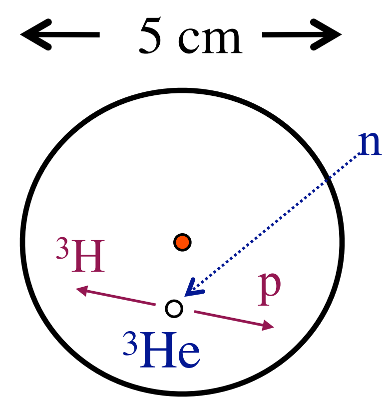
2 t NaCl. n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
σ = 44 b
Observe multiple γ's
PMT array readout
Enhanced NC



Phase III (^3He)

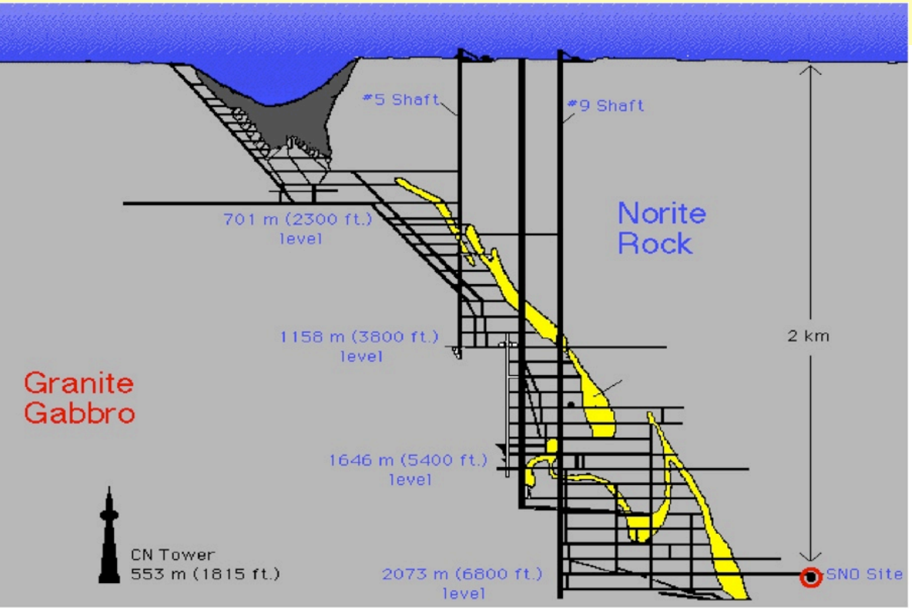
Nov. 04 - Nov. 06

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



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

Sudbury Neutrino Observatory



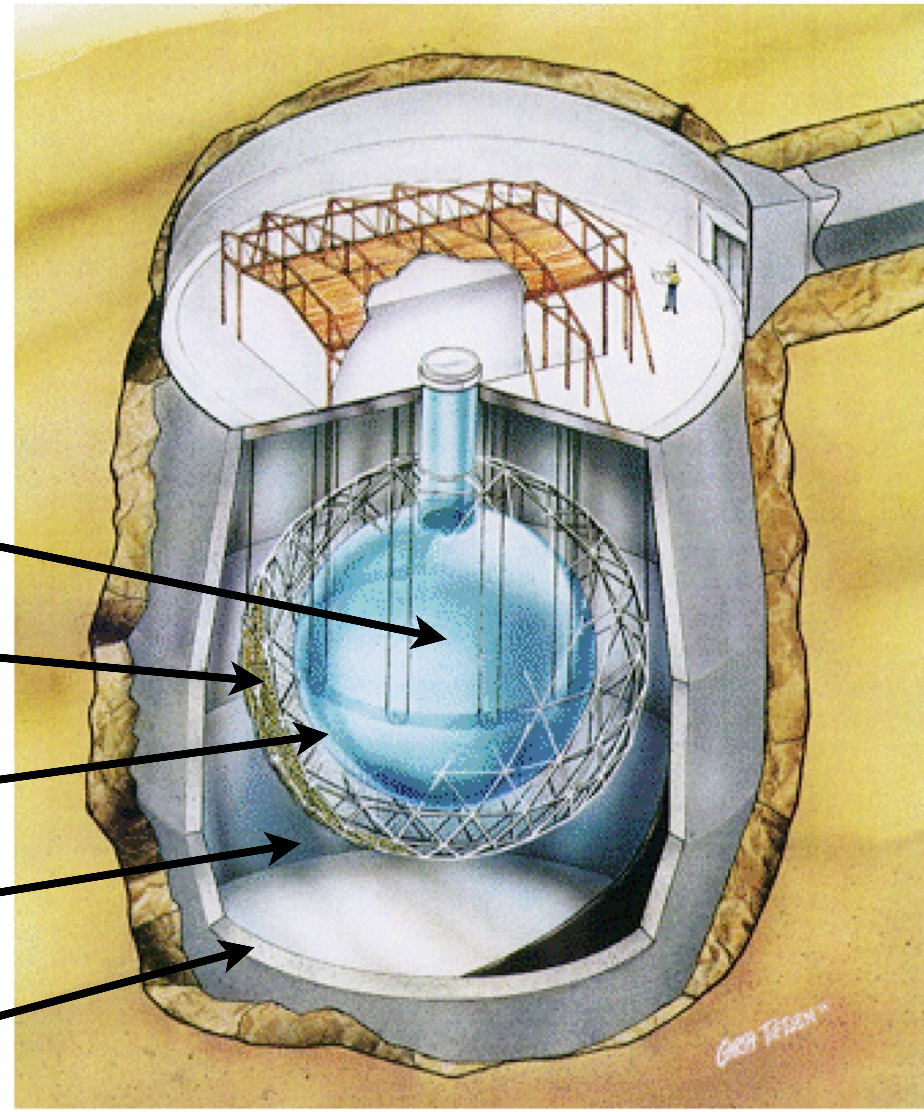
1000 tonnes D_2O

Support structure for 9500 PMTS, 54% coverage

12 m diameter Acrylic Vessel

7000 tonnes H_2O shielding

Urylon liner and Radon seal



Timeline for SNO

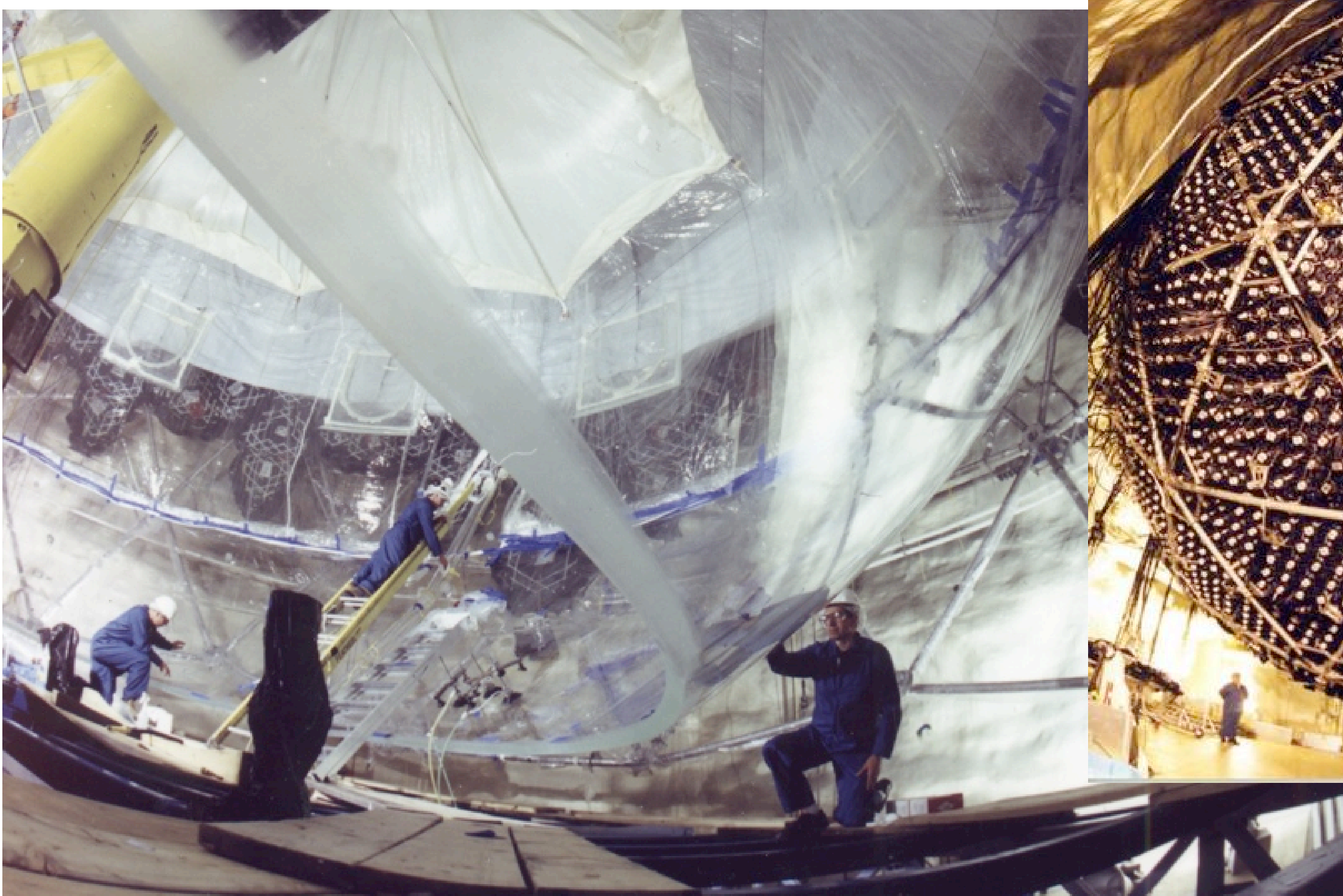
1990: Funding begins from US, Canada, UK

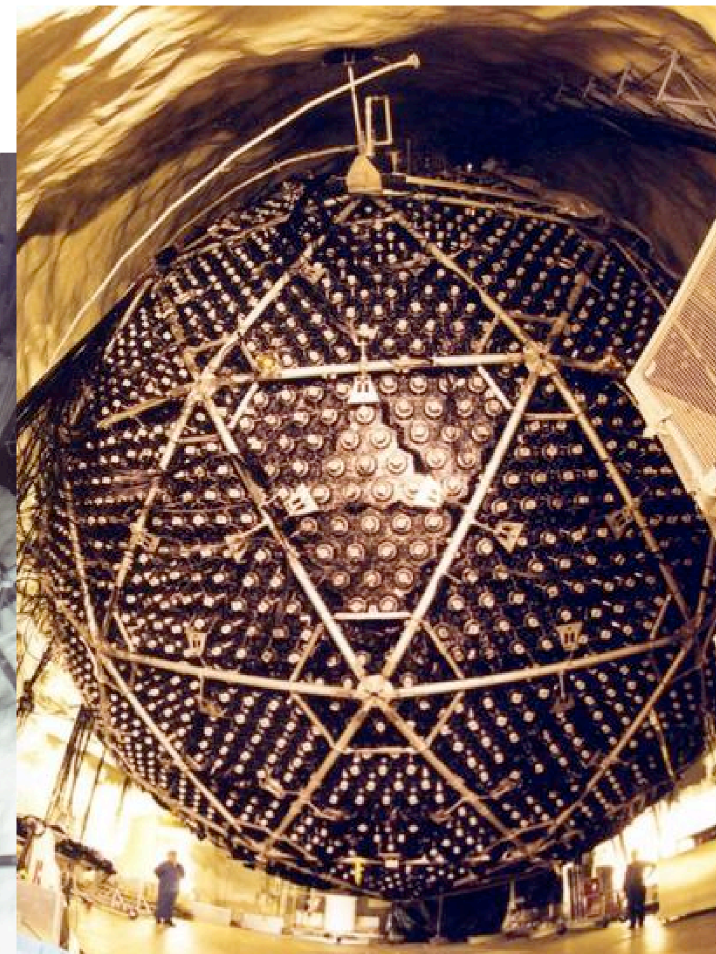
Timeline for SNO

1990-93: Excavation of largest underground cavity this deep

Timeline for SNO

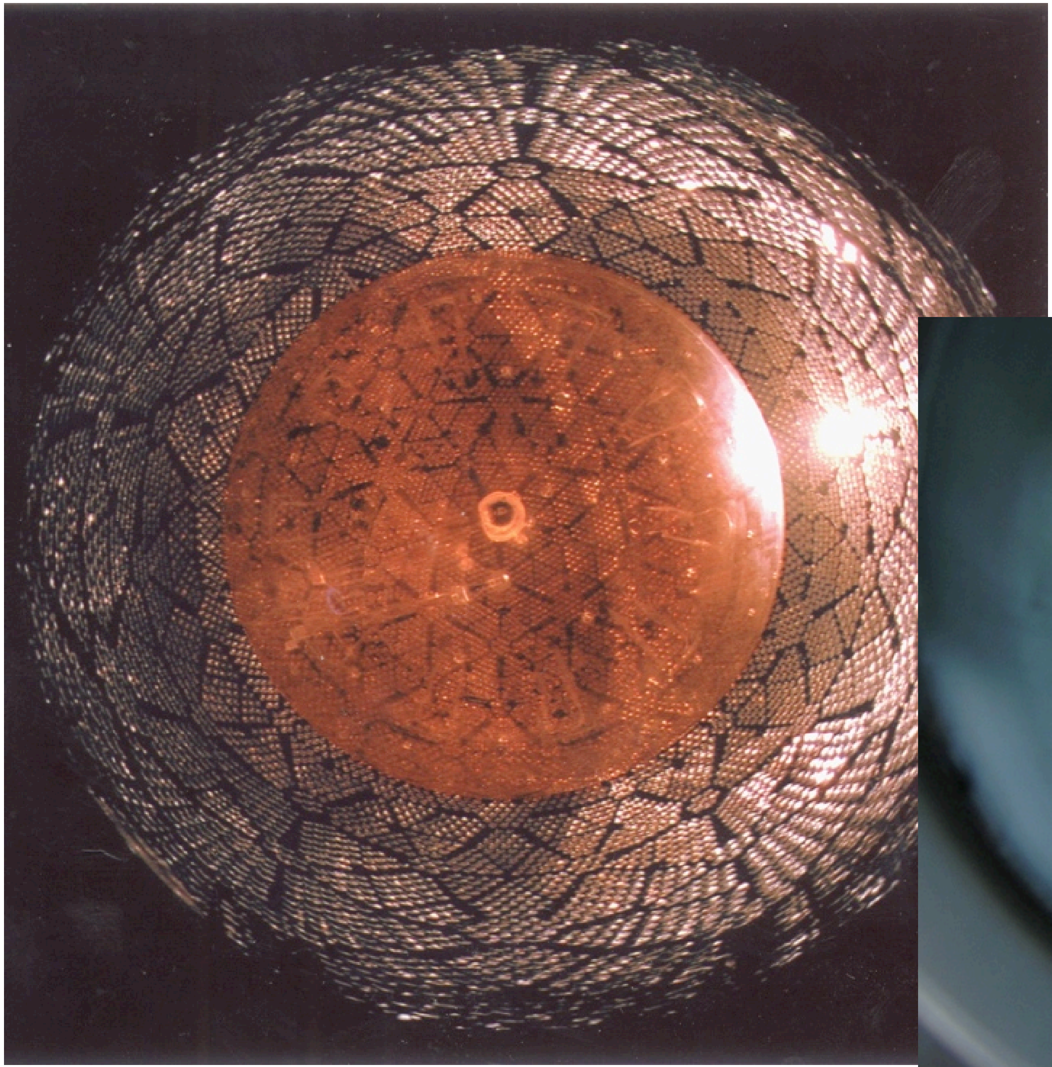
1995-98: Acrylic Vessel and PMTs installed



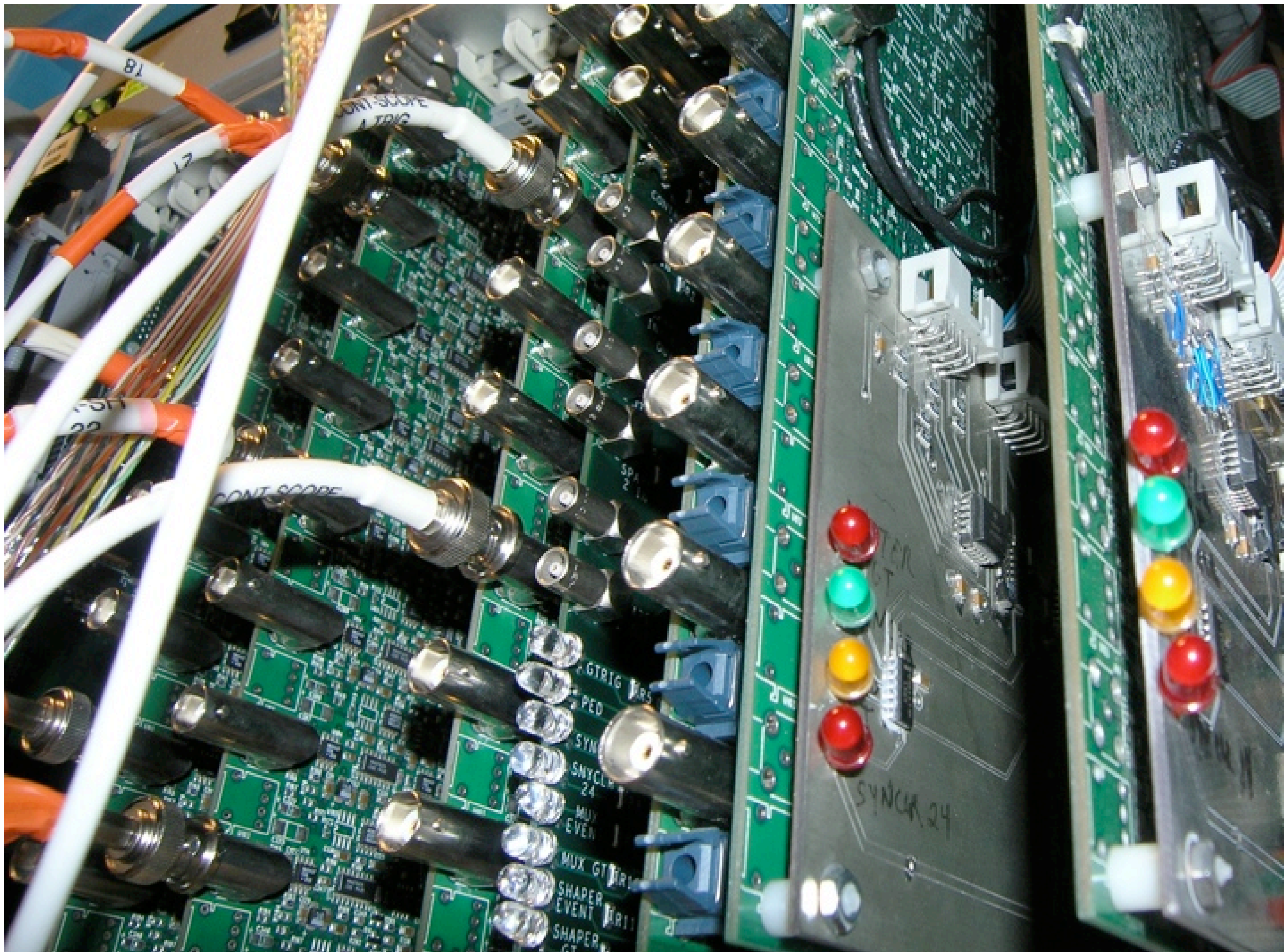


Timeline for SNO

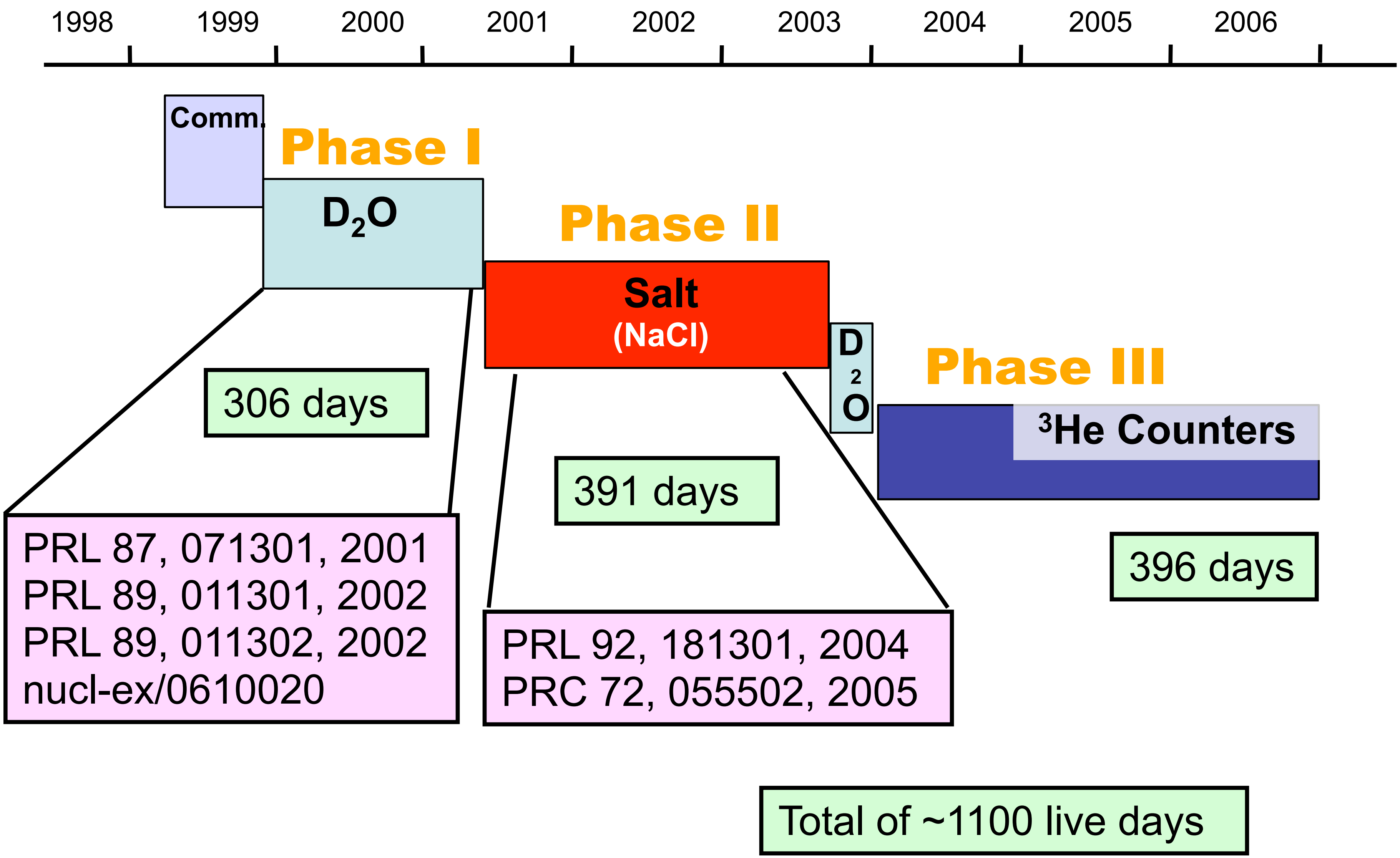
1998-99: Filled with light and heavy water



1999: Data taking begins

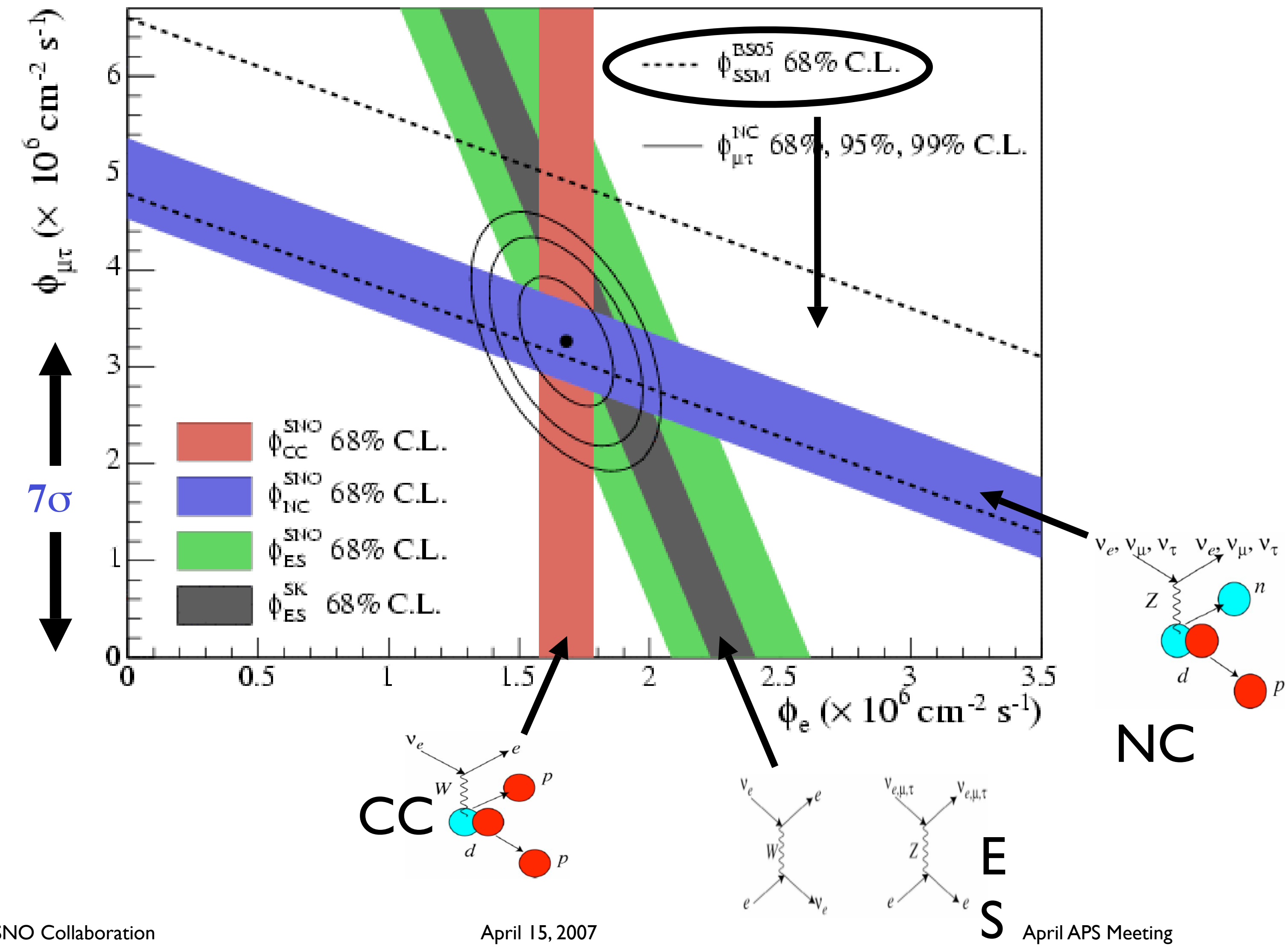


SNO Measurement Phases



Latest Flux Measurements

SNO Collaboration, PRC 72, 055502 (2005)
391 Days of Dissolved Salt Data



CC Spectrum & Day-Night Asymmetry

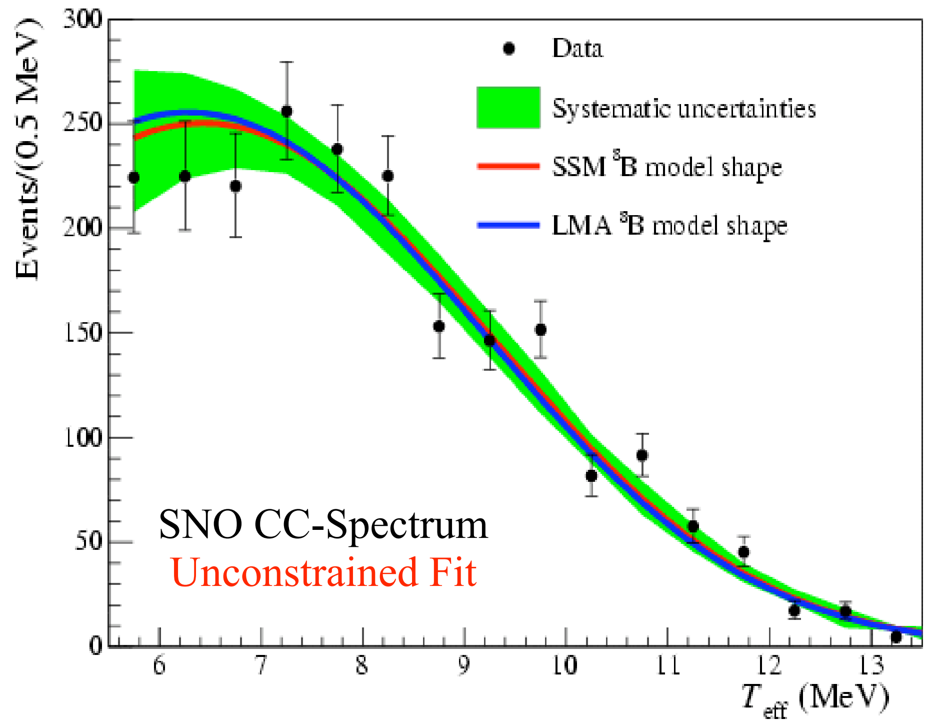
SNO Collaboration, PRC 72, 055502 (2005)
391 Days of Dissolved Salt Data

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

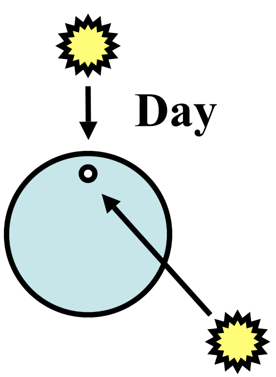
$$\phi_{NC} = 4.94 \;^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

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

x 10^{6} cm^{-2} s^{-1}



$$A_{DN} = \frac{\text{(Night-Day)}}{\text{(Day+Night)/2}}$$



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

(assuming A_{NC} = 0)

Statistical Limitation for Observing "Small" Day-Night Asymmetry

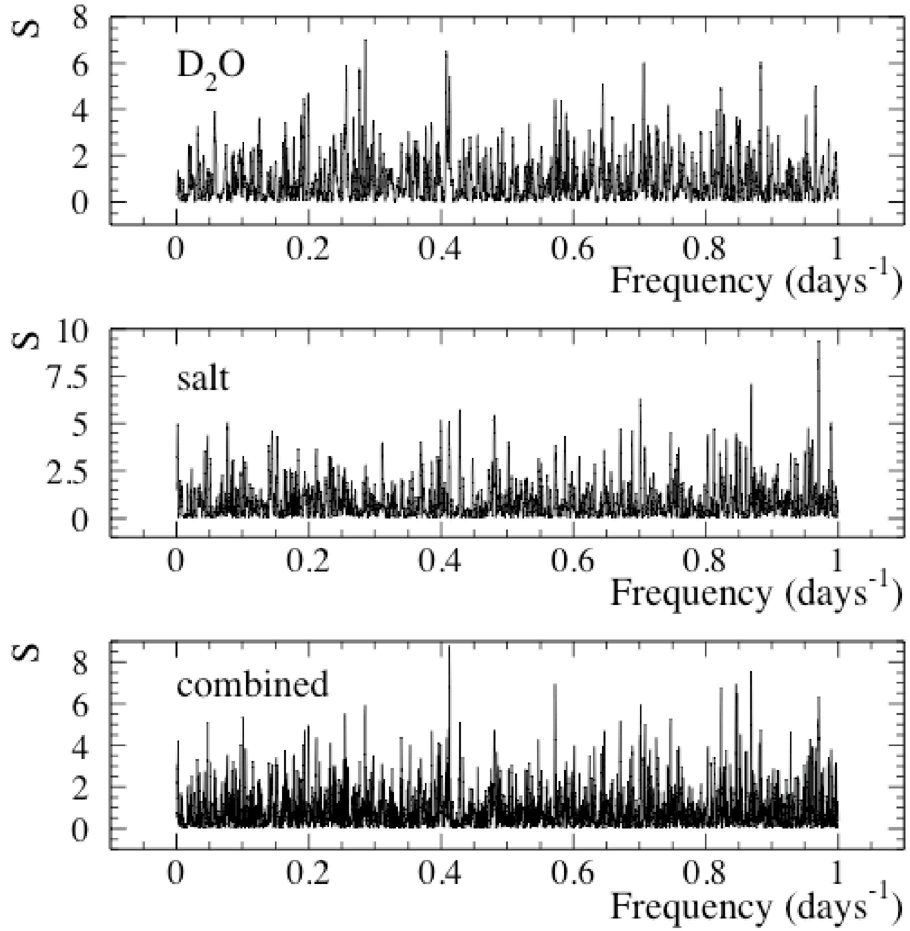
Periodicity Analysis of SNO Data

A periodicity analysis on the D_2O and salt data sets was performed using both a Lomb-Scargle periodogram and an unbinned maximum likelihood fit (PRD 72 052010, 2005)

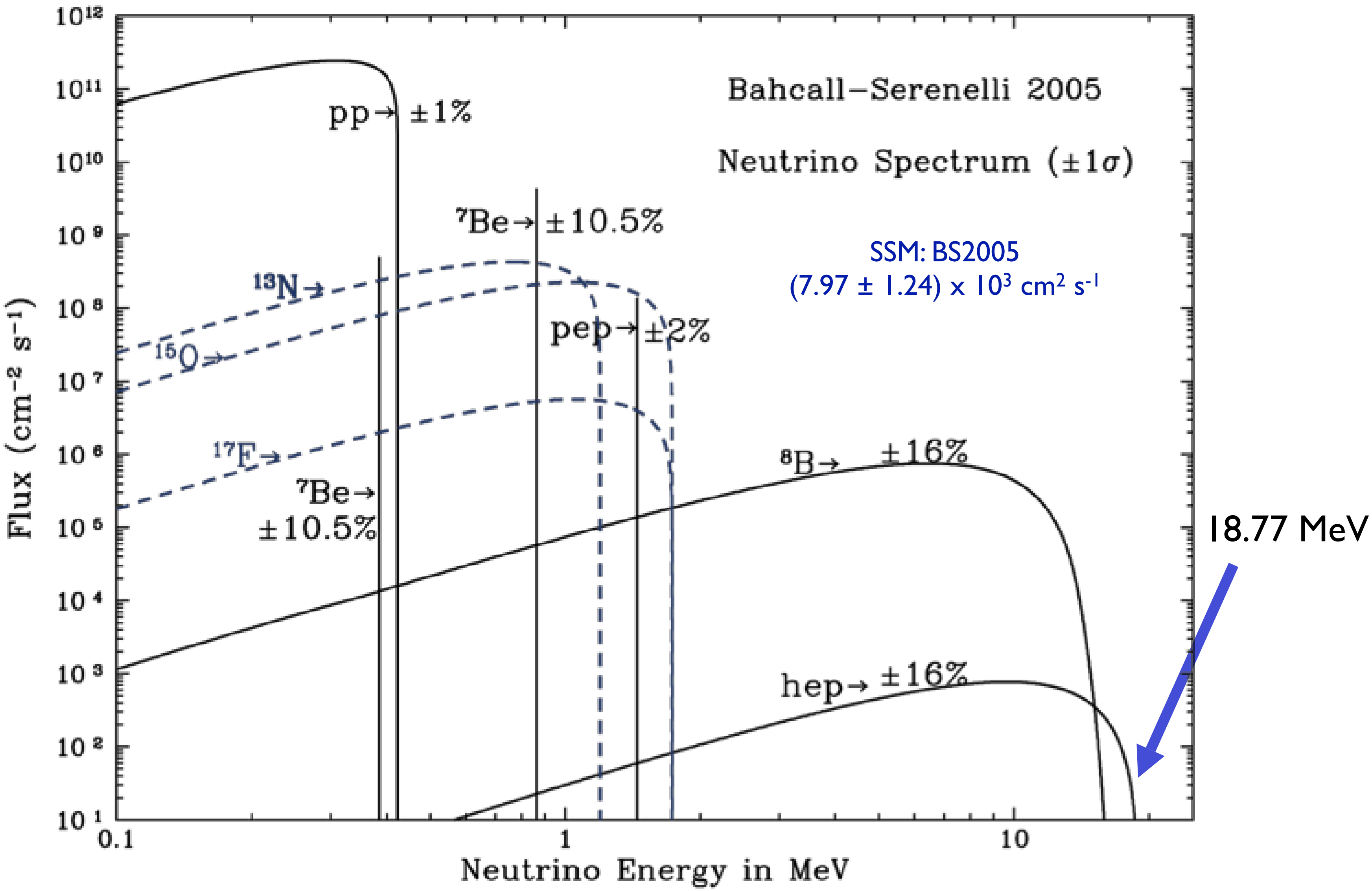
For the combined data sets, the largest peak occurs at a period of 2.4 days, with a statistical significance of S=8.8

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

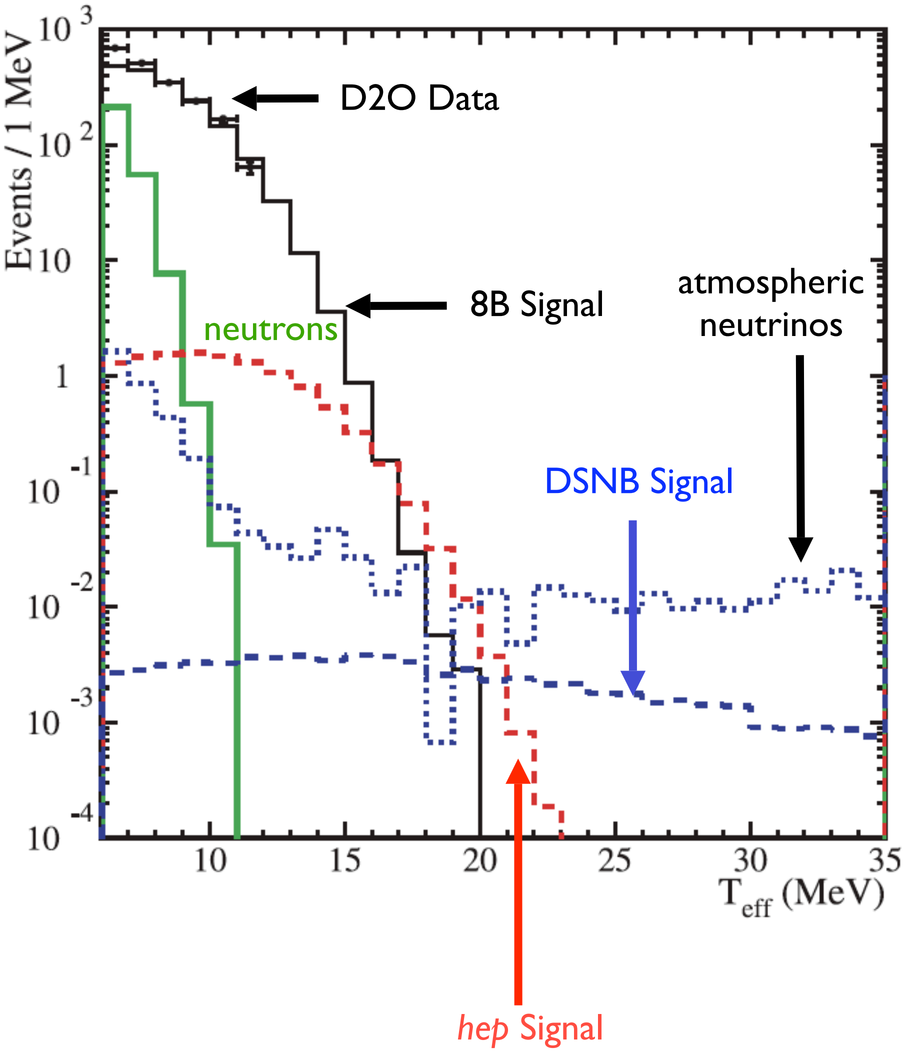
No statistically significant periodicity was found



hep Solar Neutrinos



hep and Diffuse Supernova Neutrinos



→Both signals lie in the region between ^{8}B solar neutrinos and atmospheric neutrinos

→Search by counting number of events within a predefined energy window or signal box …

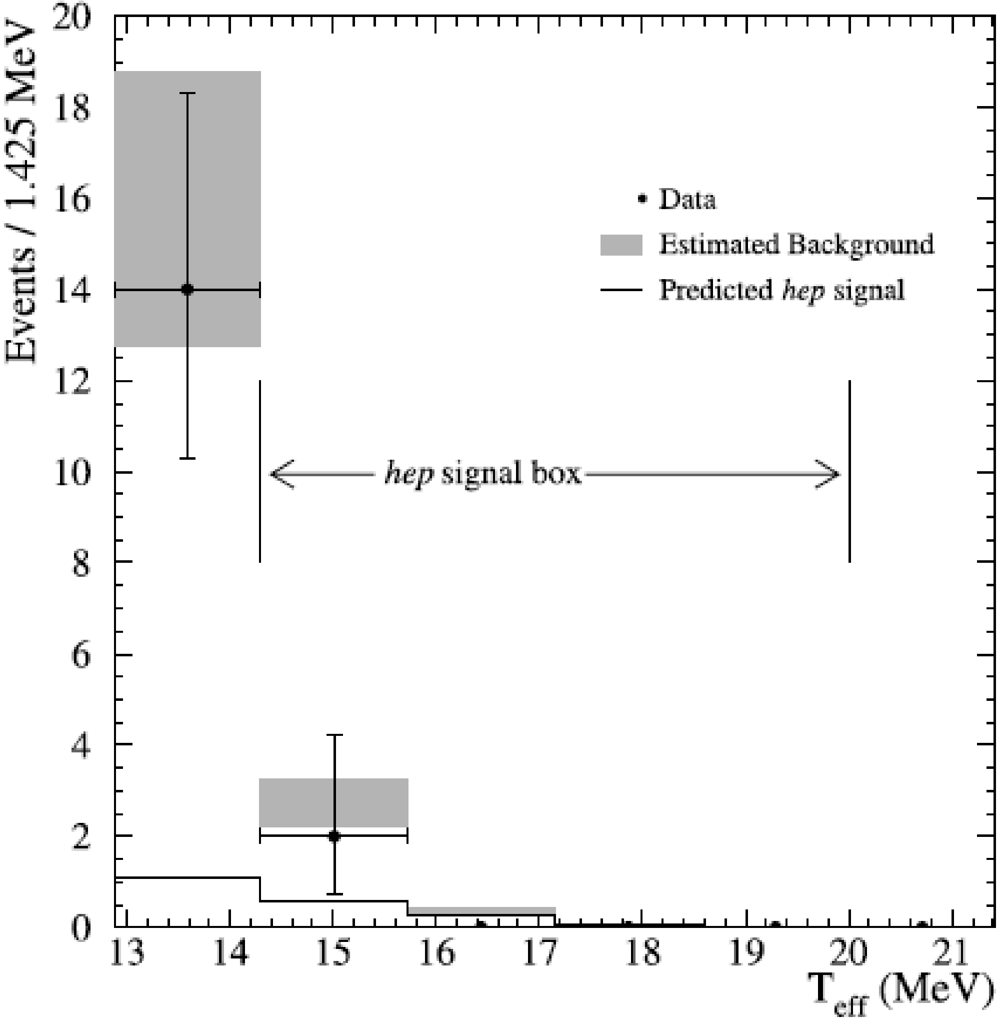
hep neutrinos

- Dominant background is ^{8}B solar neutrinos
- Normalize with low-energy fit with account for neutrino oscillations ($6 < T_{eff} < 12$ MeV)

DSNB neutrinos

- Dominant background is atmospheric neutrinos
- Signal region $21 < T_{eff} < 35$ MeV

hep and Diffuse Supernova Neutrinos



(Astrophys. J. 653, 1545, 2006)

hep neutrinos

- 2 events in signal box
- consistent with expected backgrounds

$\Phi_{hep} < 2.3 \times 10^4$ cm^{-2} s^{-1}
- 90% confidence level upper limit
- 2.9 times SSM prediction

DSNB neutrinos

- Zero events in signal box
- 0.18 background events expected

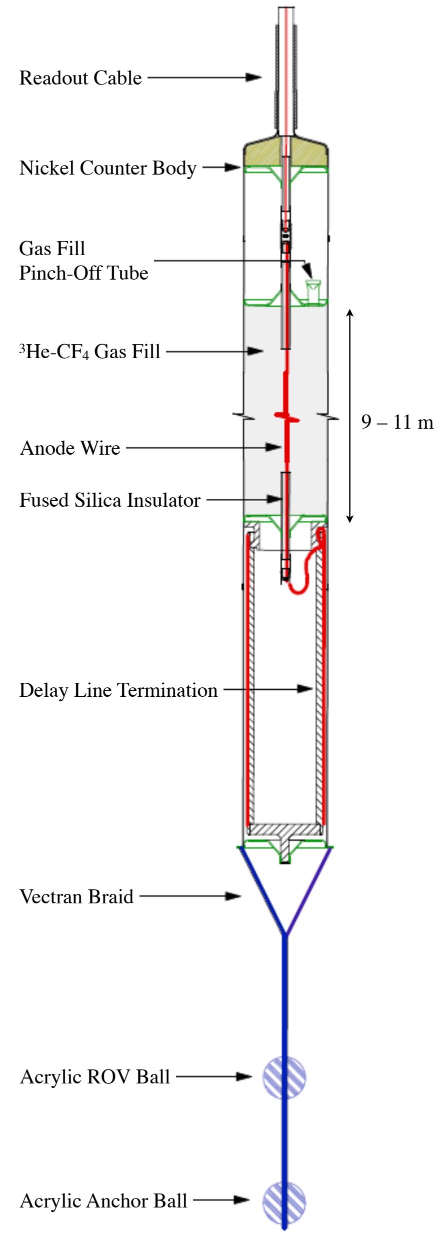
$\Phi_{DSNB, \nu_e} < 70$ cm^{-2} s^{-1} for 22.9 MeV < E_ν < 36.9 MeV
- 90% confidence level upper limit
- average of 5 models

The SNO Neutral Current Detector Array

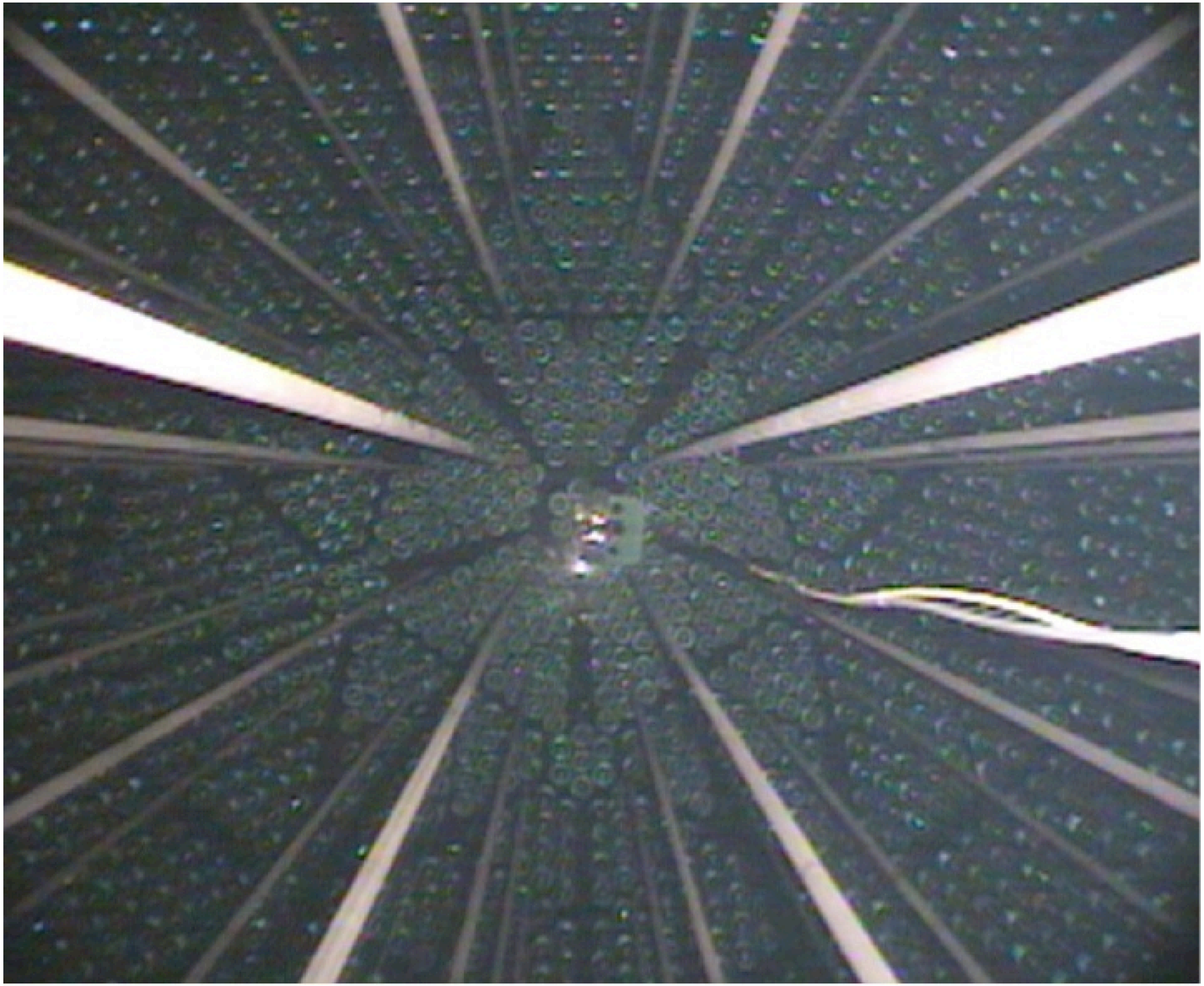
- First two phases of SNO relied on statistical separation of NC, CC, and ES signals using energy, radial distribution, angle with respect to the sun, and isotropy (salt phase only)
- Third phase has separate system to detect neutrons from NC interactions, so no statistical separation necessary
- NCD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

The SNO Neutral Current Detector

- 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



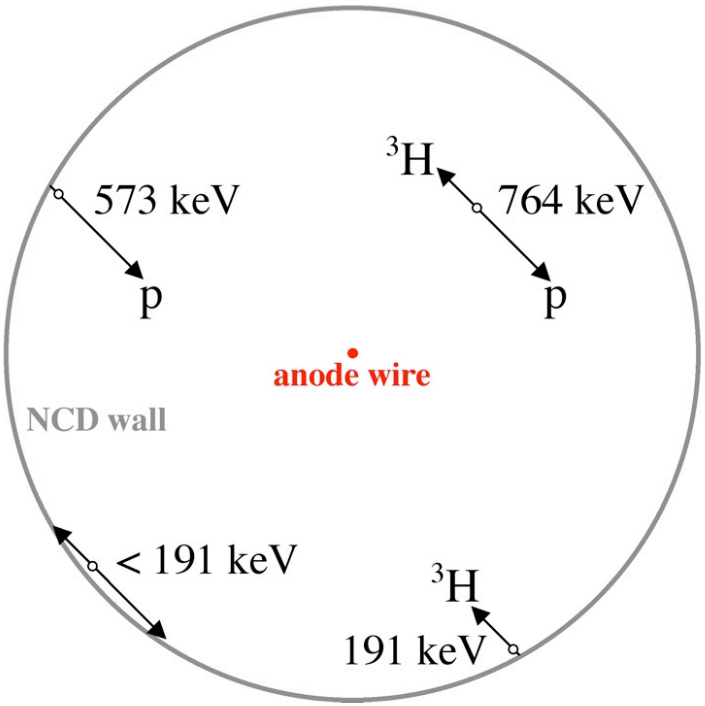
The SNO Neutral Current Detector Array



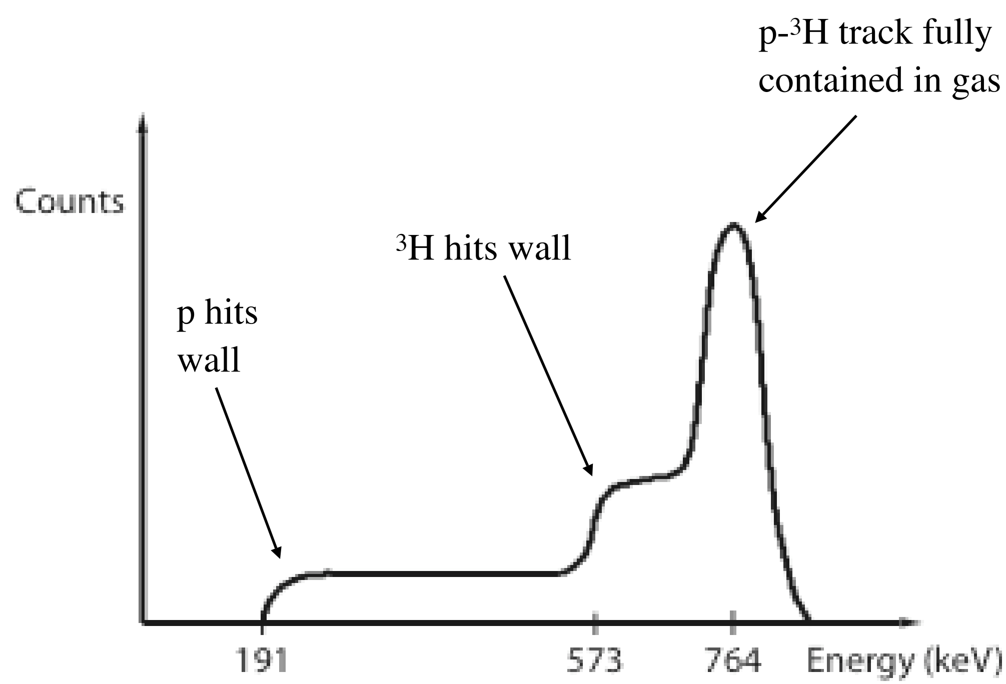
Neutron Capture in the NCDs

~ 1200 n captures per year in NCDs from solar ν

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

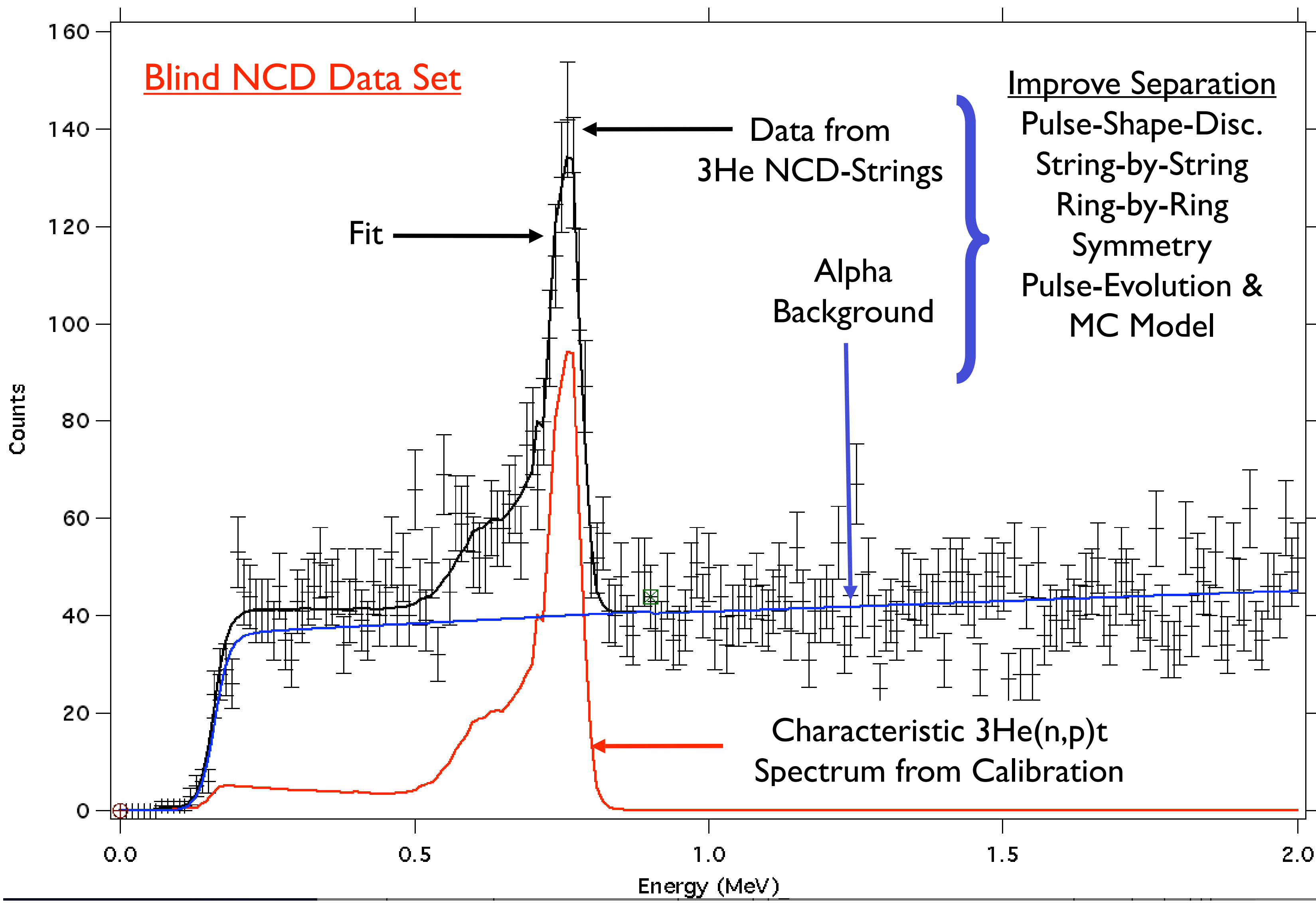


End view of an NCD with representative ionization tracks



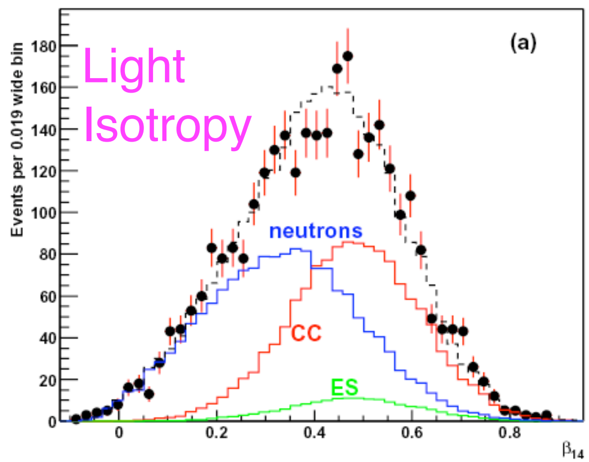
Idealized energy spectrum in a ^{3}He proportional counter

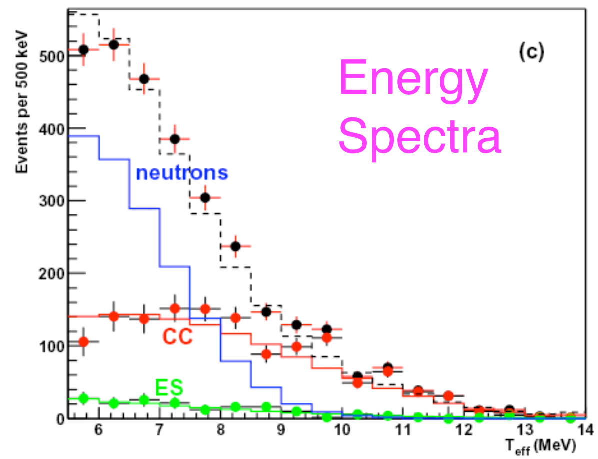
Blind Data from NCDs



Correlation Coefficients

Recall
Salt phase
analysis

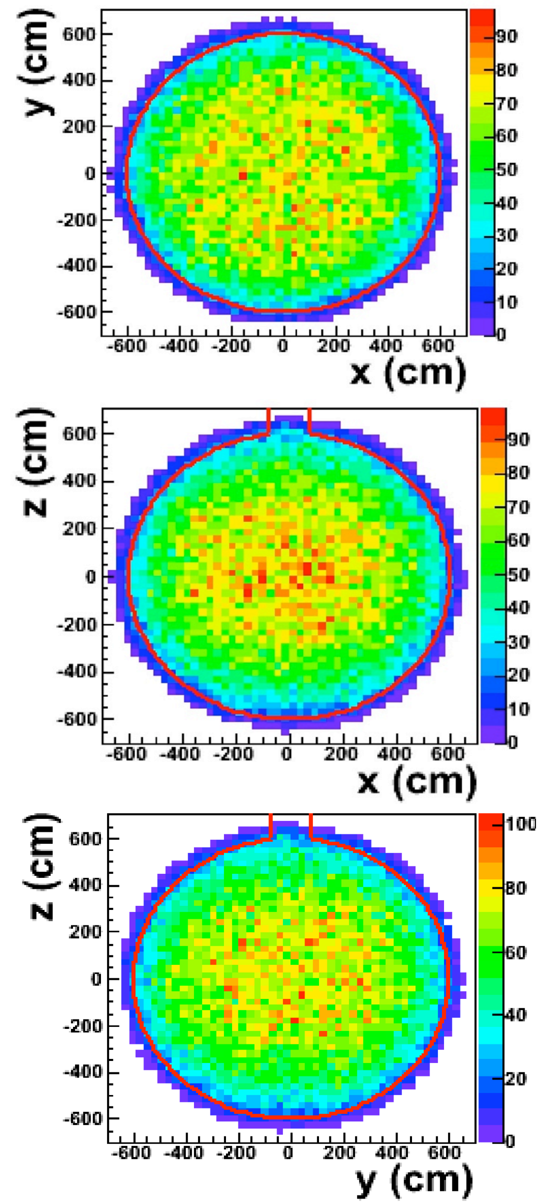




	D_2O unconstrained	D_2O constrained	Salt unconstrained	^3He
NC,CC	-0.950	-0.520	-0.521	~0
CC,ES	-0.208	-0.162	-0.156	~-0.2
ES,NC	-0.297	-0.105	-0.064	~0

Calibrations for NCD Phase

- In this phase need to improve NC systematics - increased calibration time (10% of time in D_2O phase, 30% in NCD phase)
- Neutron capture efficiency determined by adding ^{24}Na spike to D_2O and mixing to uniform distribution
- Neutron source scans every month with ^{252}Cf and AmBe
- Continued monthly optical and energy calibrations along with a number of special calibrations (thorium, ^{8}Li, radon)



Status of Analysis

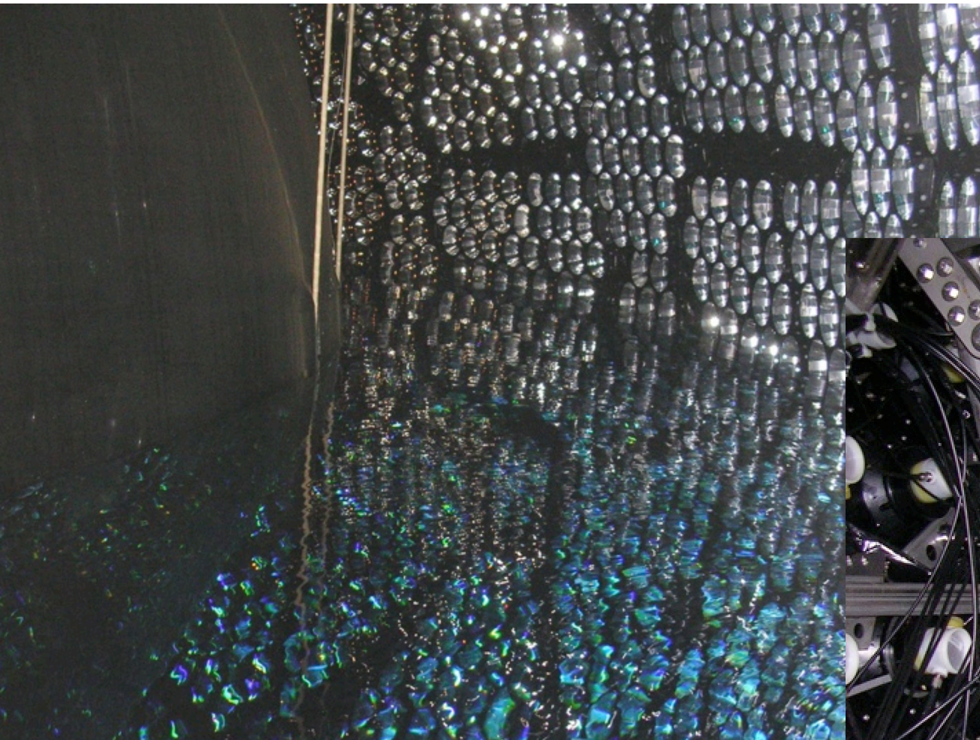
- Reprocessing data from entire data set (Nov. 2004 to Nov. 2006) with reconstruction and energy estimation - takes into account shadows of NCDs
- Analysts finalizing evaluation of systematics
- Results will include NC and CC flux
- Plan for publication in summer
- Also technical paper covering NCD construction, deployment, and operations
- Day-Night Asymmetry and CC spectrum will be next

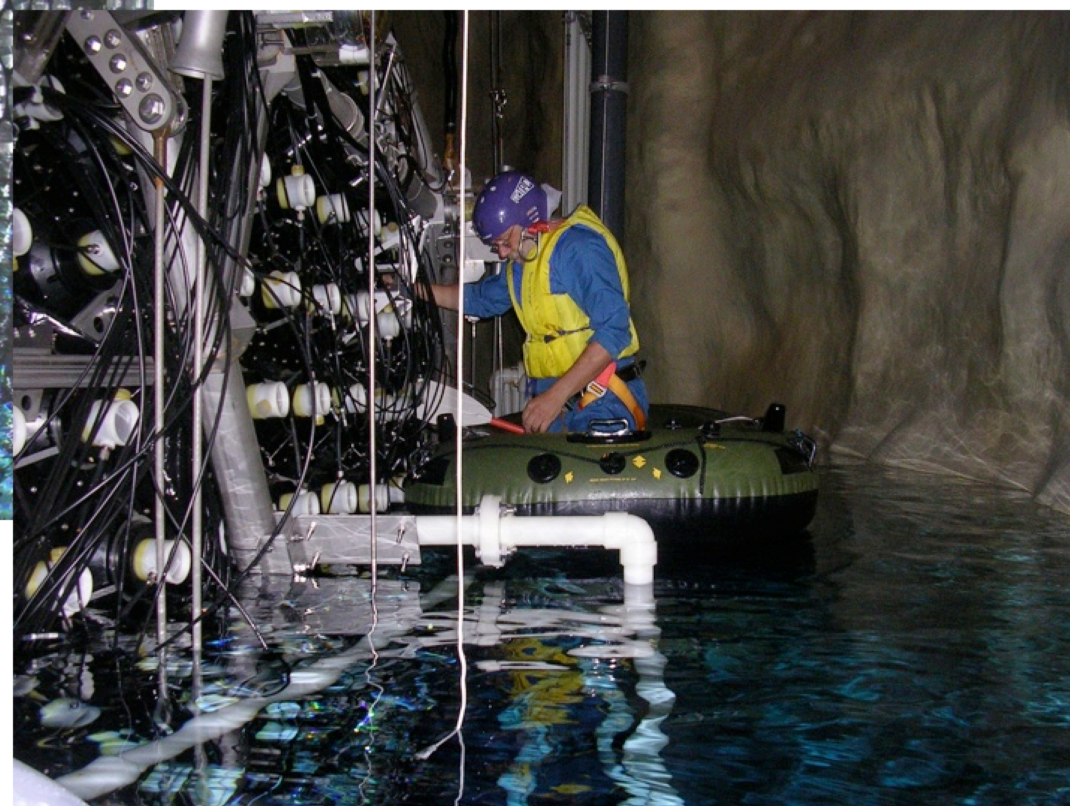
Decommissioning

- Completed removal of the NCDs for possible future use

Decommissioning

- Return of D_2O has begun
- Boating expeditions to examine state of detector continue





Future Plans for Detector

• Half of D_2O has been removed and return, completion expected in July

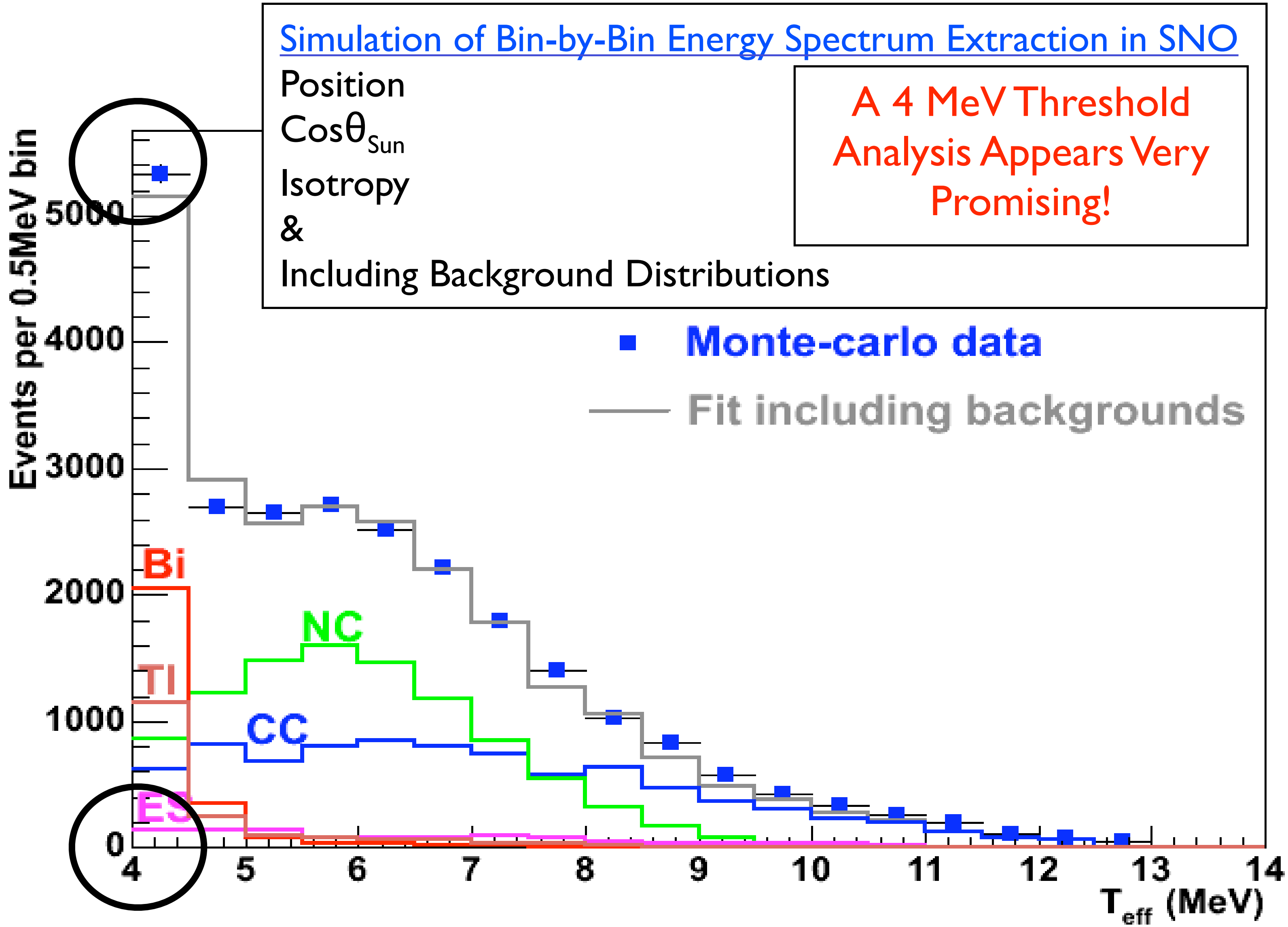
• SNO+ plans to replace the D_2O with liquid scintillator and examine pep solar neutrinos, geoneutrinos and ^{150}Nd neutrinoless double-beta decay

• Current plans are to "mothball" the detector with light water until SNO+ funding is complete and work begins

• Operations and staff are moving to SNOLab - an expansion of the underground lab for use by other experiments starting in 2008

• SNO will continue to analyze data and evaluate systematics, including:

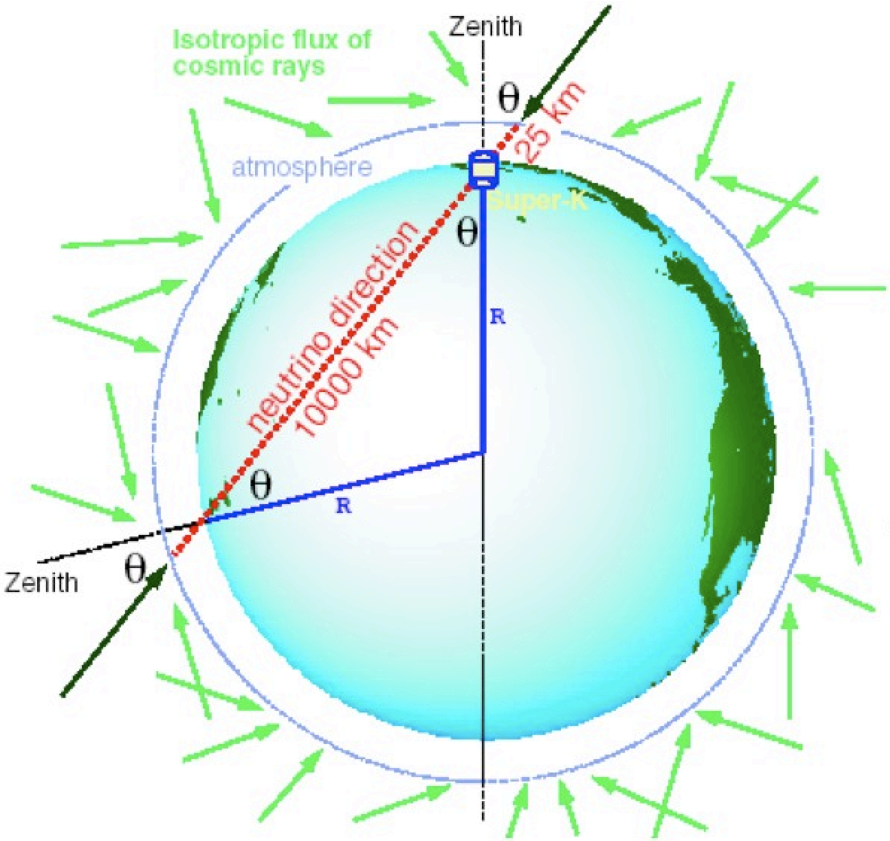
Low Energy Threshold Analysis



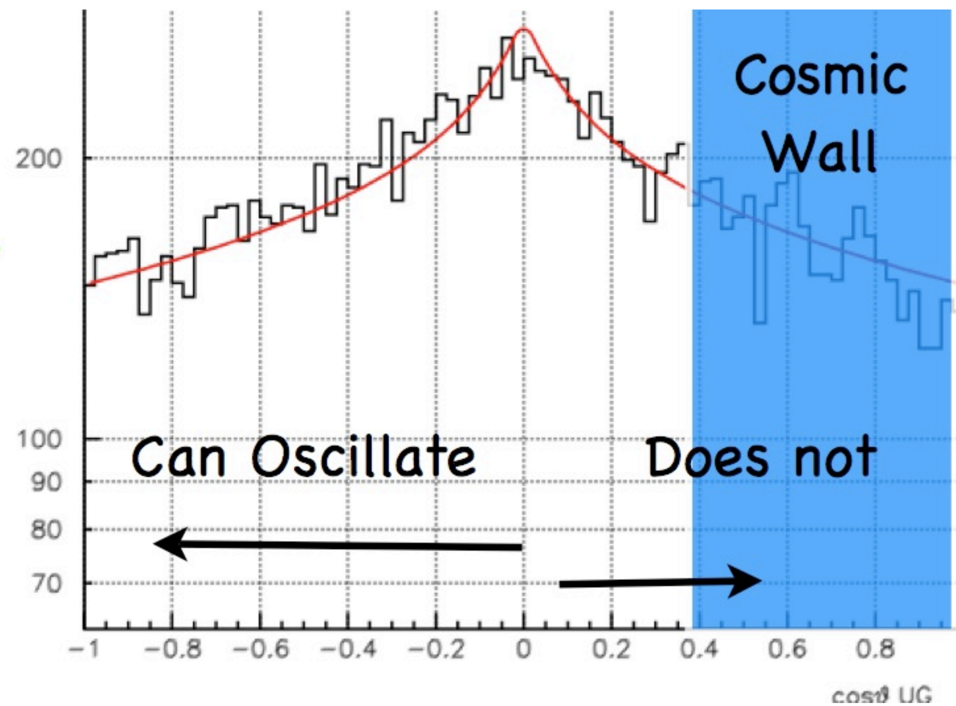
Low Energy Threshold Analysis

- Analysts currently working on combination of D_2O and Salt Phases with lower energy threshold
- Many improvements included -- things learned over the past 8 years
- Systematics have been improved
- Plans for Fall 2007 publication
- Start combined 3-phase low energy threshold analysis after that

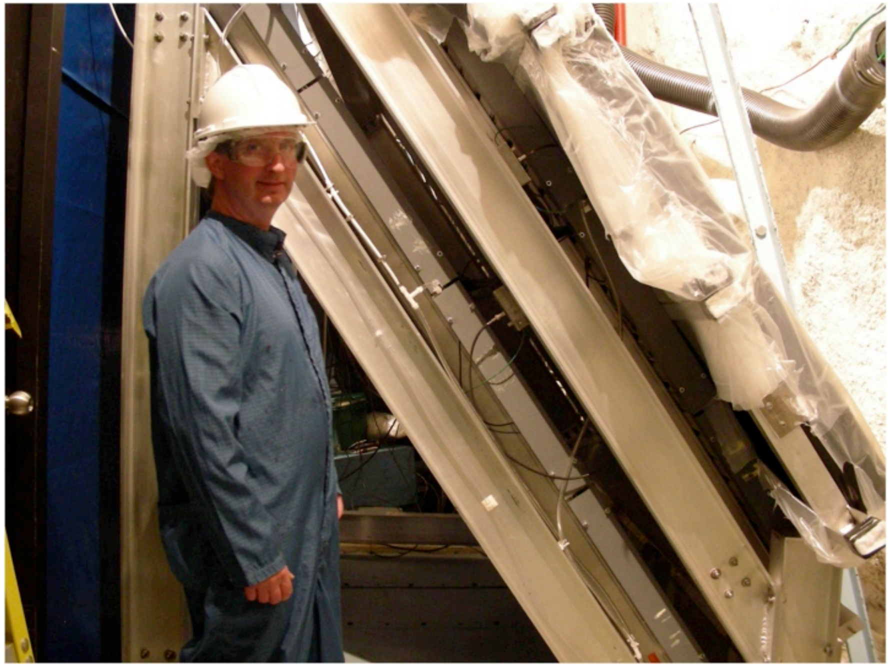
Atmospheric Neutrinos



• Provide a measurement of the neutrino-induced atmospheric flux as a function of zenith angle
• Analysis of through-going; expand into stopping vs. through-going muons

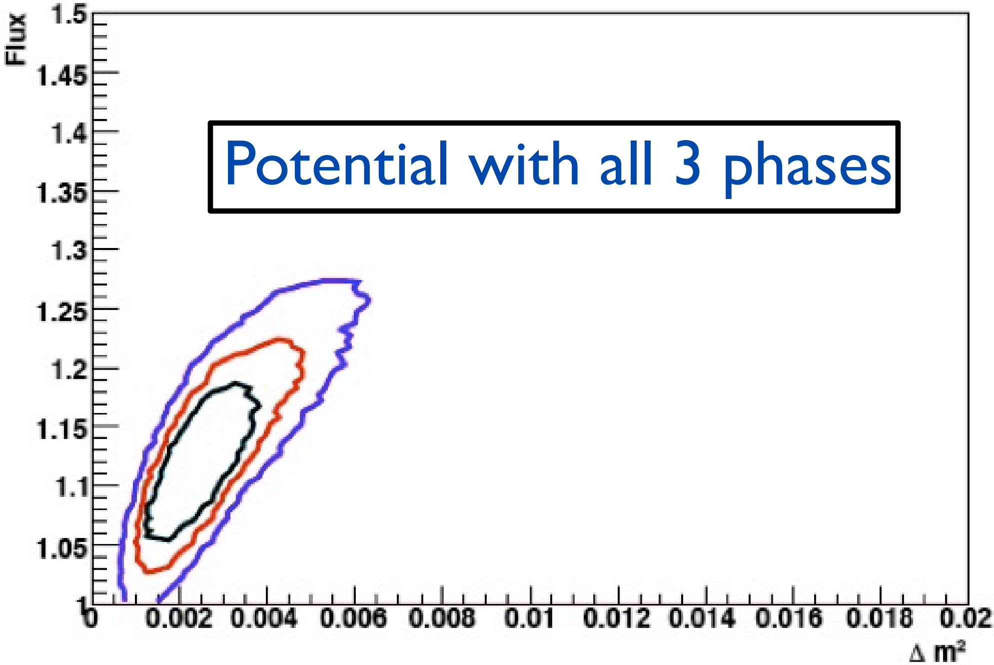


Atmospheric Neutrinos



- Summer 2006 -- added an external muon detection system
- 4 wire proportional counters and trigger scintillators
- Goal is one degree accuracy of muon fitter in SNO

- Analysis of D_2O phase data is complete (335 days)
- Working on Salt and NCD data will increase statistics
- Total of >1200 days
- Statistical and systematic uncertainty equivalent



Other Analyses

- *hep* neutrino analysis for all 3 phases
- Periodicity of flavor content and burst search for all 3 phases
- Low energy threshold analysis for all 3 phases
- Day-Night analysis for all 3 phases
- Atmospheric neutrino analysis with through-going and stopping muons for all 3 phases
- Spallation neutrons and cosmic-ray flux at depth
- Other topics as time and manpower allow

The SNO Collaboration

- Brookhaven National Laboratory
- Lawrence Berkeley National Laboratory
- Los Alamos National Laboratory
- Louisiana State University
- Massachusetts Institute of Technology
- University of Pennsylvania
- University of Texas at Austin
- University of Washington
- University of British Columbia
- Carleton University
- University of Guelph
- Laurentian University
- Queen's University
- TRIUMF
- University of Oxford
- LIP, Lisbon, Portugal