UNIVERSITY OF LIVERPOOL

The Sudbury Neutrino Observatory

NEIL MCCAULEY FOR THE SNO COLLABORATION

The Nobel Prize in Physics 2015

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2015 to

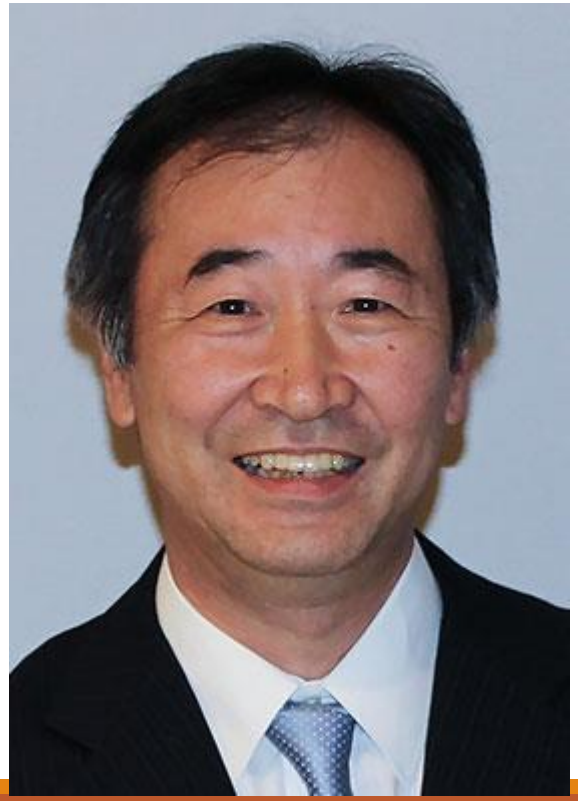
Takaaki Kajita

Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald

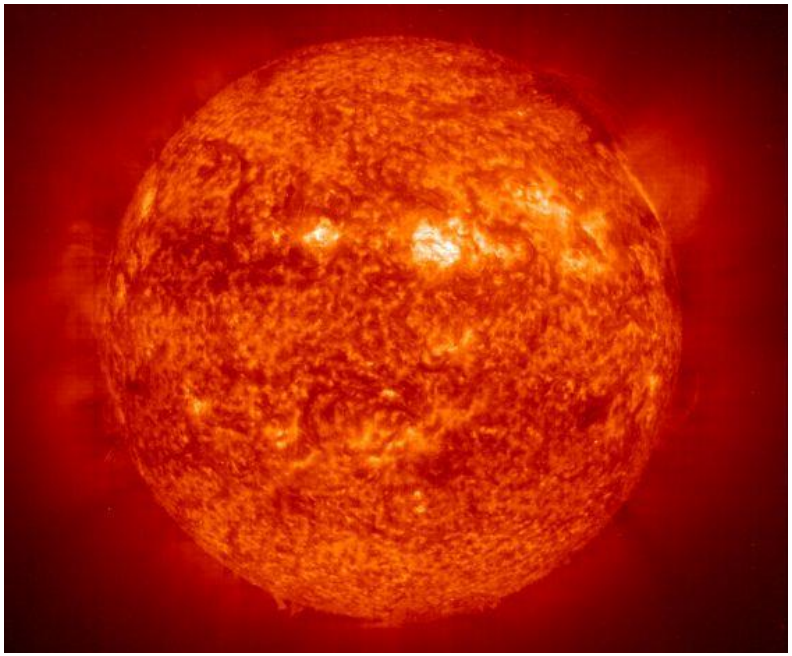
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

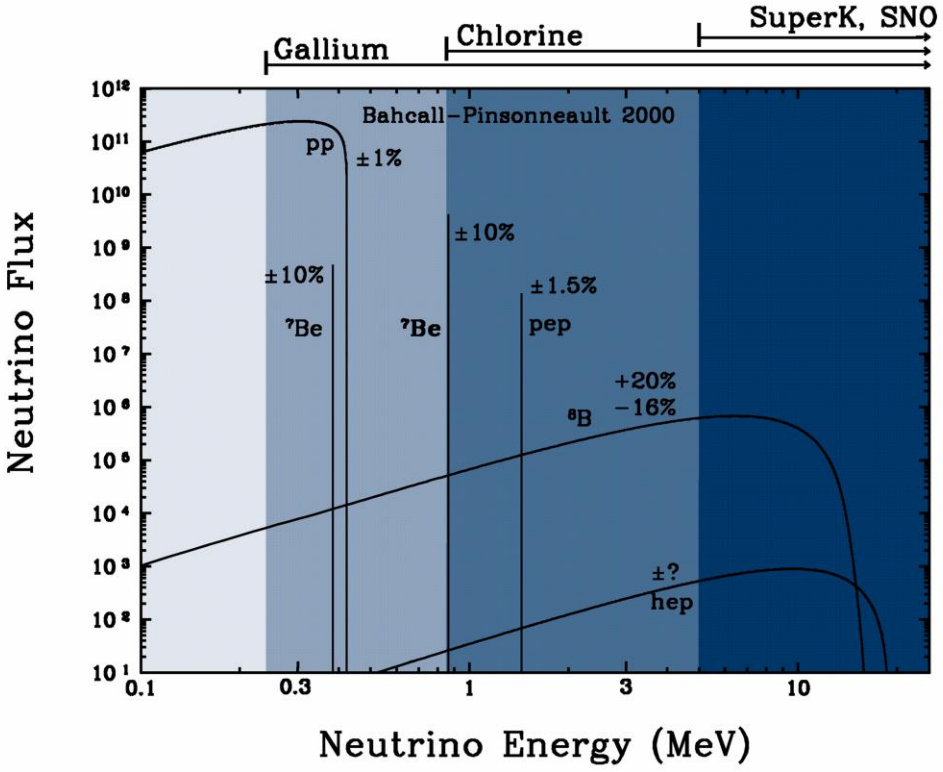
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"



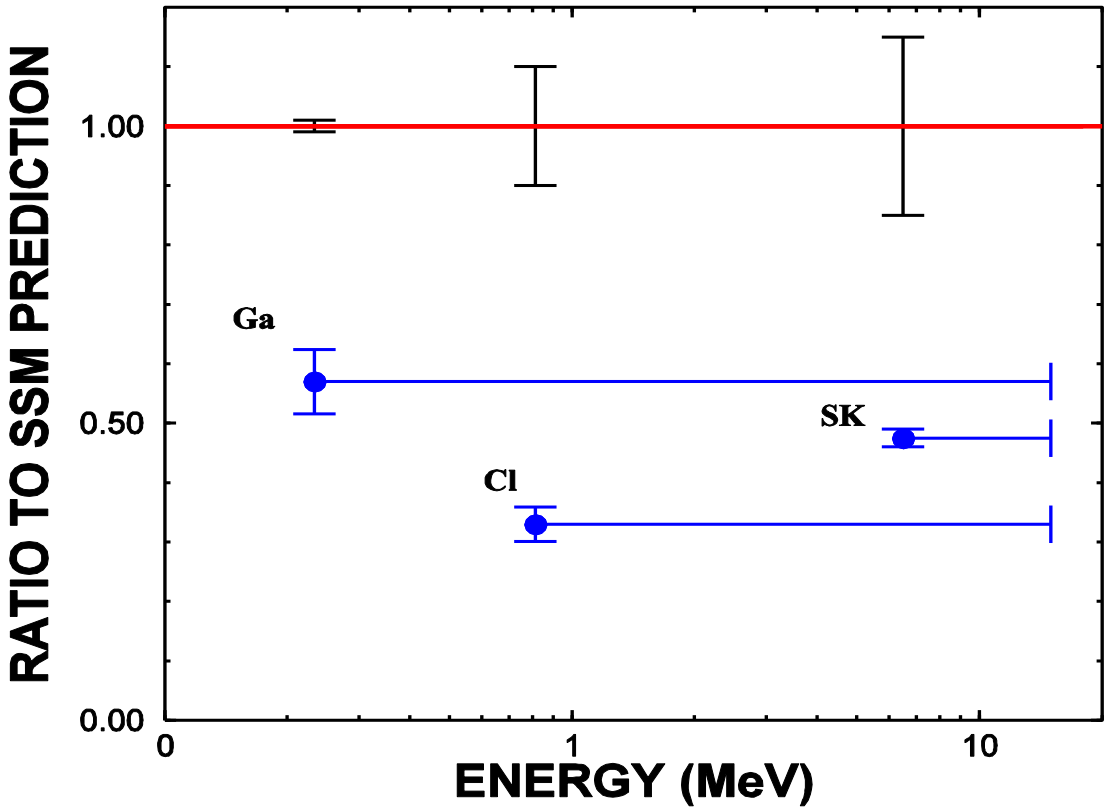
Solar Neutrinos

$4p \rightarrow \alpha + 2e^{+} + 2\nu_e + \text{energy}$





The Solar Neutrino Problem c. 2000



Energy dependent deficit is observed solar neutrinos

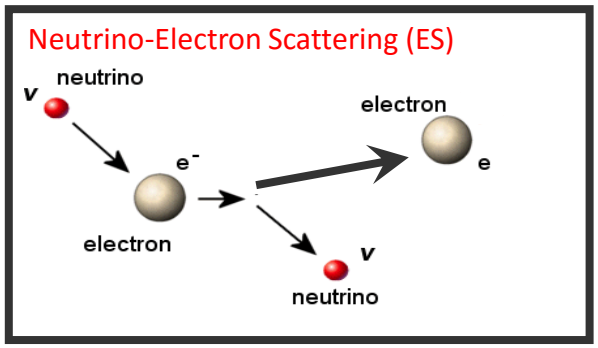
SNO Collaboration Meeting, Chalk River, 1986

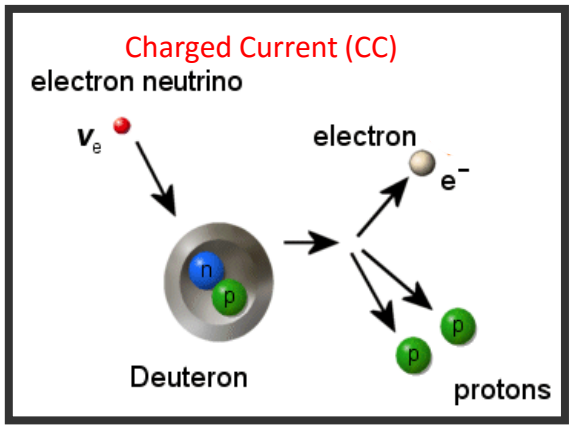
PROPOSAL TO BUILD A NEUTRINO OBSERVATORY IN SUDBURY, CANADA

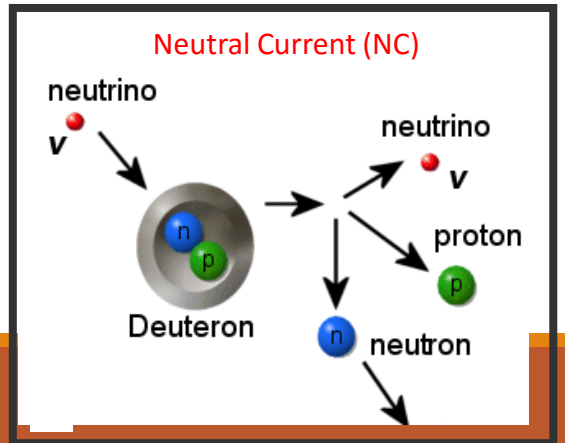
D. Sinclair, A.L. Carter, D. Kessler, E.D. Earle, P. Jagam, J.J. Simpson, R.C. Allen, H.H. Chen, P.J. Doe, E.D. Hallman, W.F. Davidson, A.B. McDonald, R.S. Storey, G.T. Ewan, H.-B. Mak, B.C. Robertson Il NuovoCimentoC9, 308 (1986)

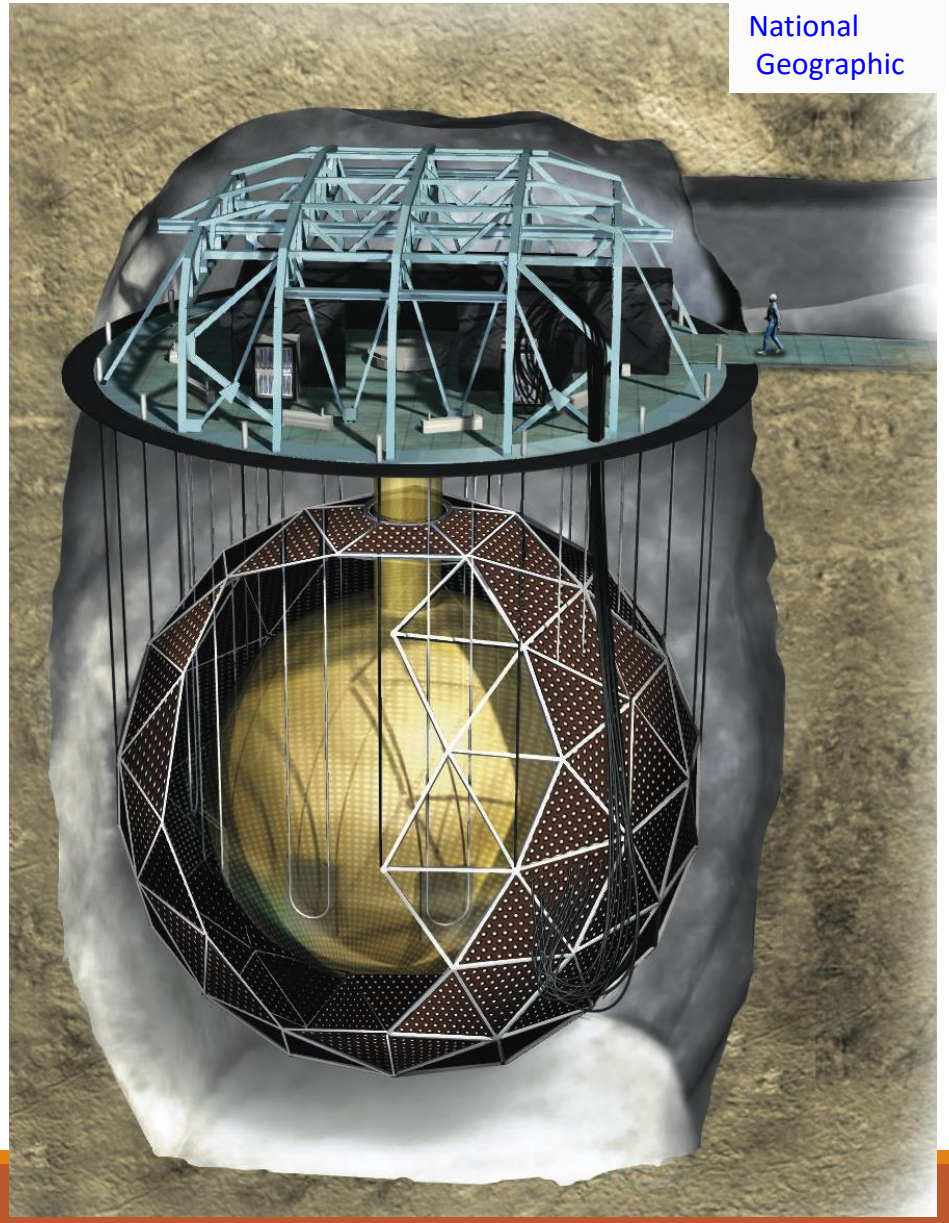
Sudbury Neutrino Observatory

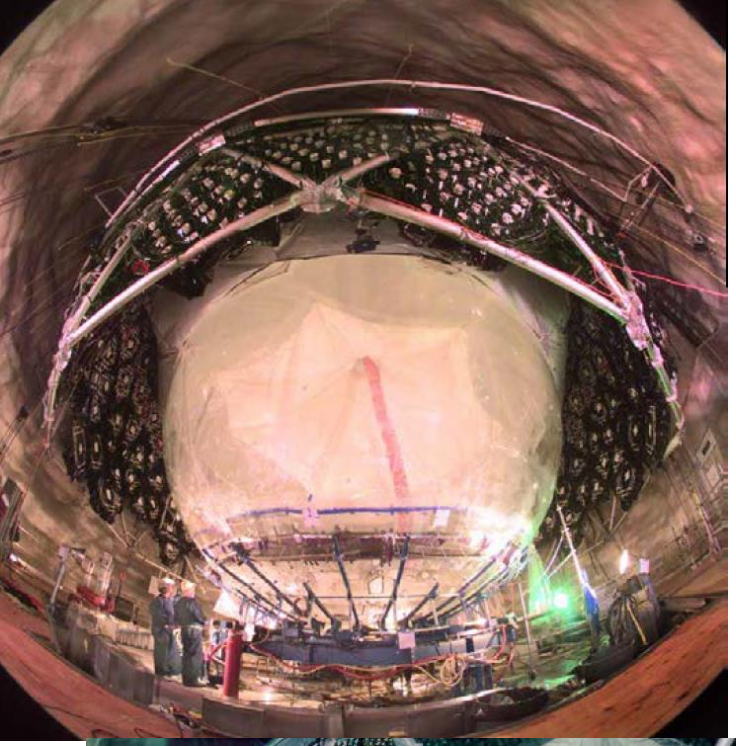
- neutrino reactions on deuterons





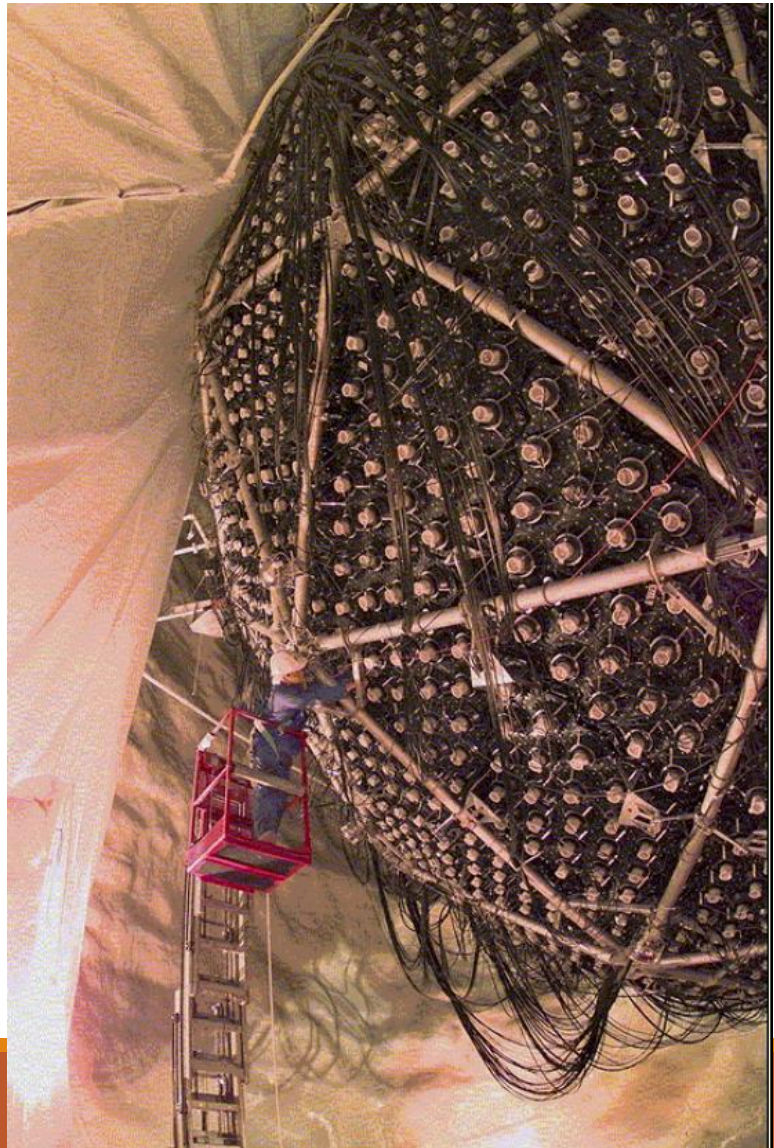




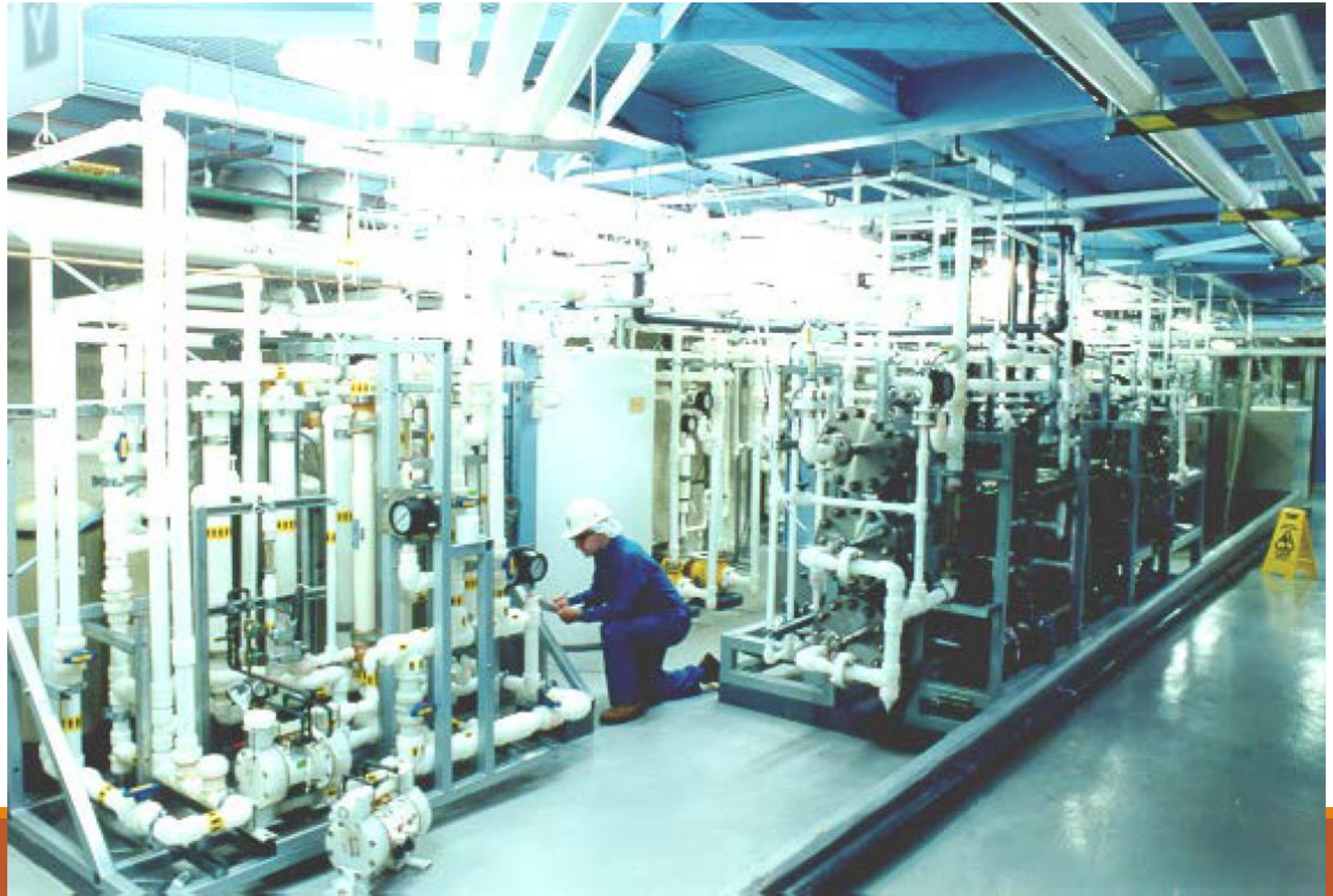


SNO: One million pieces transported down in the 3x3x4 m mine cage and reassembled in ultra clean conditions. Every worker takes a shower and wears clean, lint free clothing.

70000+ showers taken during the project.



Water systems were developed to provide low radioactivity light water and heavy water: 1 billion times better than tap water. Less than one radioactive decay per day per ton of water!!

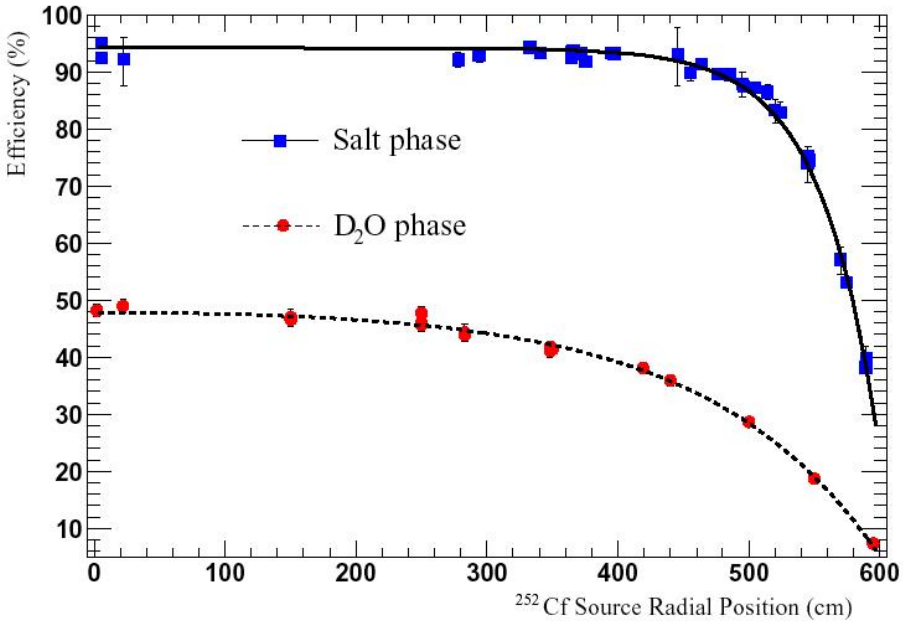


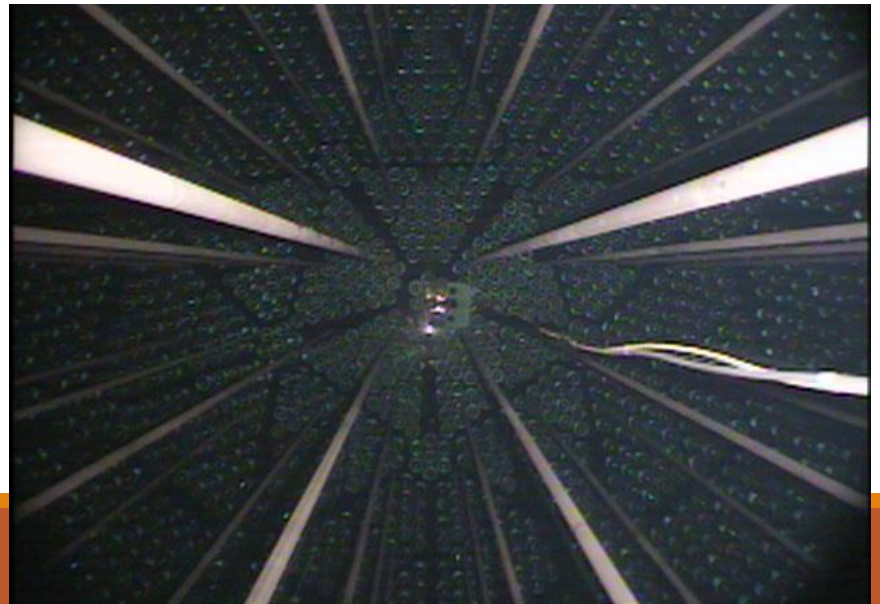
Detecting Neutrons: The Three Phases of SNO

Phase 1: Pure D_2O.
- Nov 1999 – May 2001 : 306 days.
- Neutrons Capture on D
  - Detect 6.25MeV γ-ray.

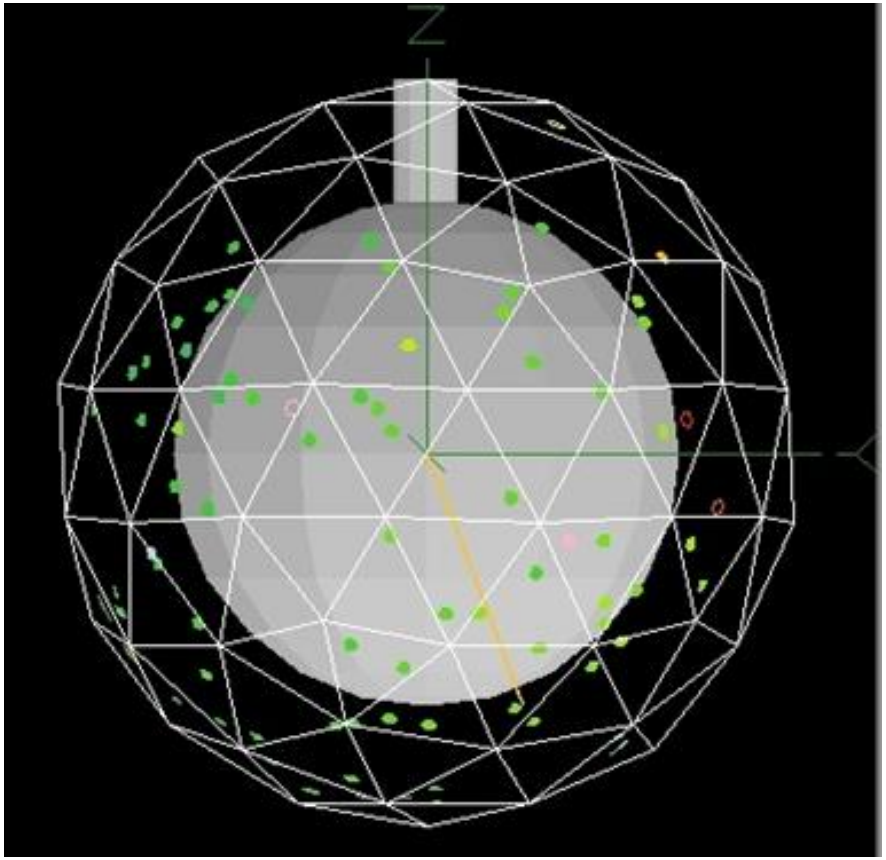
Phase 2: D_2O+NaCl
- Jul 2001 - Sep 2003 : 391 days.
- Neutrons Capture on ^{35}Cl
  - Detect multiple γ-rays. ΣE=8.6MeV

Phase 3: ^3He Proportional Counters (NCD)
- Nov 2004 - Nov 2006 385 days.
- Neutrons capture on ^3He
  - Detected in the counters.





A Typical Solar Neutrino Event in SNO



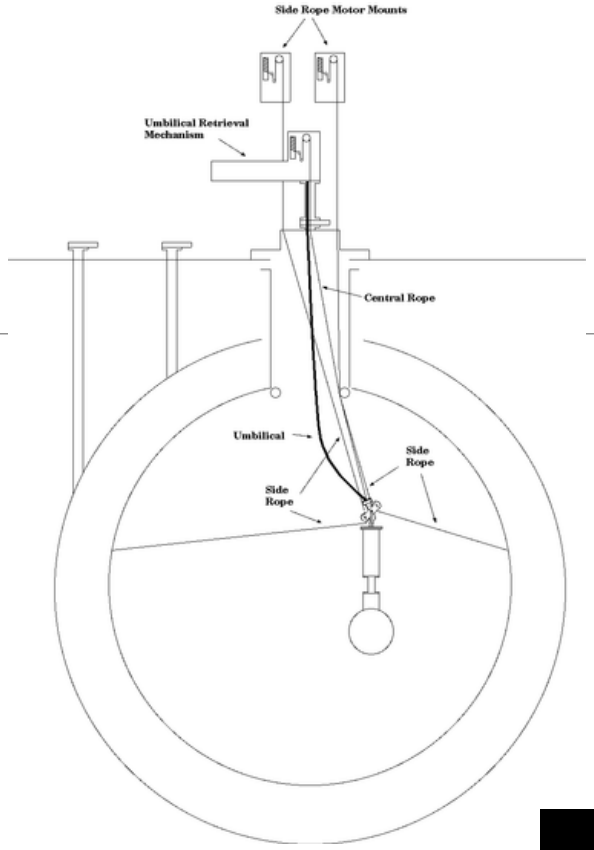
We measure
- Number of hit PMTs
- PMT times, charges
- Global event time

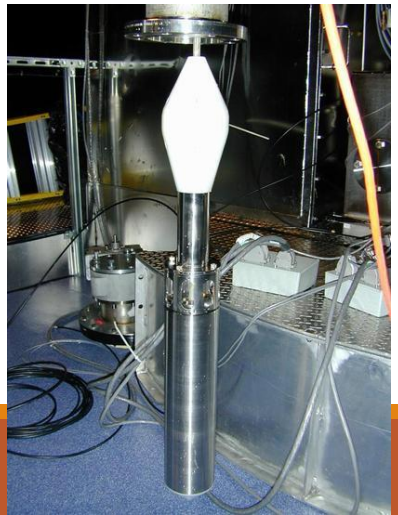
We derive
- Position
  - Vertex Resolution 16cm
- Direction
  - Angular Resolution 26.7^{o}
- Energy
- Isotropy

Calibration

Deployment of multiple calibration sources was essential to produce the systematic uncertainties achieved.

- Laserball
- ^{16}N
- ^{8}Li
- pT
- ^{252}Cf
- AmBe
- Encapsulated U & Th
- Rn, ^{24}Na spikes

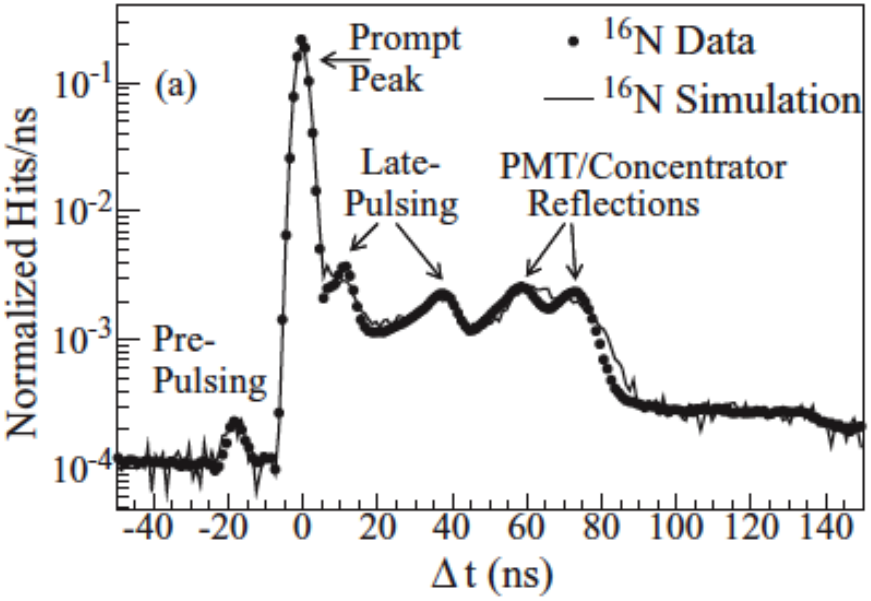


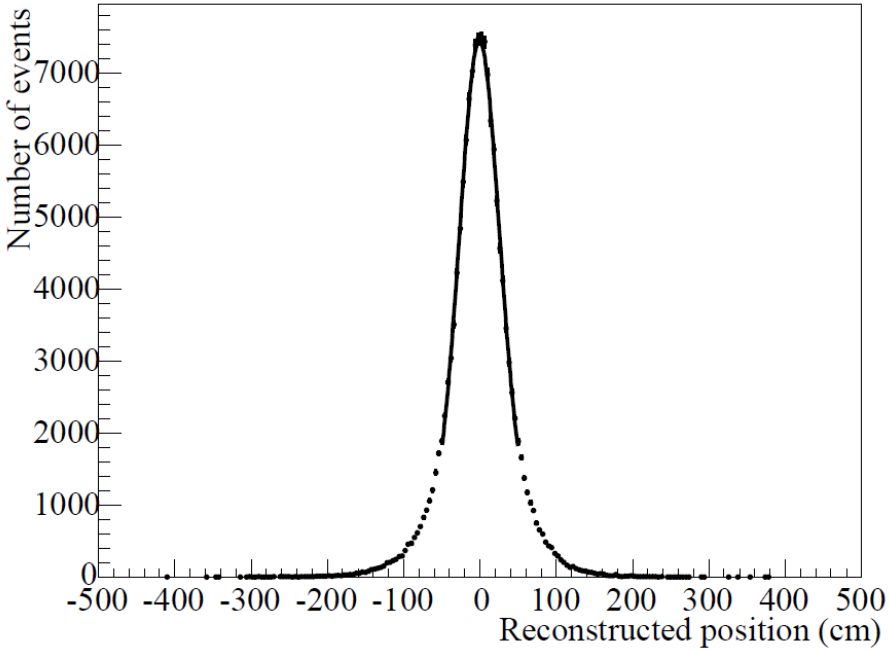


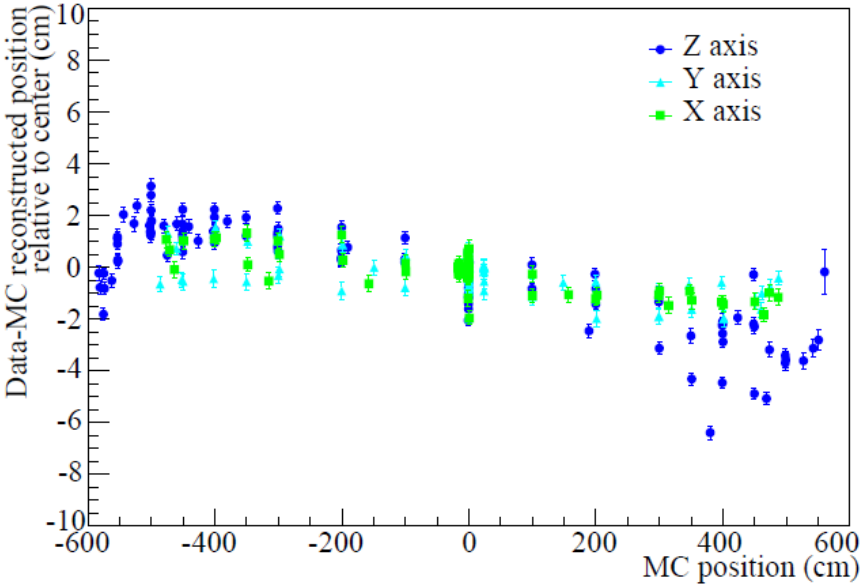
Reconstruction

Reconstruct vertex fitting time residual distribution

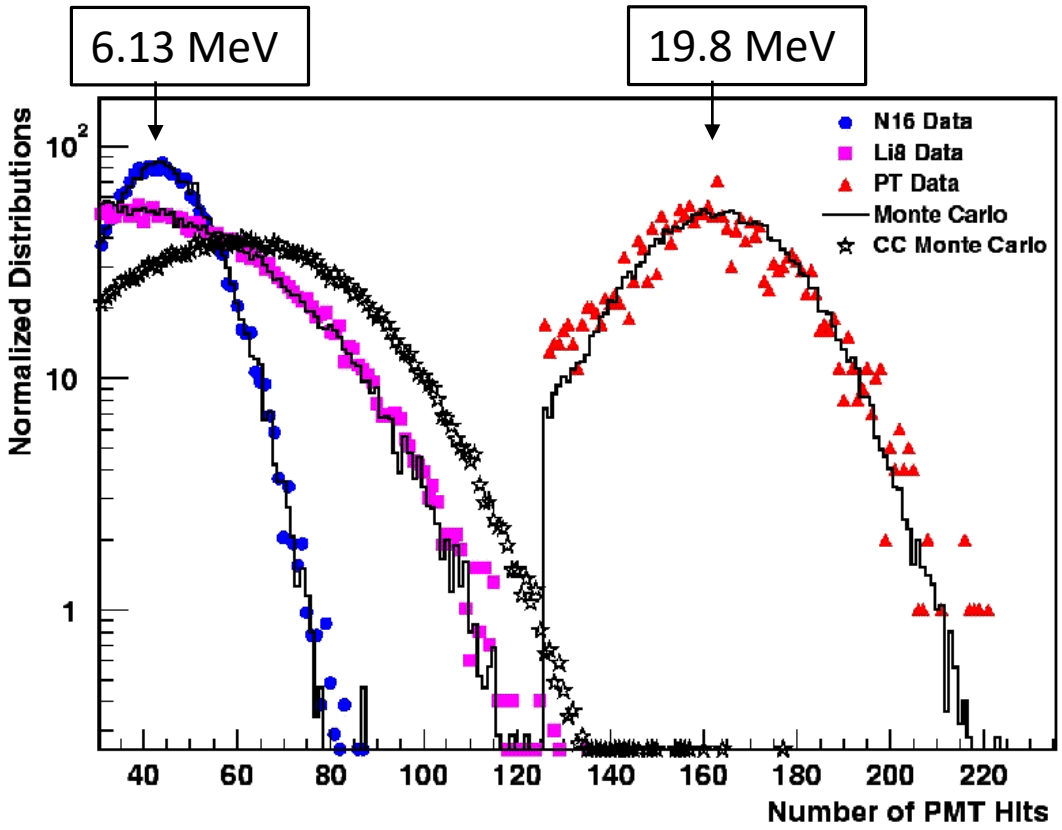
Fiducial volume uncertainty ~0.5%





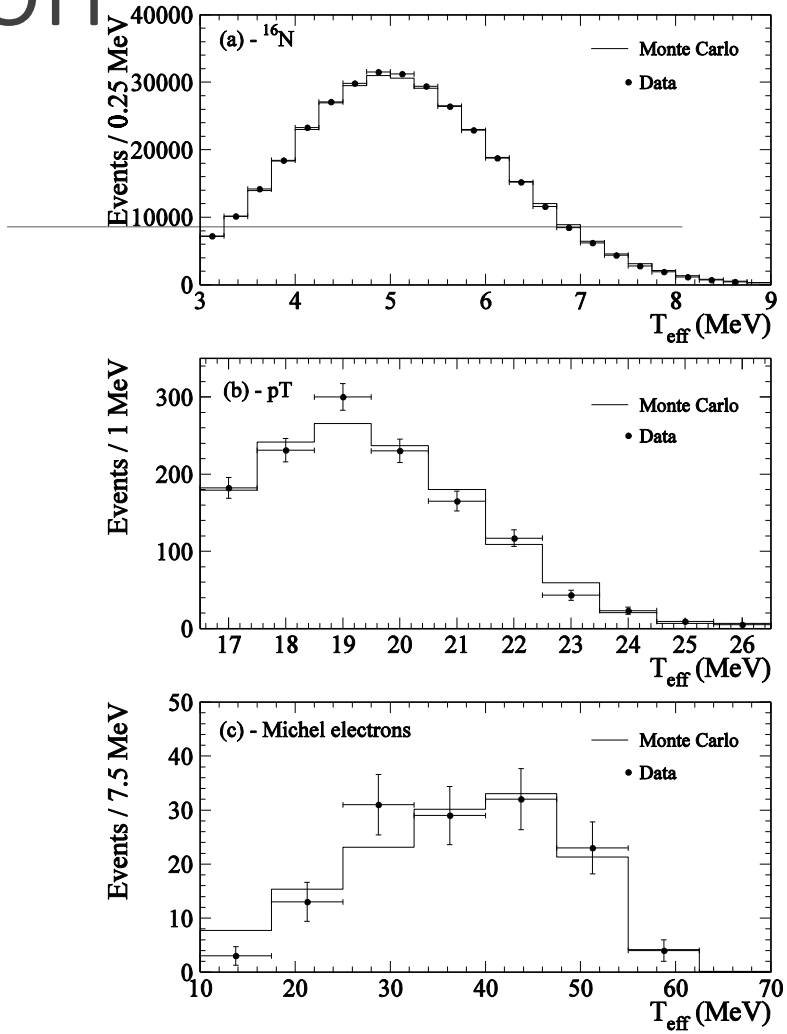


Energy Reconstruction



Uncertainty	Phase I	Phase II
PMT Status	±0.01%	±0.01%
Threshold/Gain	+0.18 − 0.31%	+0.13 − 0.07%
Rate	±0.3%	±0.05%
Source	±0.4%	±0.4%
Spatial Variation	±0.18%	±0.31%
Total	+0.56 − 0.62%	+0.52 − 0.51%

TABLE III: Summary of energy scale uncertainties.

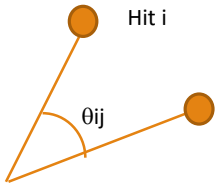


Isotropy

Isotropy Parameters

- θ_{ij}
  - Relatively simple, mean of average hit pair opening angle from vertex.

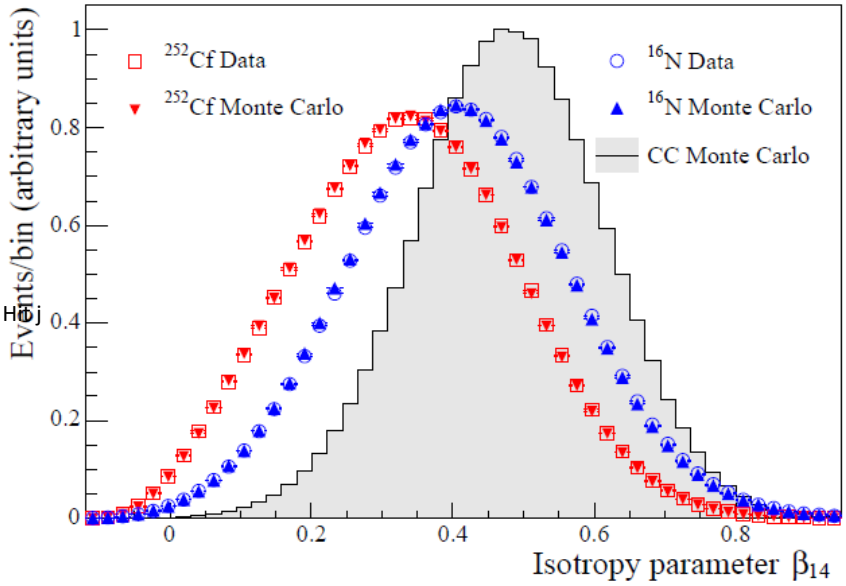
$$\langle \theta_{ij} \rangle = \frac{2}{N(N-1)} \left[\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \theta_{ij} \right]$$



- β_{14}
  - β parameters result from decomposition of hit angular distribution via spherical harmonics

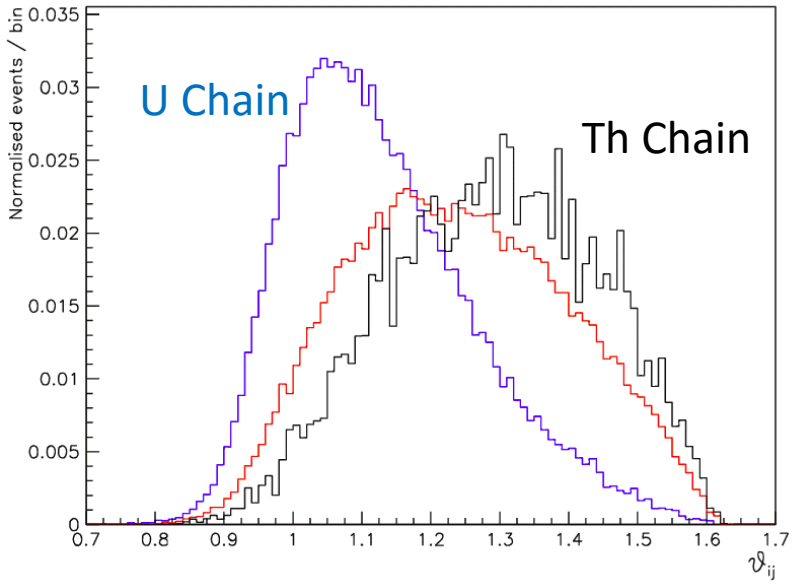
$$\beta_l = \frac{2}{N(N-1)} \left[\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} P_l(\cos\theta_{ij}) \right]$$

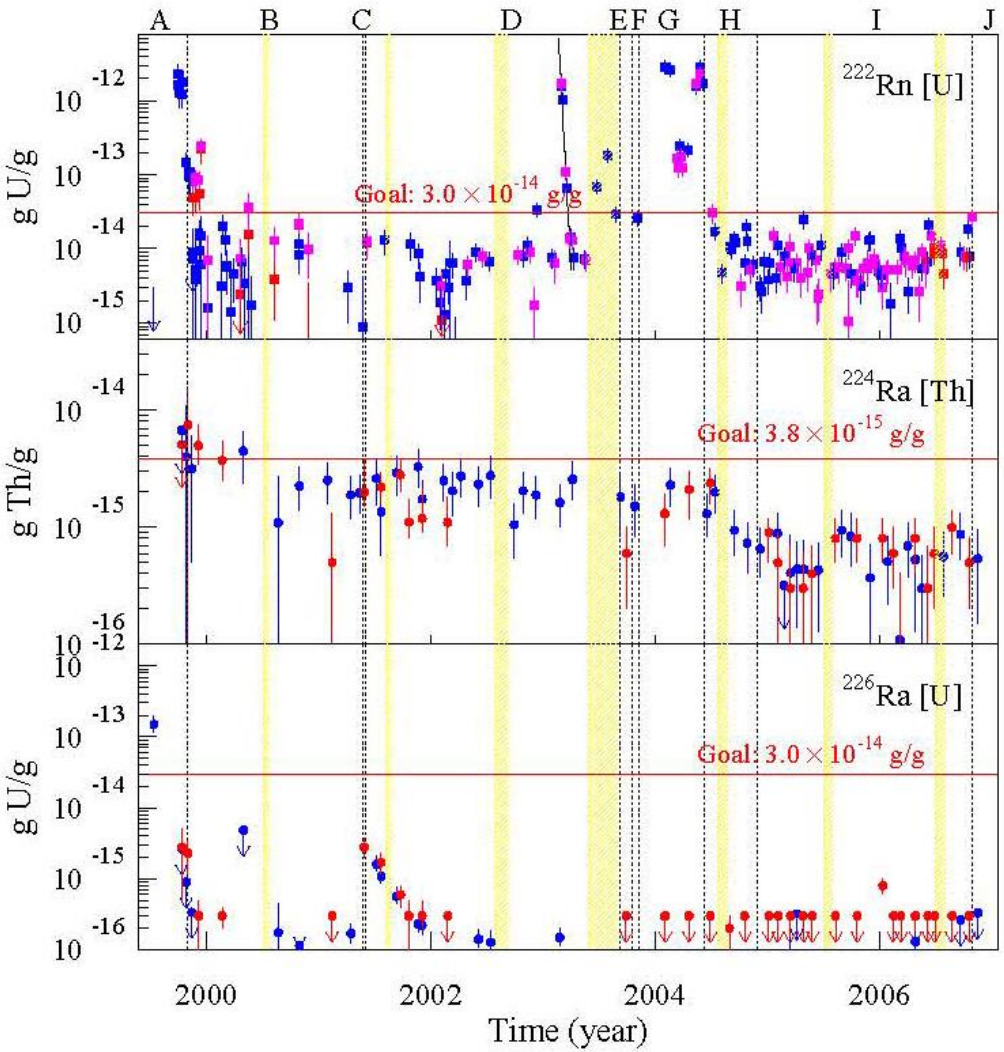
  - $\beta_{14} = \beta_1 - 4\beta_4$ was found to be the best combination to separate neutron captures on ^{35}Cl



Uncertainties ~0.4% on mean and width.

U/Th Content





Exsitu

- Ion Exchange
- Membrane degassing
- Count daughters

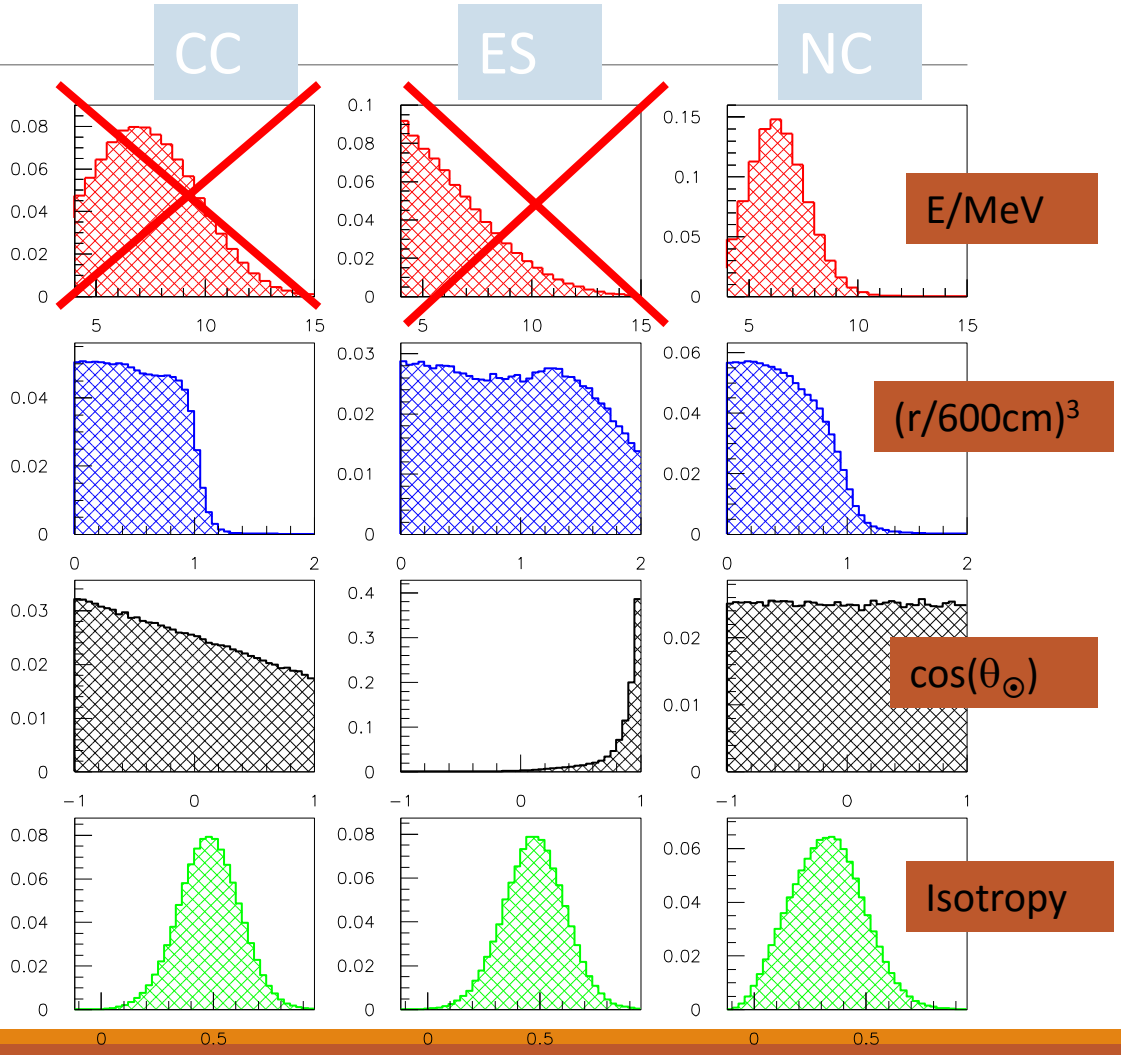
Insitu

- Fit to isotropy of low energy data

Photodisintegration background well understood.

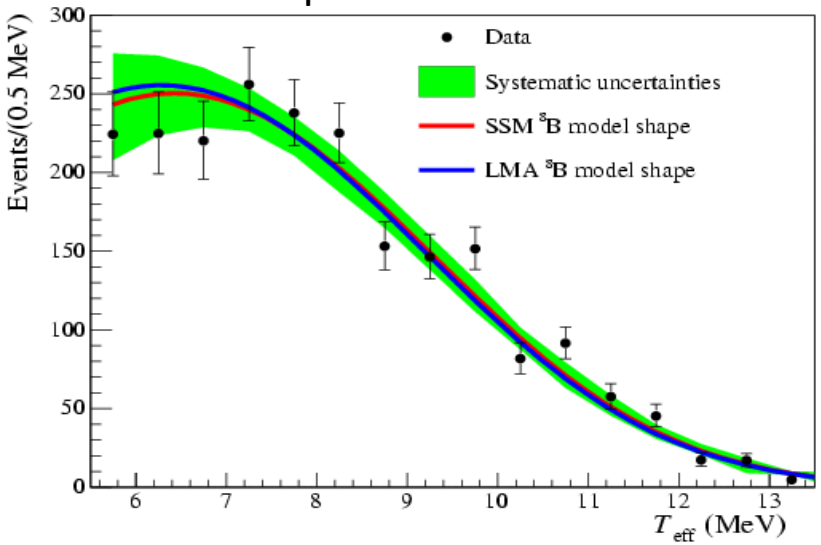
Extraction of Neutrino Signals.

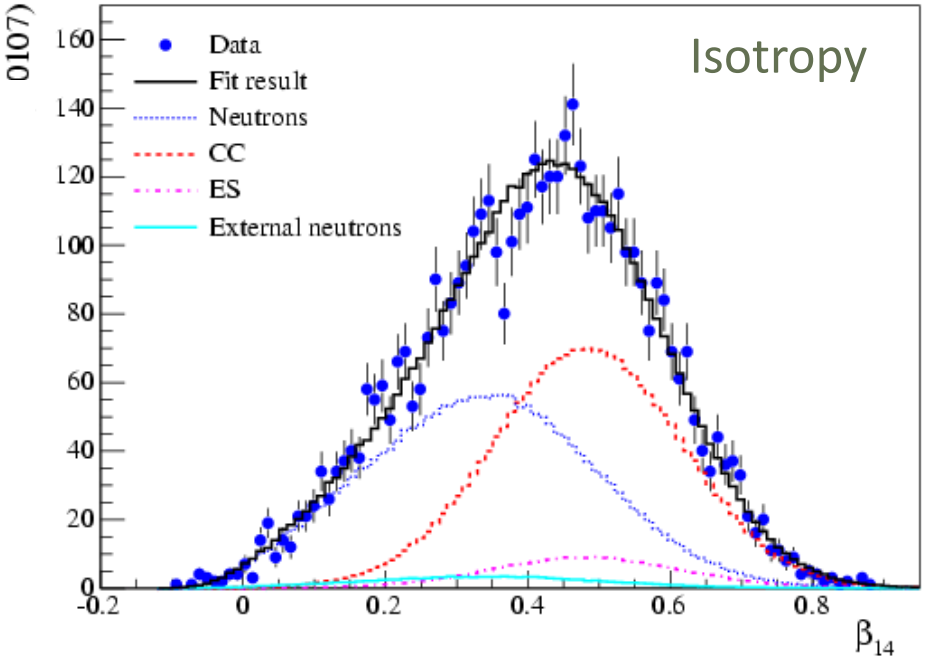
- Carry out a maximum Likelihood fit of the data to signal PDFs.
  - 4 Dimensional fit.
    - Energy.
    - Radius.
    - Direction.
    - Isotropy (salt only).
- Isotropy allows us to remove CC and ES energy PDFs.
  - Model Independent Flux Extraction.
  - Extract the Spectrum.

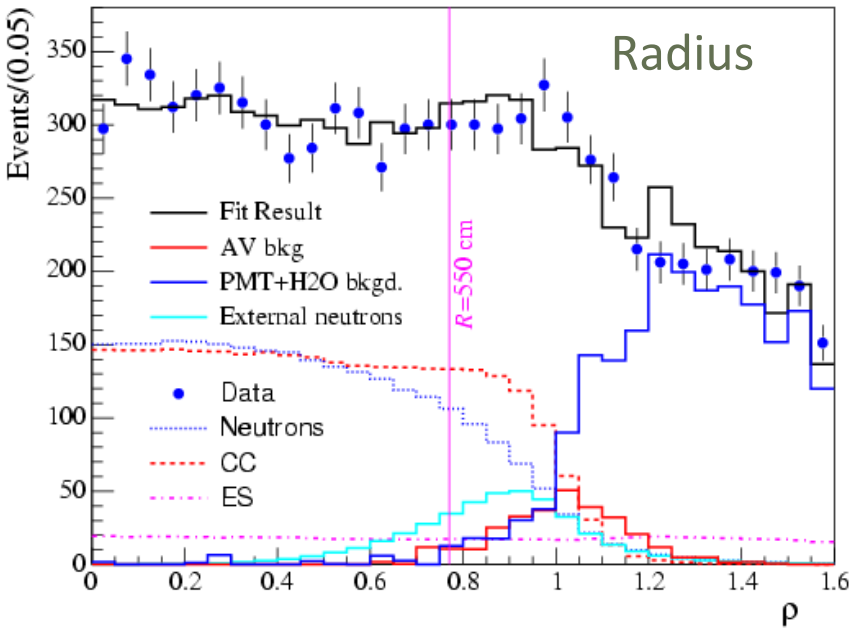


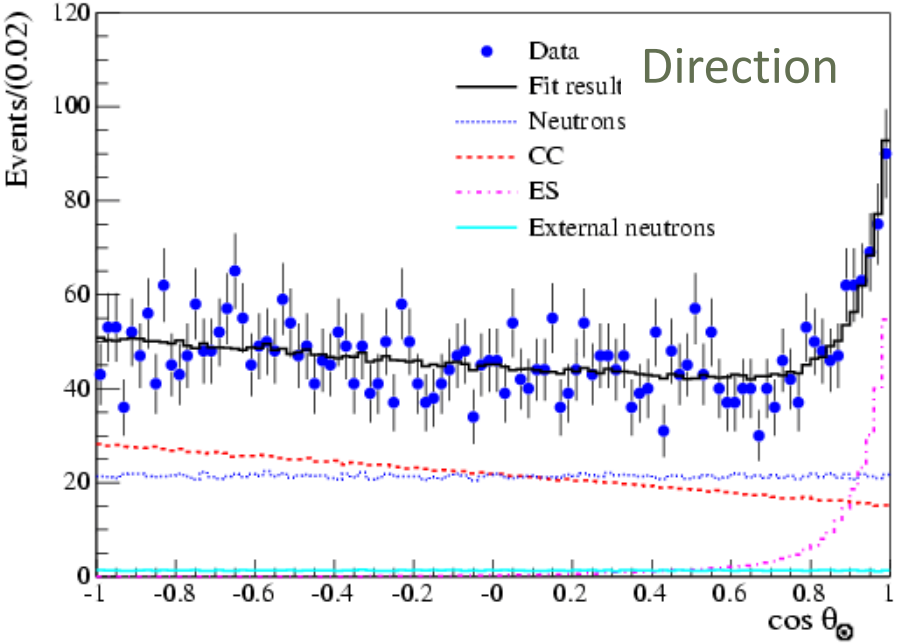
Salt Data

CC Spectrum and LMA



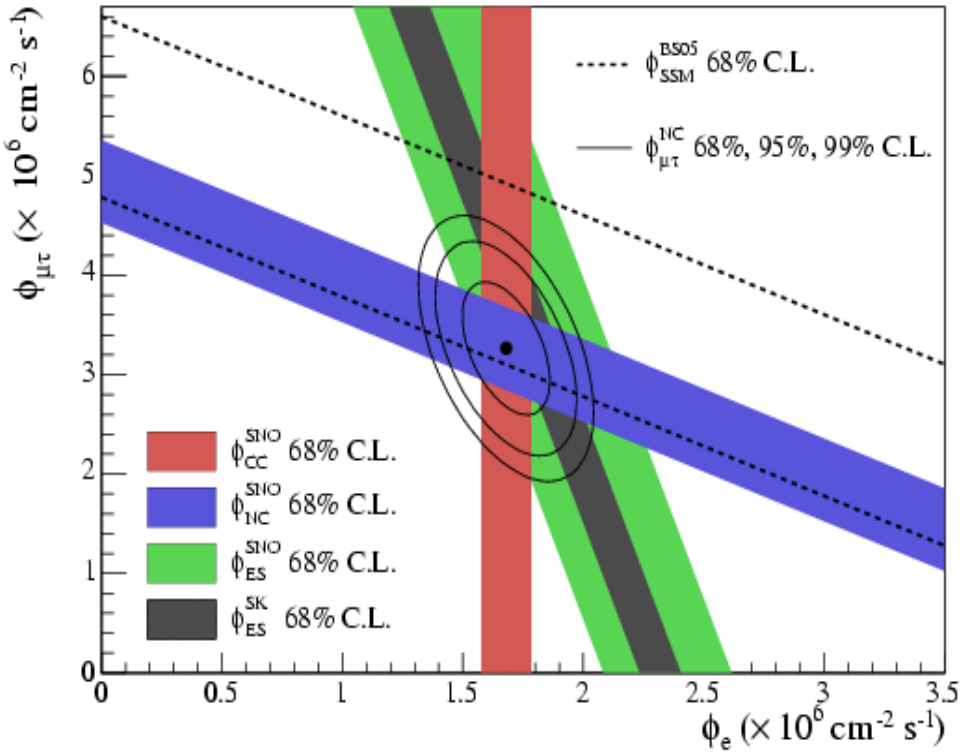






Neutrino Flavour Change

Flavour content of solar flux.



$$\Phi_{CC} = 1.68^{+0.06}_{-0.06}(stat.)^{+0.08}_{-0.09}(sys.)\times 10^6 cm^{-2}s^{-1}$$

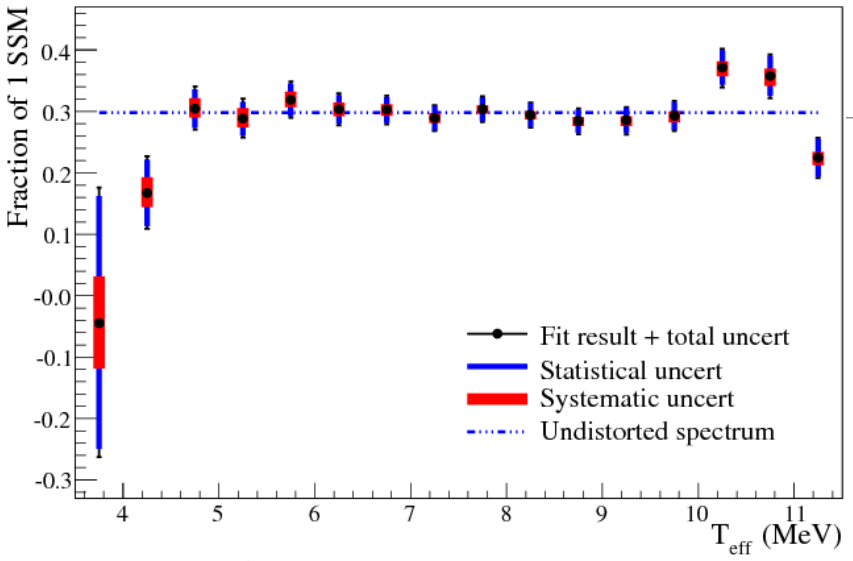
$$\Phi_{ES} = 2.35^{+0.22}_{-0.22}(stat.)^{+0.15}_{-0.15}(sys.)\times 10^6 cm^{-2}s^{-1}$$

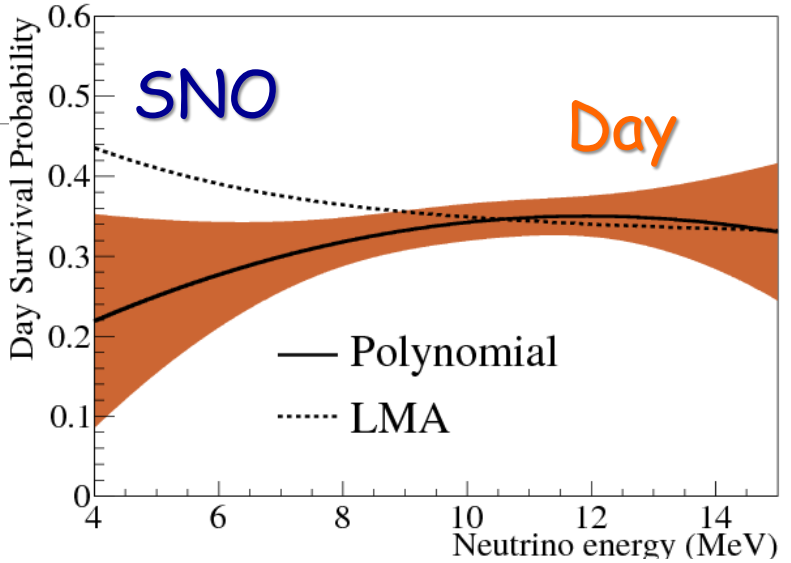
$$\Phi_{NC} = 4.94^{+0.21}_{-0.21}(stat.)^{+0.38}_{-0.34}(sys.)\times 10^6 cm^{-2}s^{-1}$$

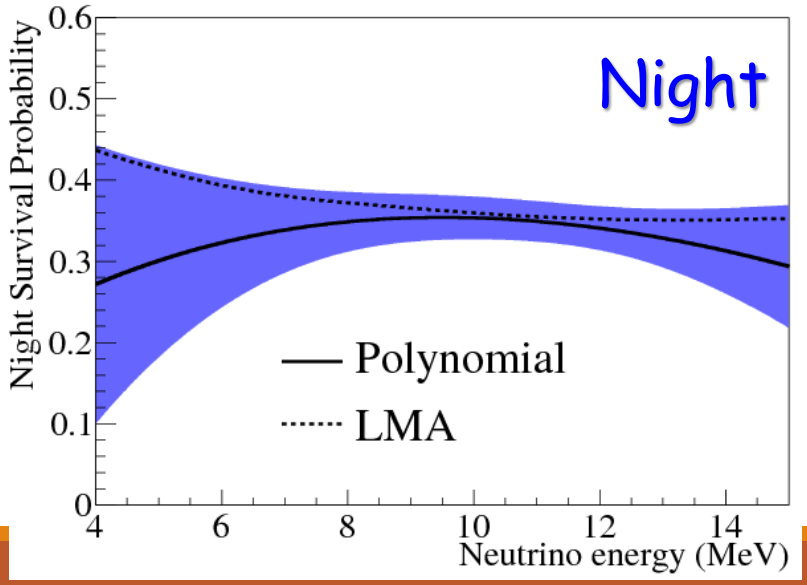
Neutrino Flavour Change Demonstrated at >7σ

Physics beyond the standard model!

Low energy threshold analysis







Search for LMA upturn

Threshold lowered to 3.5 MeV

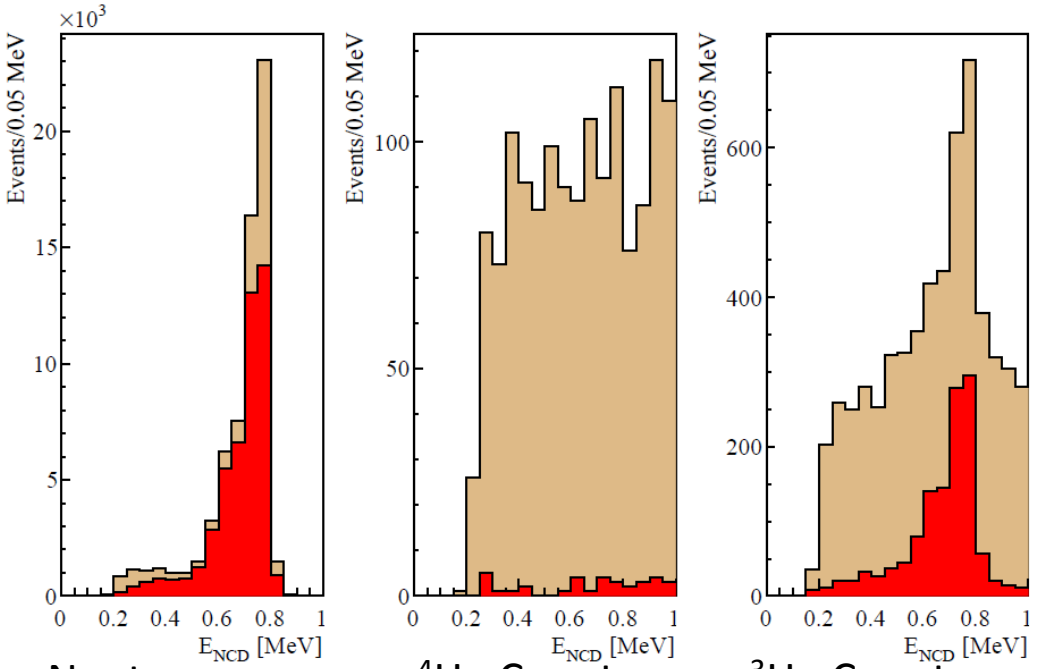
Many analysis improvements and lowered systematics

Joint fit – further break CC/NC covariance

- "beam on/beam off"

Improved NC measure as well.

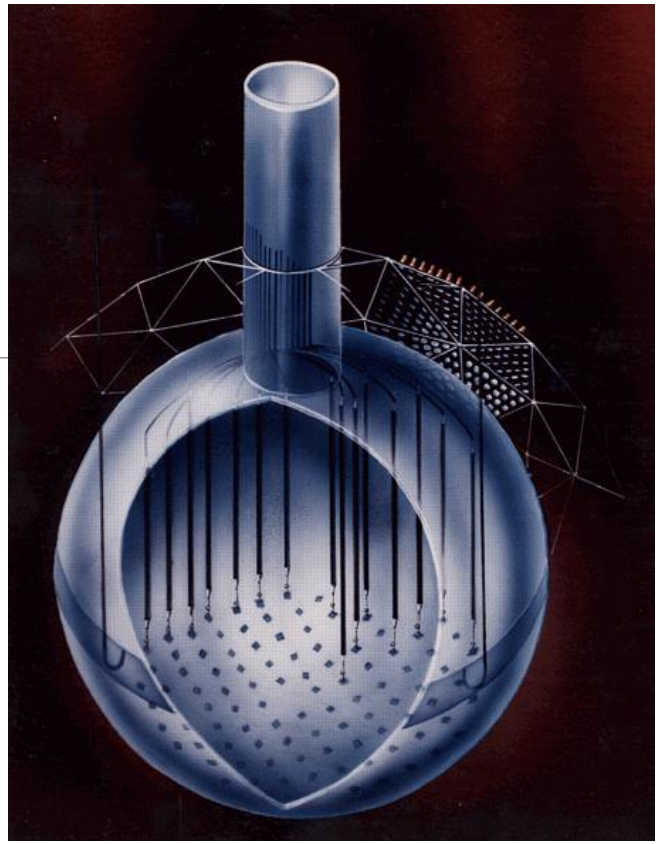
Adding NCDs

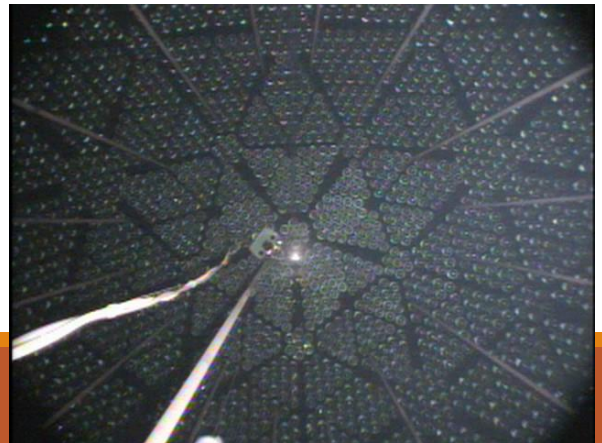


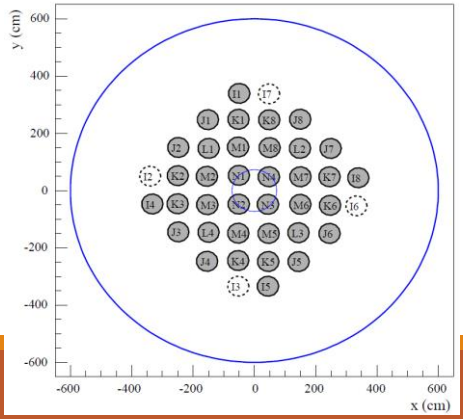
Neutron source

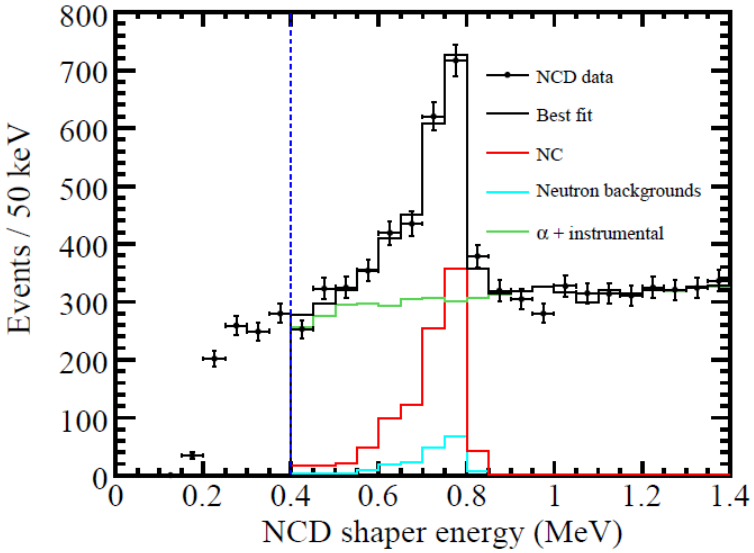
^{4}He Counters

^{3}He Counters







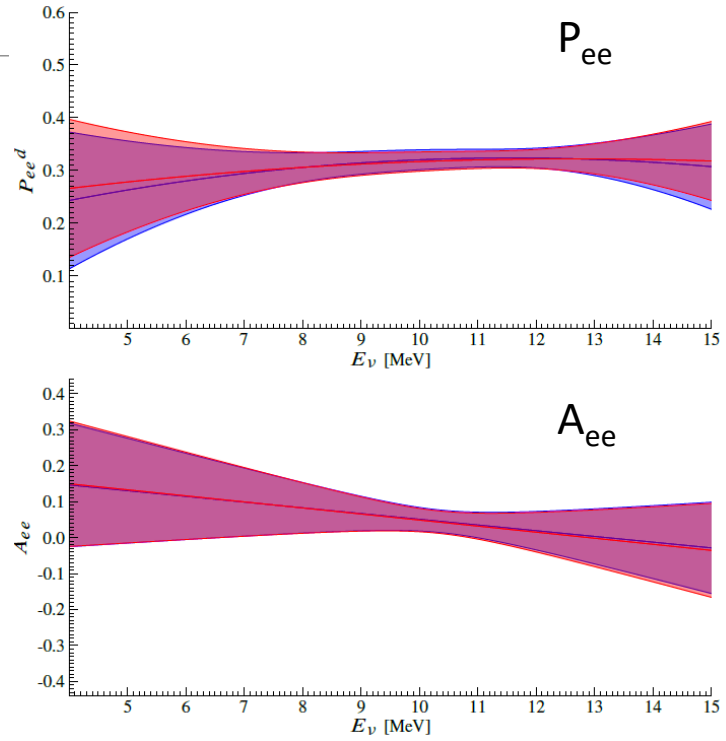


Combined phase results

Combined fit of the three phases provides most sensitive result

- Correlations broken in joint fit

Results are consistent between phases and with combined result

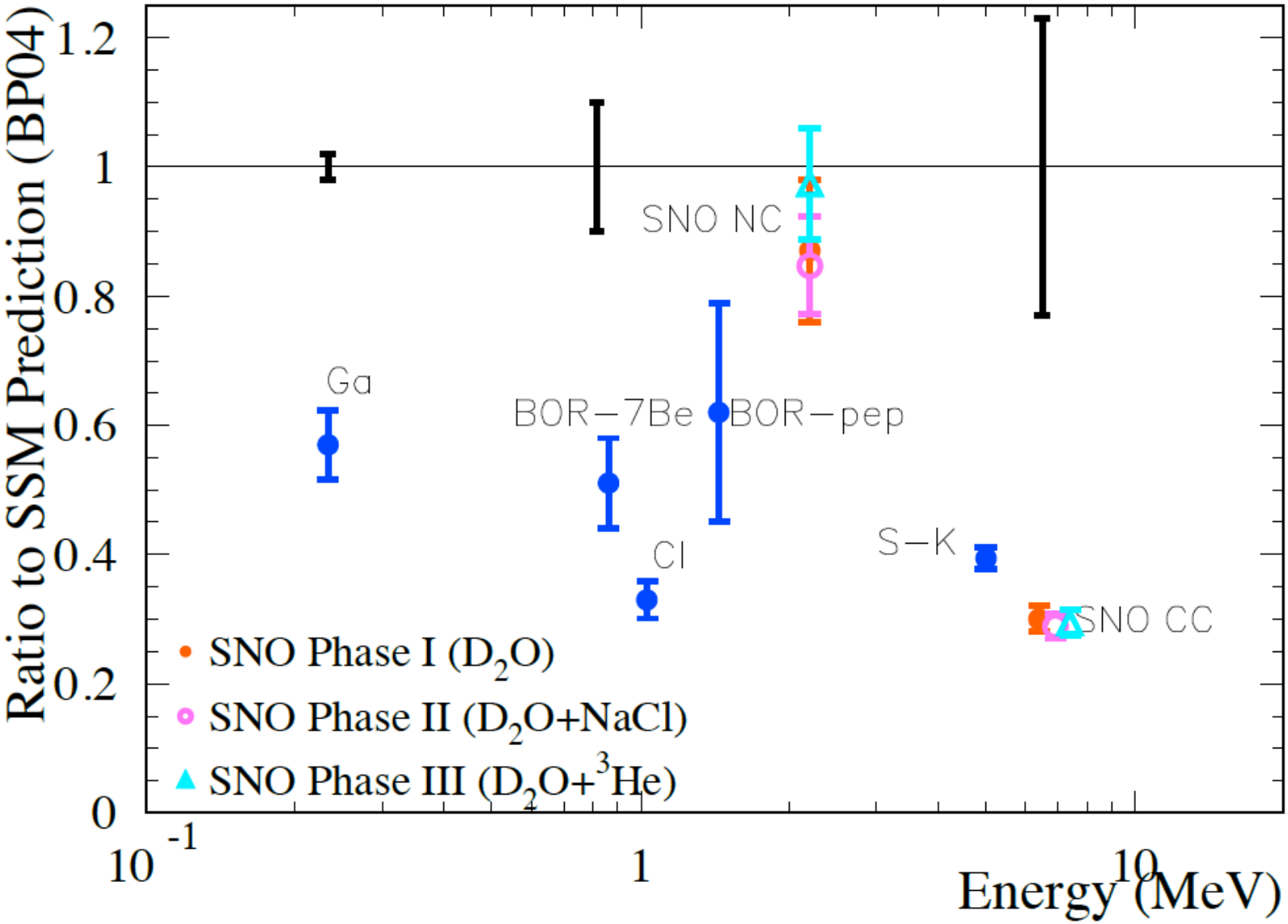


Φ_{8_B}=5.25$\pm$0.16$^{+0.11}_{-0.13}$ $\times 10^6 cm^{-2} s^{-1}$

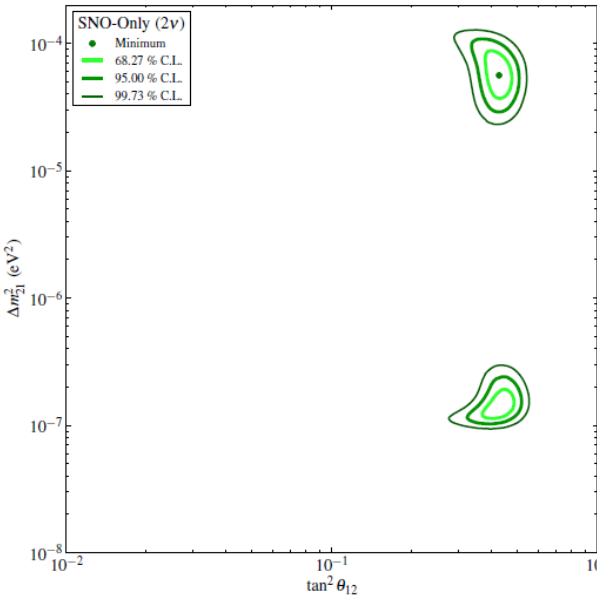
More accurate than current solar models and lying between the fluxes predicted for two values of metallicity in the sun

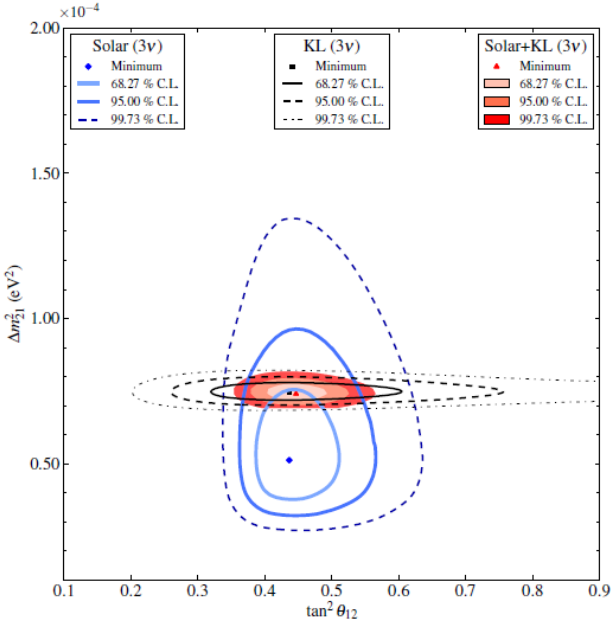
CC/NC = 0.317 ± 0.016 (stat) ± 0.009 (sys)
Implies flavour change at far more than 7 σ, shows that θ_{12} is non-maximal by more than 5σ.

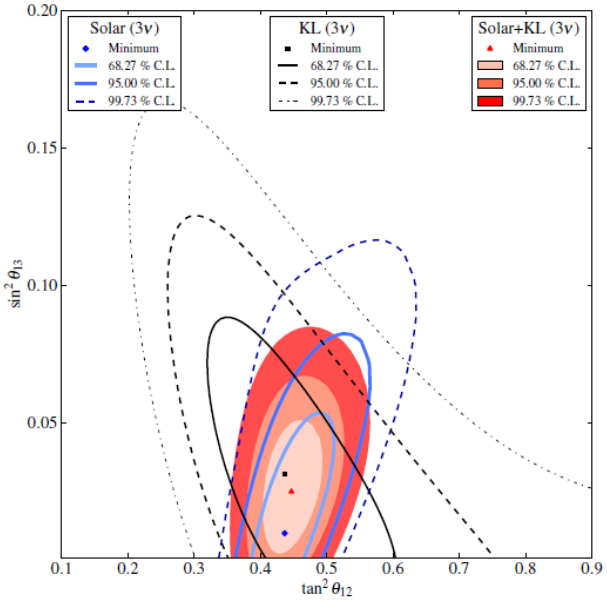
Solar Neutrino Problem Resolved



Neutrino Oscillation Results







SNO Only

Solar + KamLAND 3 flavour fits

Solar *hep* neutrinos

The highest energy solar neutrinos
- $^3He + p \rightarrow {}^4He + e^+ + \nu_e$

Exploit strong correlation between neutrino and electron energy in CC interaction

Search in 14.3 < T < 20 MeV signal box

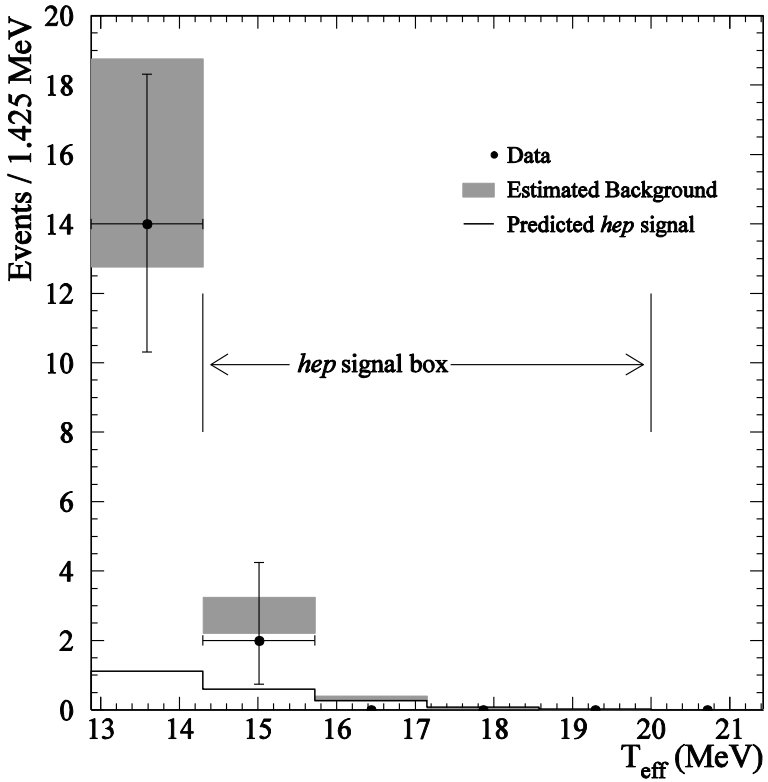
D_2O phase

Expect:
- 3.13±0.60 Background
- 0.99±0.09 Signal

Observe 2 events

$\Phi_{hep} < 2.3 \times 10^4$ cm^{-2}s^{-1} @ 90% c.l.

Three phase results coming soon



Additional Analyses

SNO also exploited its data to search for other signals.

- Transient supernova neutrino bursts
- Diffuse supernova neutrino background
- Solar neutrino periodicities
- Invisible modes of nucleon decay
- Down going neutrino induced muons

SNO is now completing a number of analyses to exploit the rich data set including:

- Solar hep search
- Diffuse supernova neutrinos
- Spallations
- n-n bar oscillations
- Lorentz violations

The Sudbury Neutrino Observatory

Funding Agencies, Other Support for SNO

CANADA:

- NSERC
- NRC
- Industry Canada
- Northern Ontario Heritage Fund Corp.
- INCO
- AECL
- Ontario Power Generation
- Nortel

USA:

- US Department of Energy

UK:

- Particle Physics and Astronomy Research Council

Institutions:

Canada

University of Alberta (since 2005)
Chalk River Labs (until 1992)
Carleton University
University of Guelph
Laurentian University
NRC (until 1992)
Queen's University
University of British Columbia
TRIUMF Laboratory

UK

Oxford

Portugal

LIP Lisbon (since 2005)

USA

Brookhaven National Lab
Princeton University (until 1992)
University of Texas at Austin (2002- 2008)
Los Alamos National Lab
Lawrence Berkeley National Lab
University of Pennsylvania
University of Washington
UC Irvine (until 1989)
Louisiana State University (since 2005)
MIT (since 2005)
UC Berkeley (since 2011)

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