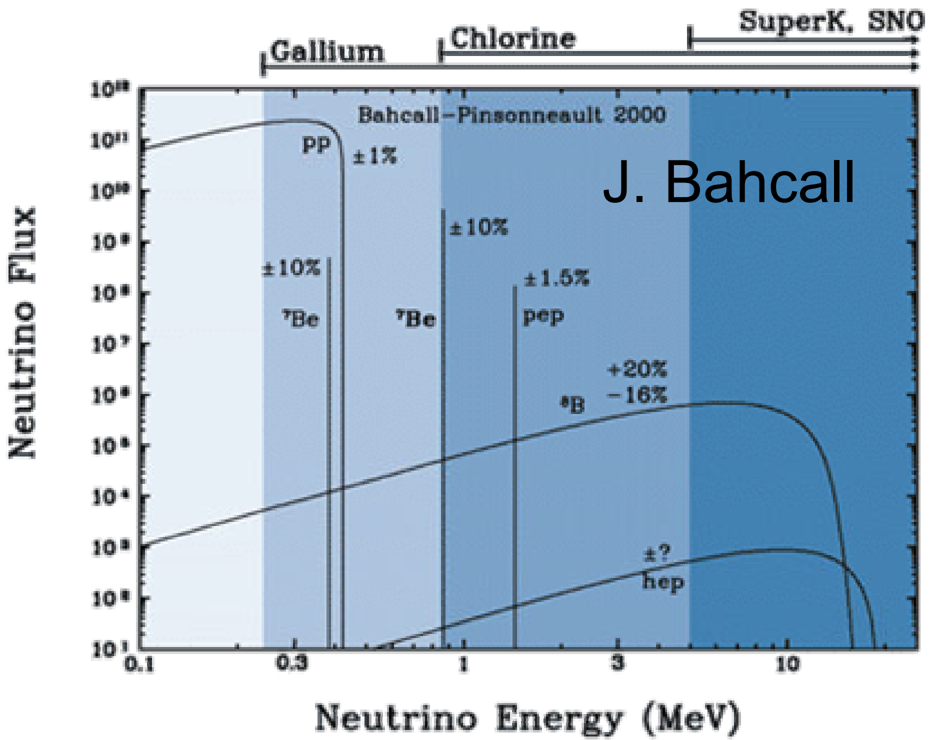
Solar Neutrino Results from SNO Salt Phase

Yasuo Takeuchi
Kamioka Observatory,
ICRR, Univ. of Tokyo

SNO Detector
Neutron Event Separation
Calibration
Backgrounds
Results from Salt Phase
Future Plan

SNO web site: http://www.sno.phy.queensu.ca/

The Solar Neutrino Problem



Experiment	Exp/SSM
•SAGE+GALLEX/GNO	0.58
•Homestake	0.33
•Kamiokande/SuperK	0.46
•SNO pure D_2O CC (June 2001)	0.35
SNO pure D_2O NC (April 2002)	~1

SNO CC vs NC implies flavor change, which can then explain other experimental results.

Precision phase (still need direct evidence of “oscillation”…)

Sudbury Neutrino Observatory (SNO)

Main goal:

Direct observation of solar neutrino flavor change via inclusive appearance with high precision

The SNO Collaboration

T. Kutter, C.W. Nally, S.M. Oser, C.E. Waltham
University of British Columbia

J. Boger, R.L. Hahn, R. Lange, M. Yeh
Brookhaven National Laboratory

A.Bellerive, X. Dai, F. Dalnoki-Veress, R.S. Dosanjh, D.R. Grant, C.K. Hargrove, R.J. Hemingway, I. Levine, C. Mifflin, E. Rollin, O. Simard, D. Sinclair, N. Starinsky, G. Tesic, D. Waller
Carleton University

P. Jagam, H. Labranche, J. Law, I.T. Lawson, B.G. Nickel, R.W. Ollerhead, J.J. Simpson
University of Guelph

J. Farine, F. Fleurot, E.D. Hallman, S. Luoma, M.H. Schwendener, R. Tafirout, C.J. Virtue
Laurentian University

Y.D. Chan, X. Chen, K.M. Heeger, K.T. Lesko, A.D. Marino, E.B. Norman, C.E. Okada, A.W.P. Poon, S.S.E. Rosendahl, R.G. Stokstad
Lawrence Berkeley National Laboratory

M.G. Boulay, T.J. Bowles, S.J. Brice, M.R. Dragowsky, S.R. Elliott, M.M. Fowler, A.S. Hamer, J. Heise, A. Hime, G.G. Miller, R.G. Van de Water, J.B. Wilhelmy, J.M. Wouters
Los Alamos National Laboratory

S.D. Biller, M.G. Bowler, B.T. Cleveland, G. Doucas, J.A. Dunmore, H. Fergani, K. Frame, N.A. Jelley, S. Majerus, G. McGregor, S.J.M. Peeters, C.J. Sims, M. Thorman, H. Wan Chan Tseung, N. West, J.R. Wilson, K. Zuber
Oxford University

E.W. Beier, M. Dunford, W.J. Heintzelman, C.C.M. Kyba, N. McCauley, V.L. Rusu, R. Van Berg
University of Pennsylvania

S.N. Ahmed, M. Chen, F.A. Duncan, E.D. Earle, B.G. Fulsom, H.C. Evans, G.T. Ewan, K. Graham, A.L. Hallin, W.B. Handler, P.J. Harvey, M.S. Kos, 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, M. Thomas, Y.Takeuchi
Queen's University

D.L. Wark
Rutherford Laboratory and University of Sussex

R.L. Helmer
TRIUMF

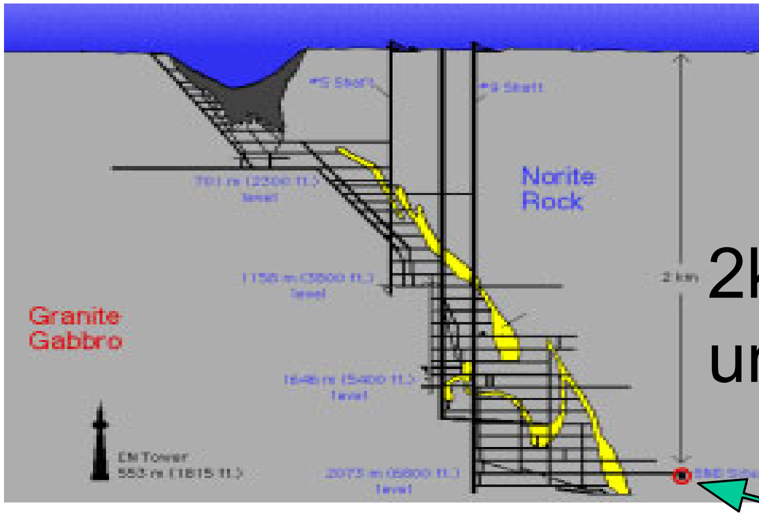
A.E. Anthony, J.C. Hall, J.R. Klein
University of Texas at Austin

T.V. Bullard, G.A. Cox, P.J. Doe, 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, R.G.H. Robertson, M.W.E. Smith, L.C. Stonehill, B.L. Wall, J.F. Wilkerson
University of Washington

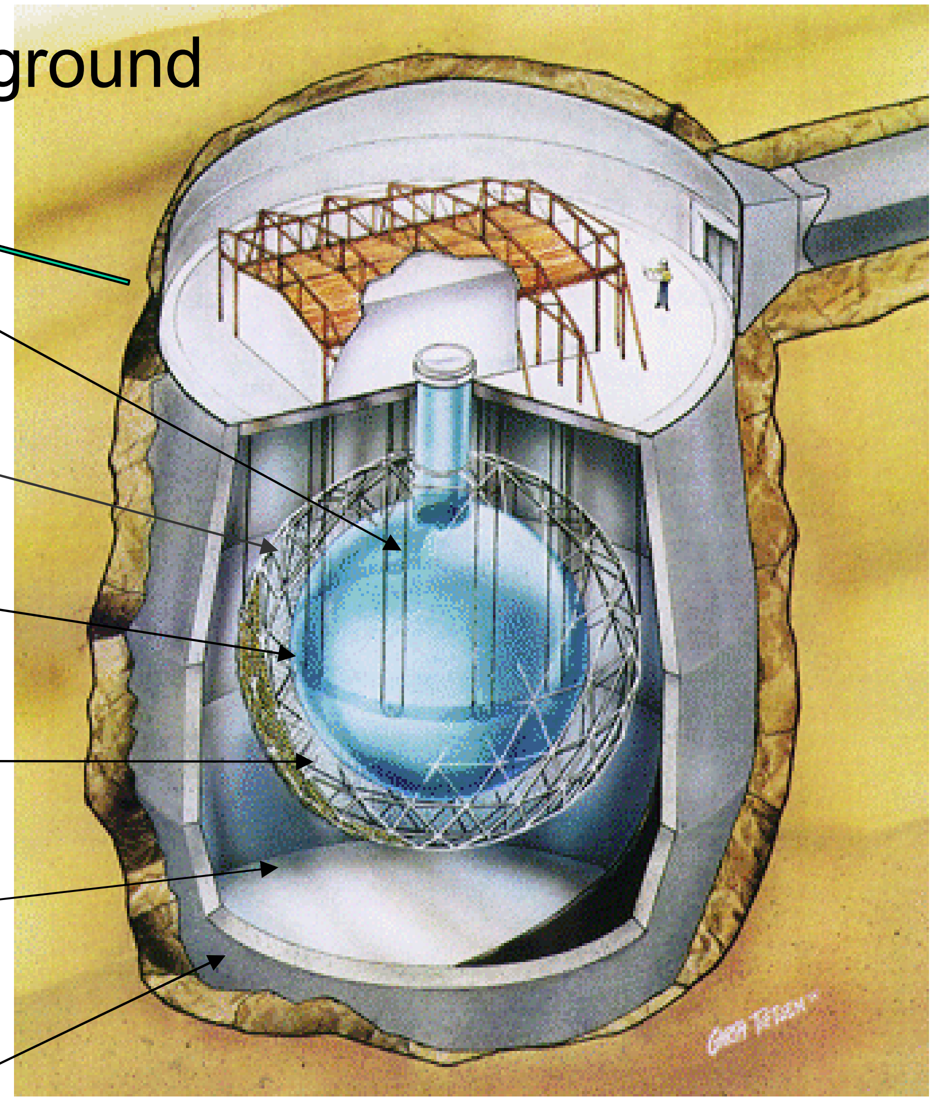
~130 people / 14 institutions

SNO Detector

Sudbury Neutrino Observatory



2km under ground



1000 tonnes D_2O

Support Structure for 9500 PMTs (8-inch), 60% coverage

12 m Diameter Acrylic Vessel

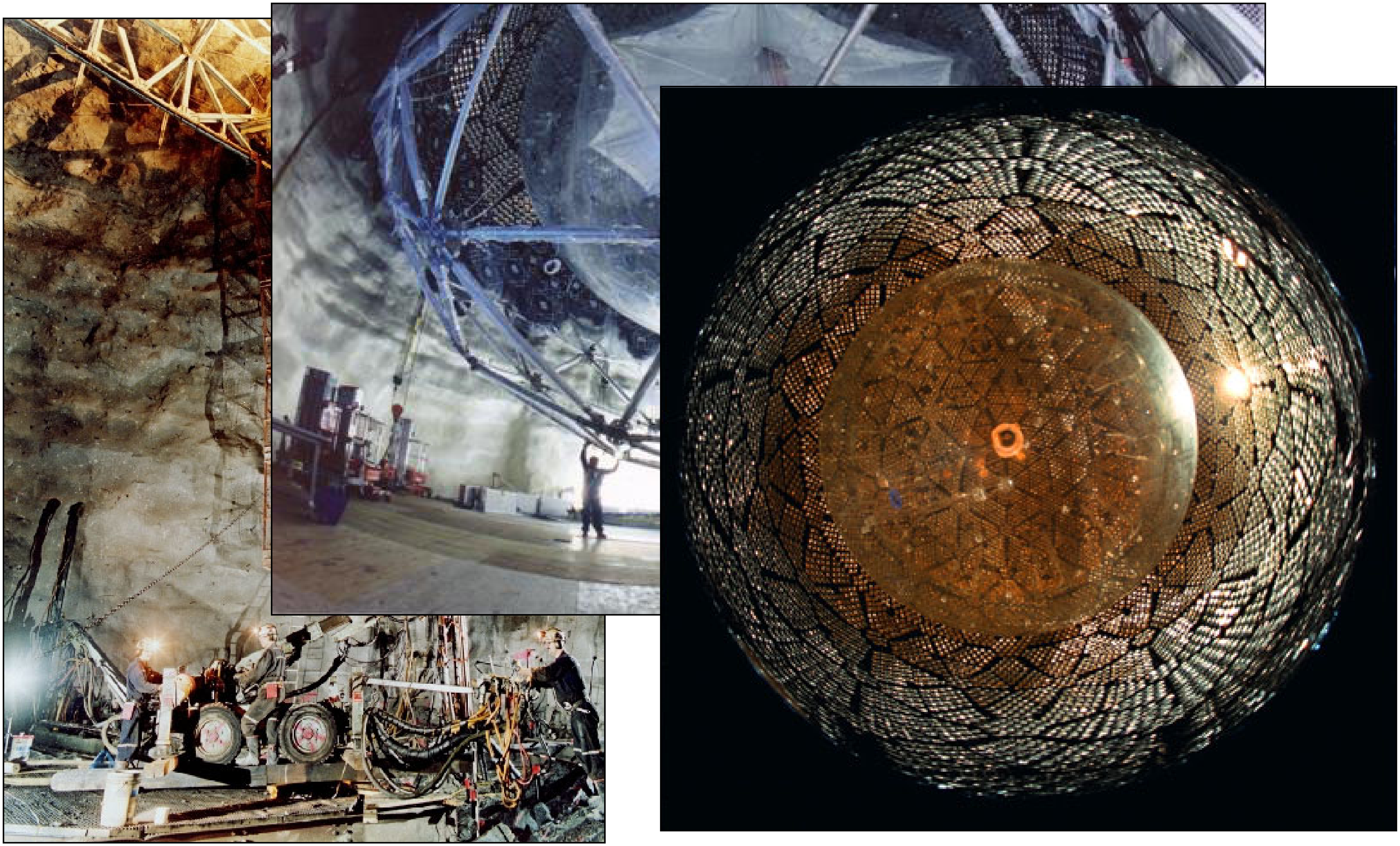
1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal

NIM A449 (2000) 172

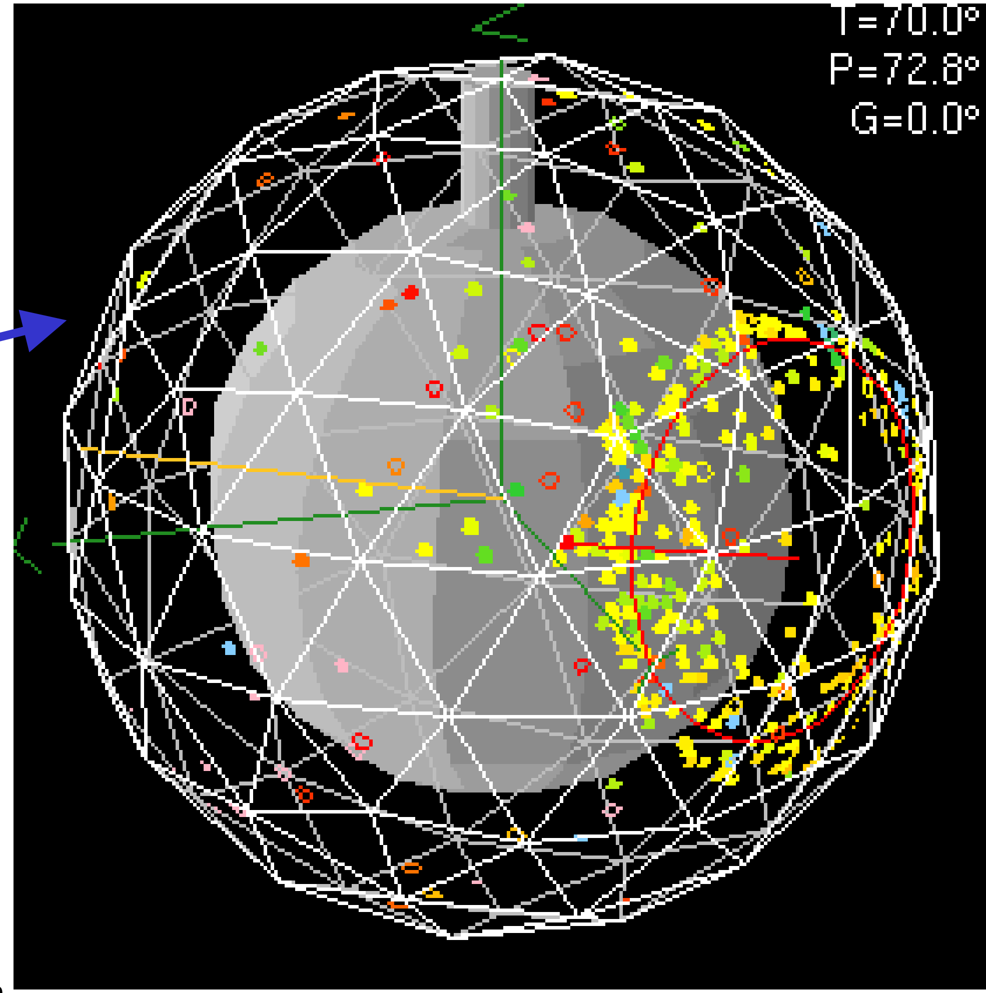
SNO during Construction

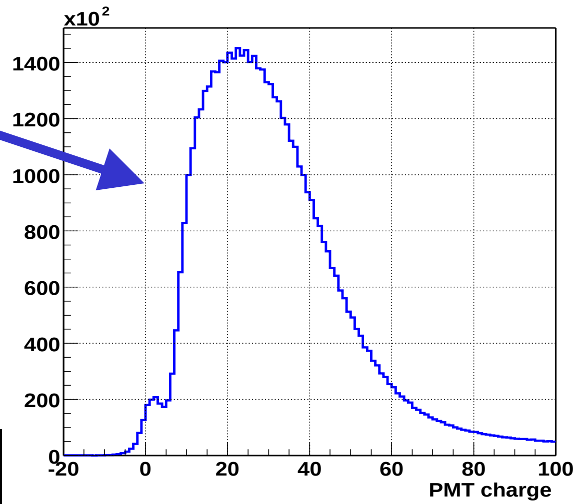


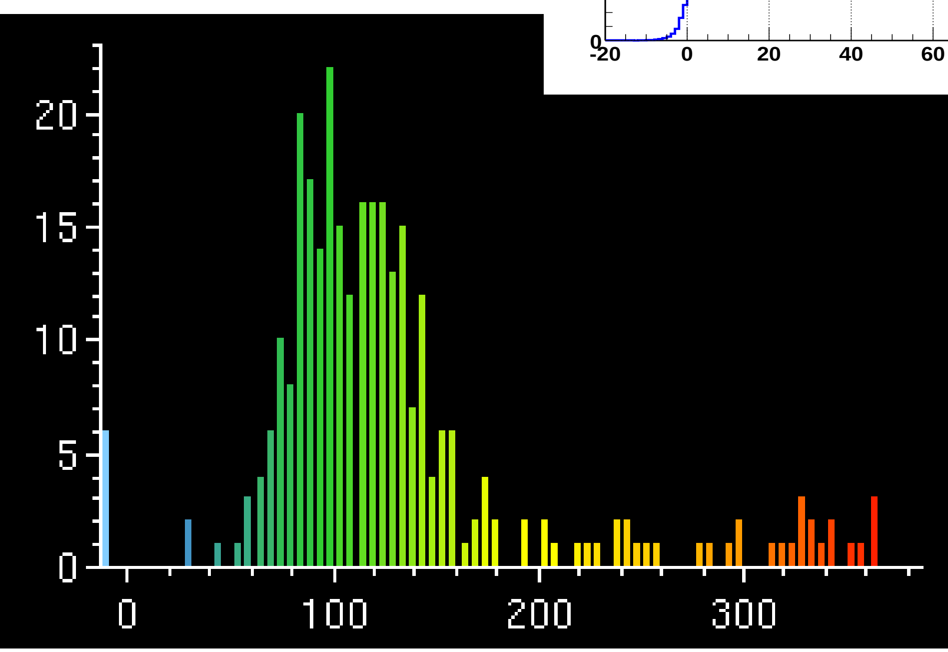
What We Measure

PMT Measurements

-position
-charge
-time







Reconstructed Event

-event vertex
-event direction
-energy
-isotropy

Neutrino Reactions in SNO

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

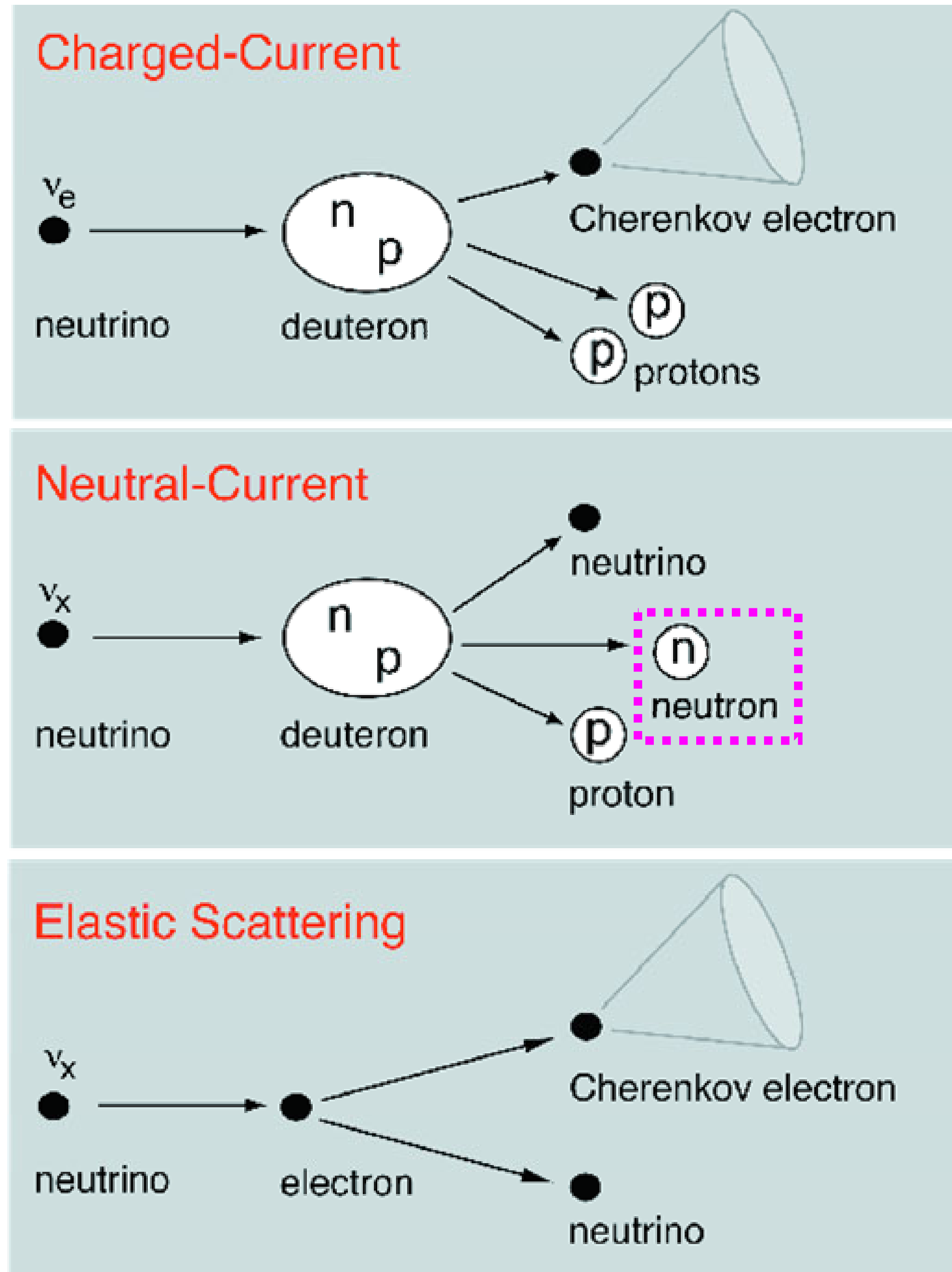
- $Q = 1.445$ MeV
- good measurement of ν_e energy spectrum
- some directional info $\propto (1 - 1/3 \cos\theta)$
- ν_e only

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

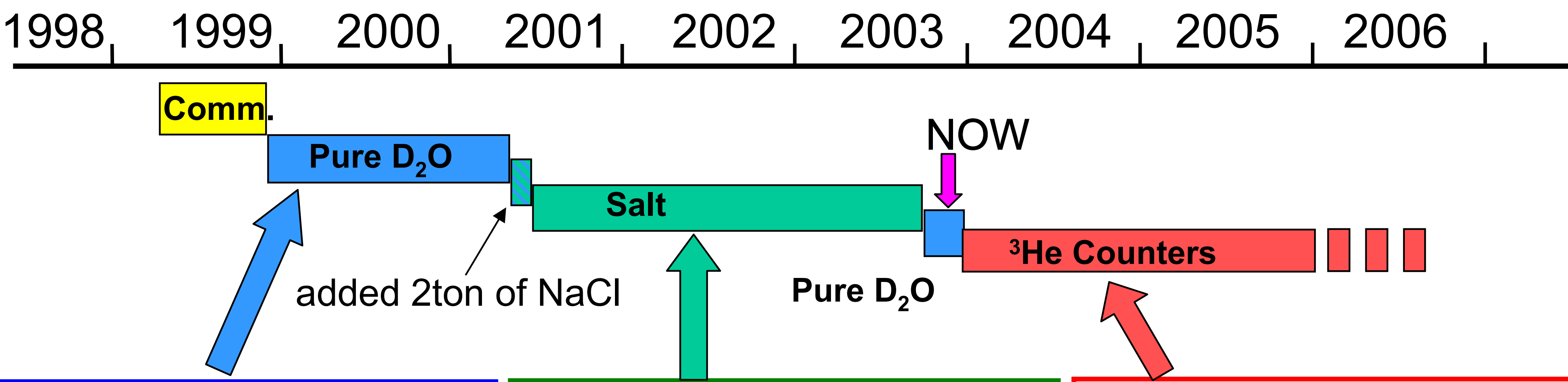
- $Q = 2.22$ MeV
- measures total ^8B ν flux from the Sun
- equal cross section for all ν types

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

- low statistics
- mainly sensitive to ν_e, some ν_μ and ν_τ
- strong directional sensitivity



SNO's response to neutron events (solar NC signal)



Phase I (pure D_2O):

Neutron capture on D

$n+{}^2H \rightarrow {}^3H+\gamma$

Single 6.25 MeV γ

Statistical separation (Energy, radius)

High CC-NC correlation

Nov. 1999~

Phase II (dissolved salt):

Neutron capture on Cl

$n+{}^{35}Cl \rightarrow {}^{36}Cl+\sum\gamma$

Multiple γ s, 8.6 MeV

Statistical separation (Isotropy)

Better CC-NC separation

Jul. 2001~

Phase III (^{3}He n counters):

$n + {}^3\mathrm{He} \rightarrow p + t$

Independent channel

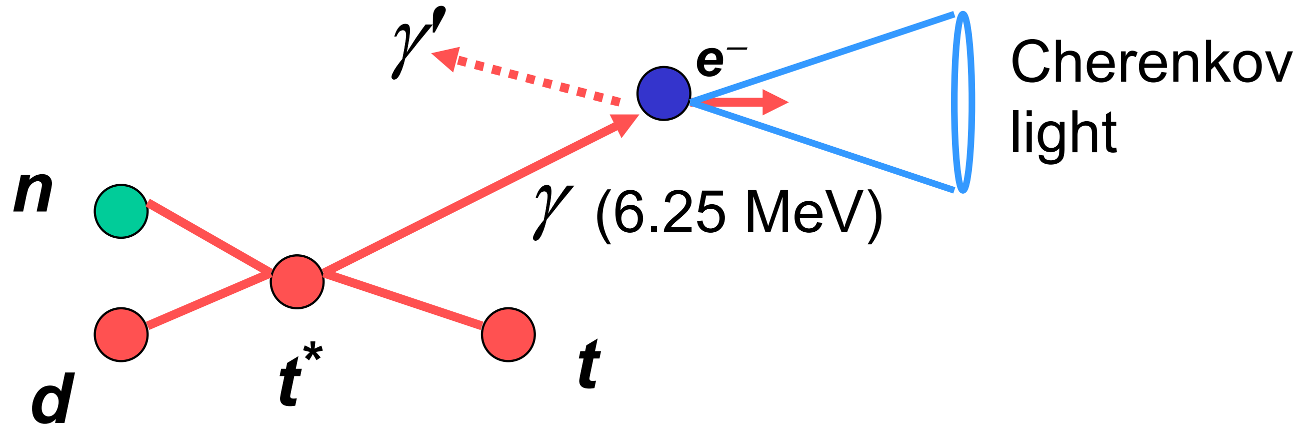
NC uncorrelated to CC

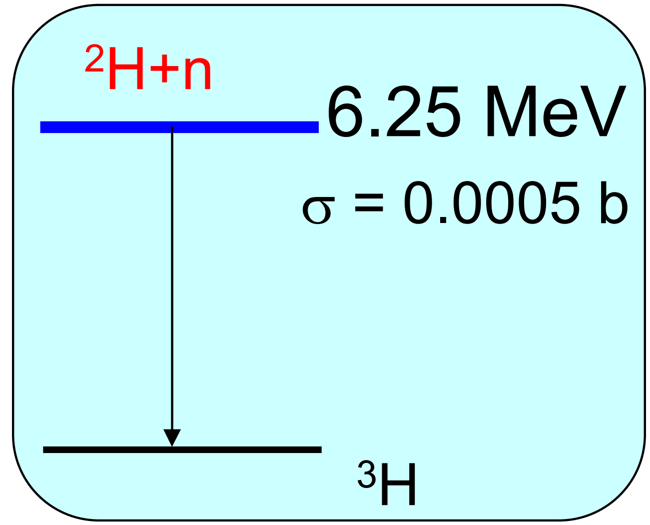
(Jan. 2004~)

Neutron Event Separation

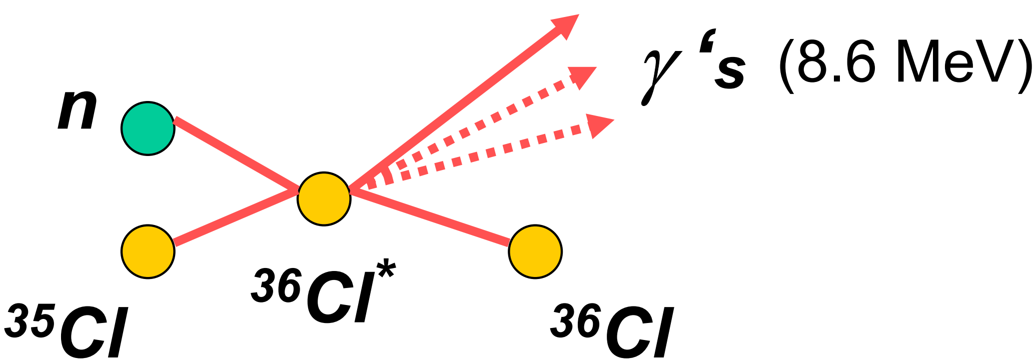
Detecting Neutrons

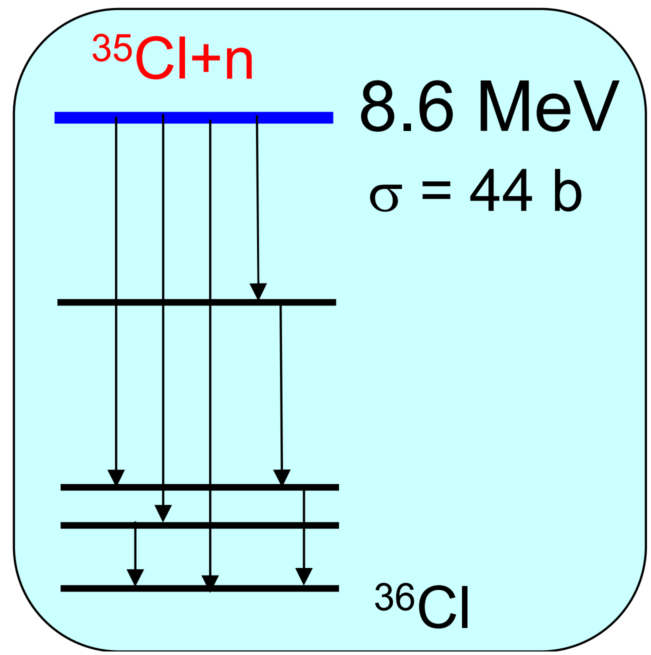
- Pure D_2O: neutron capture on deuterons





- Salt D_2O: neutron capture on ^{35}Cl





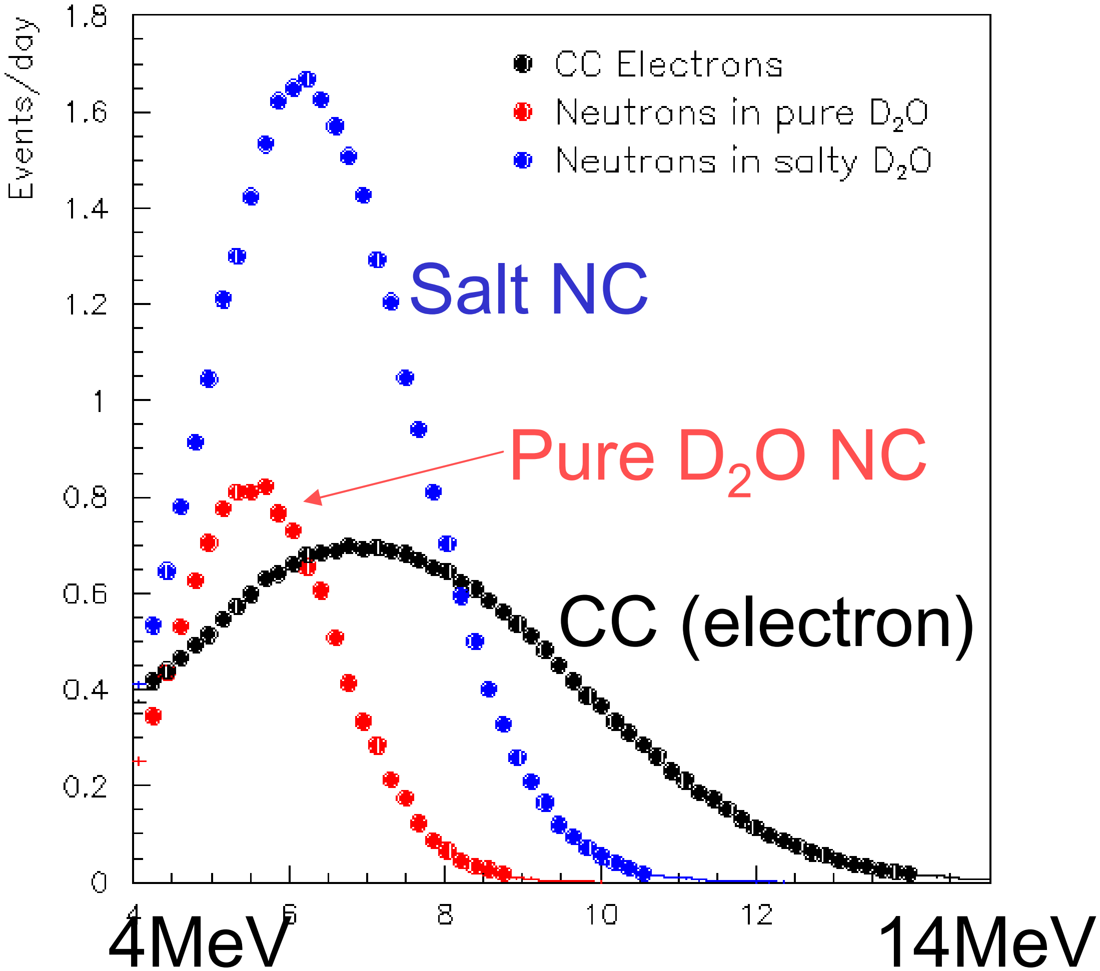
Advantages of NaCl for Neutron Detection

- Higher capture cross section
- Higher energy release

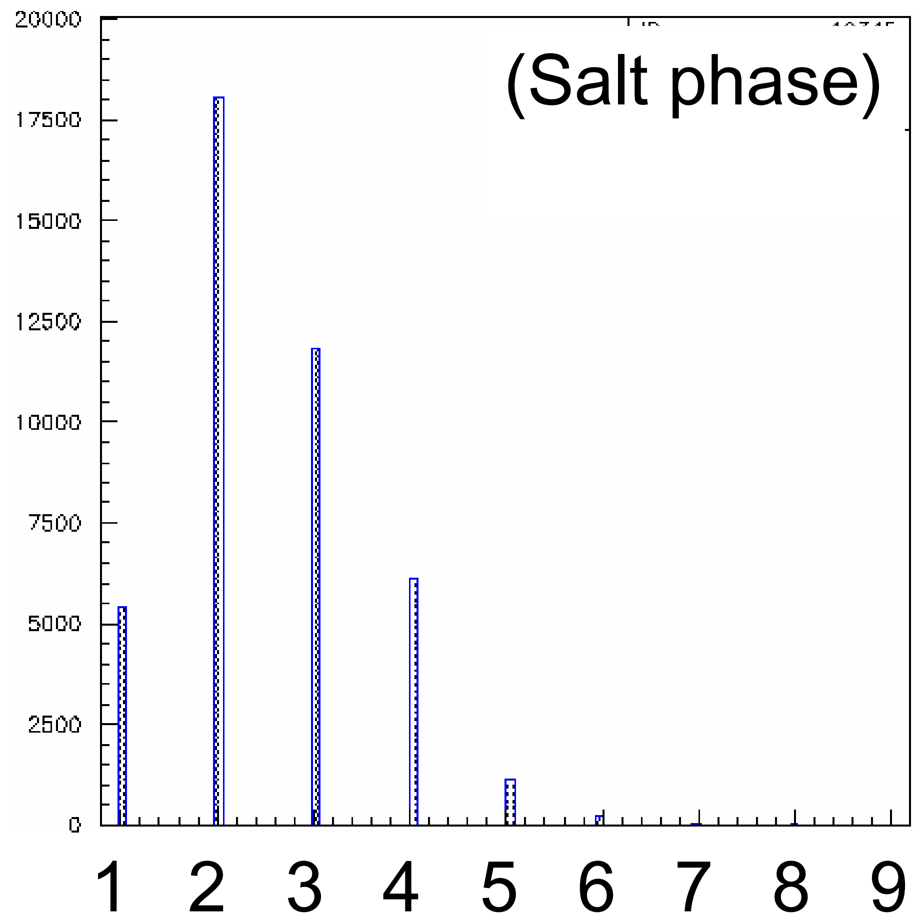
→ Statistics

- Many gammas → Neutron – electron separation

Energy distribution (MC)

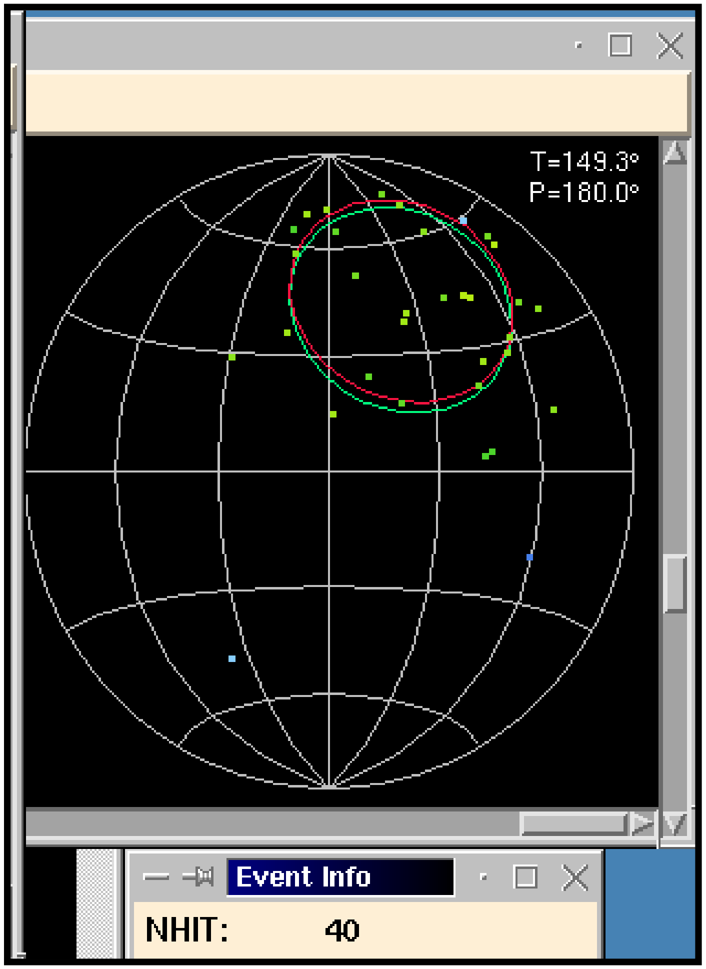


Distribution of no. γ's



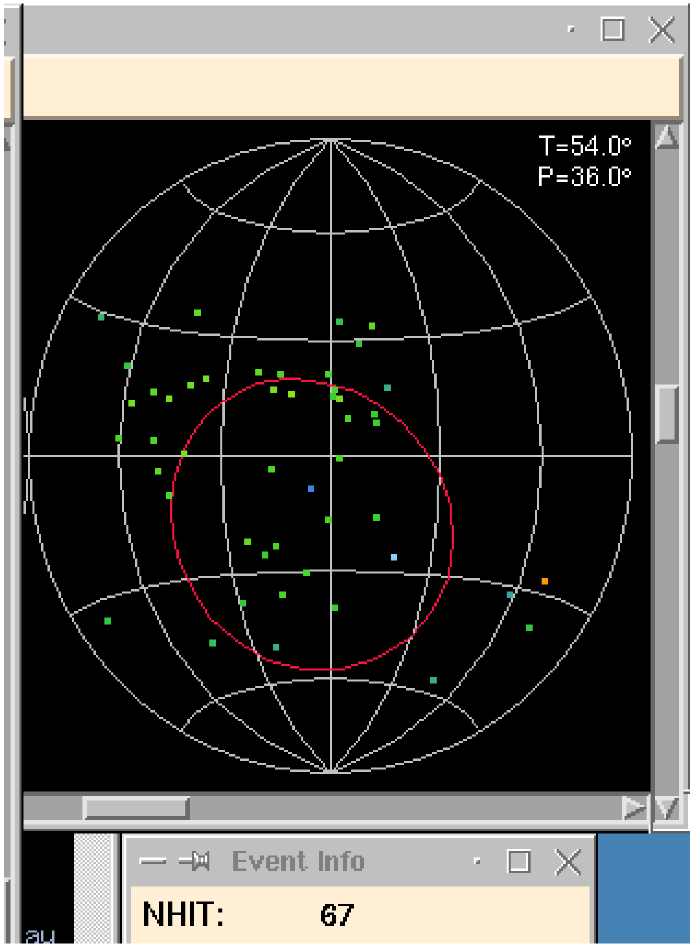
Simulated Neutron Event

Pure D_2O



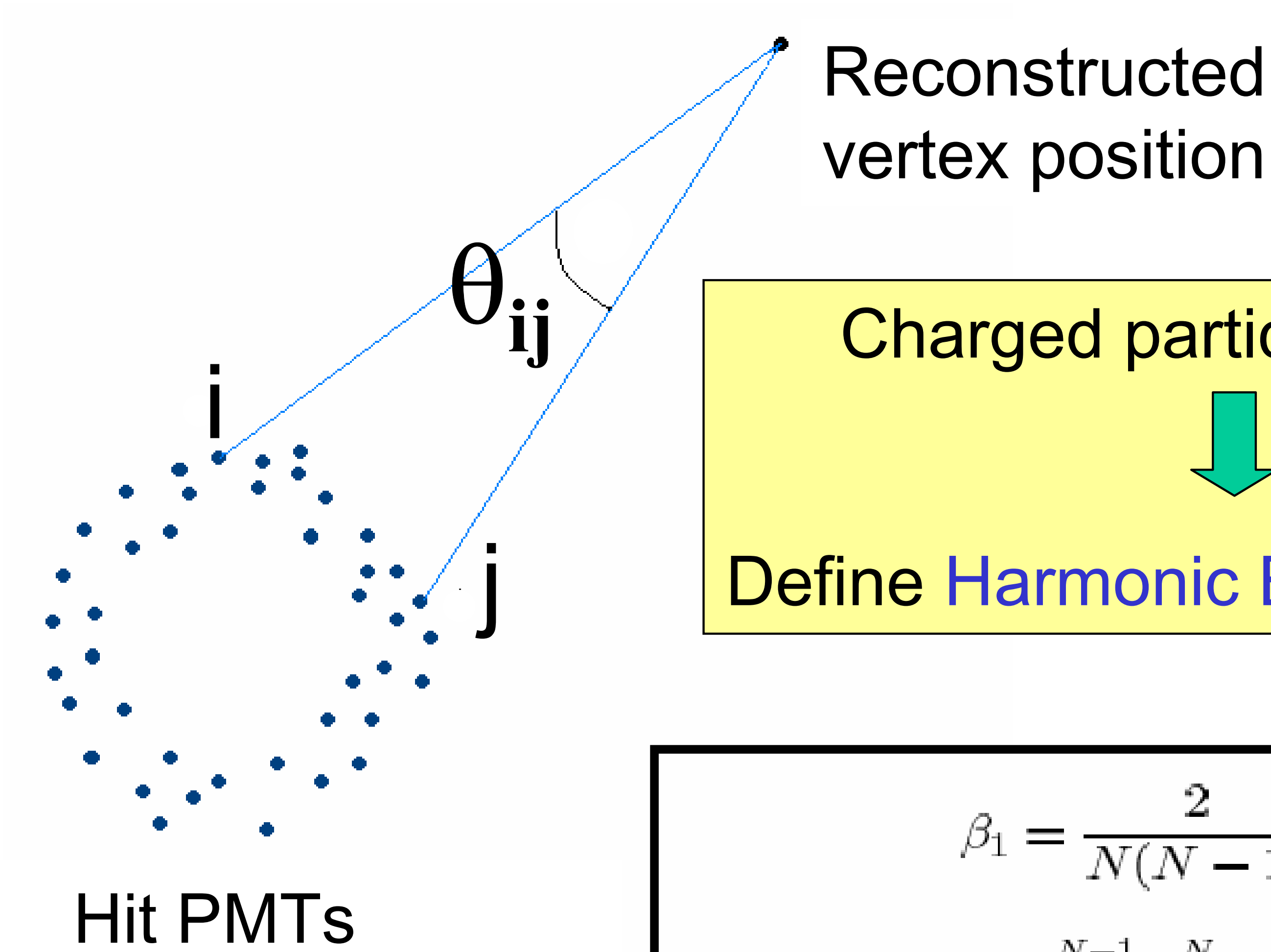
look like electron events

Salt



more isotropic than electrons

Cherenkov light and β_{14}



Charged particle light cone

⬇

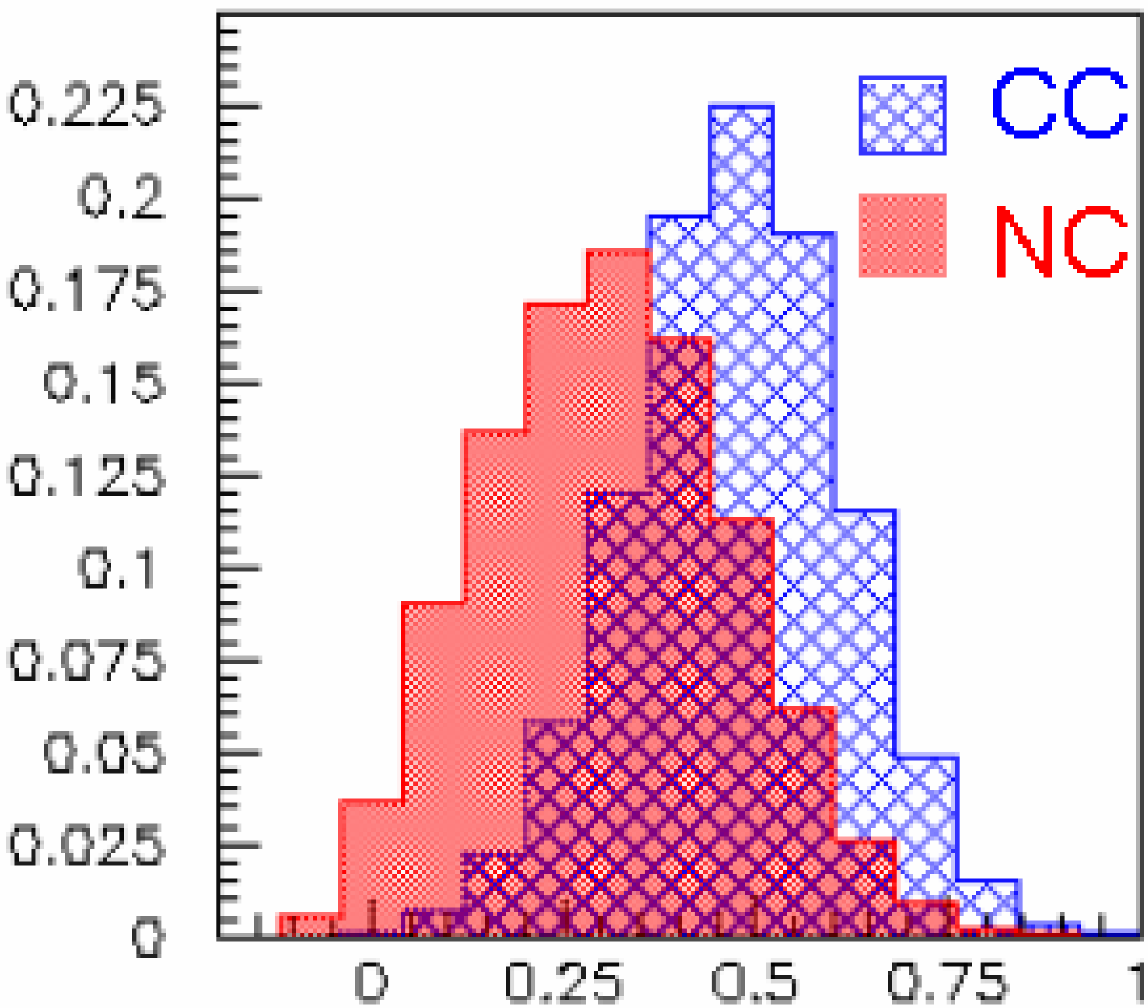
Define Harmonic Beta Parameters

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

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

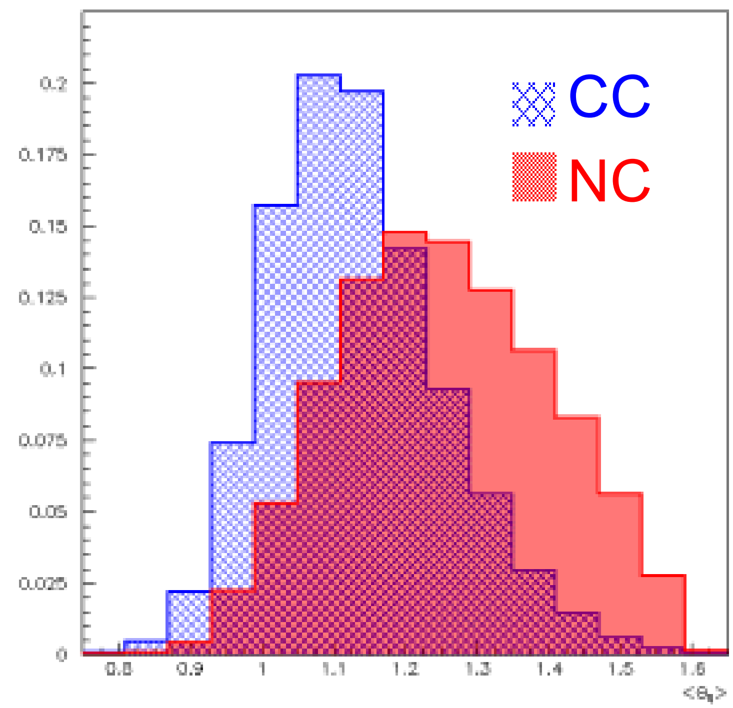
$$\beta_{14} = \beta_1 + 4\beta_4$$

Harmonic Beta Parameters



β_{14}

– β_{14} gives better separation power than using $<\theta_{ij}>$

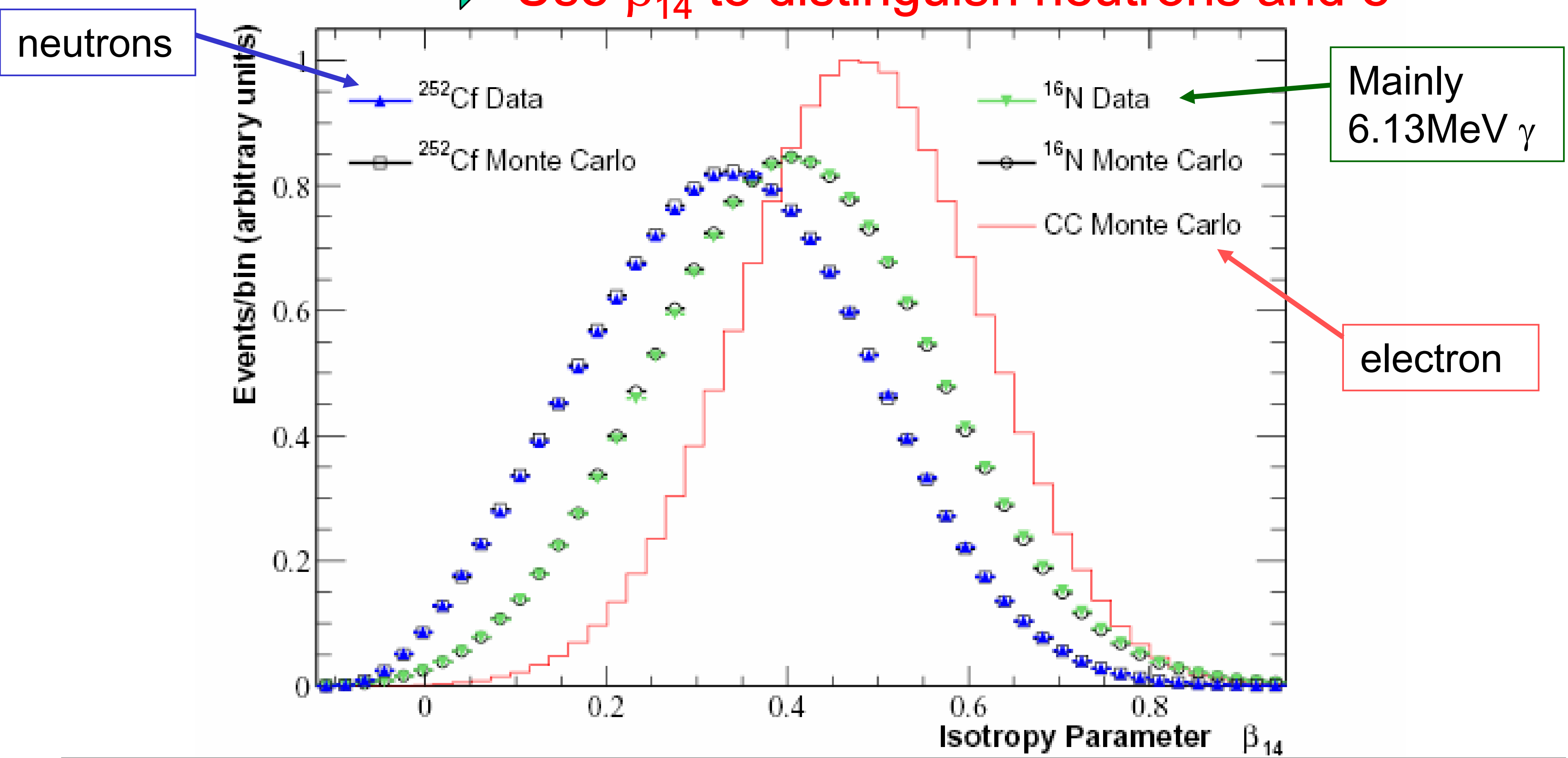


$<\theta_{ij}>$ (average angle)

Isotropy Calibration

- Calibration sources show excellent agreement between data and Monte Carlo.

Use β_{14} to distinguish neutrons and e$^-$



Uncertainty of isotropy mean on fluxes = -3.4+3.1%(NC), -3.4+2.6%(CC) anti-correlated

Uncertainty on Neutrino Fluxes

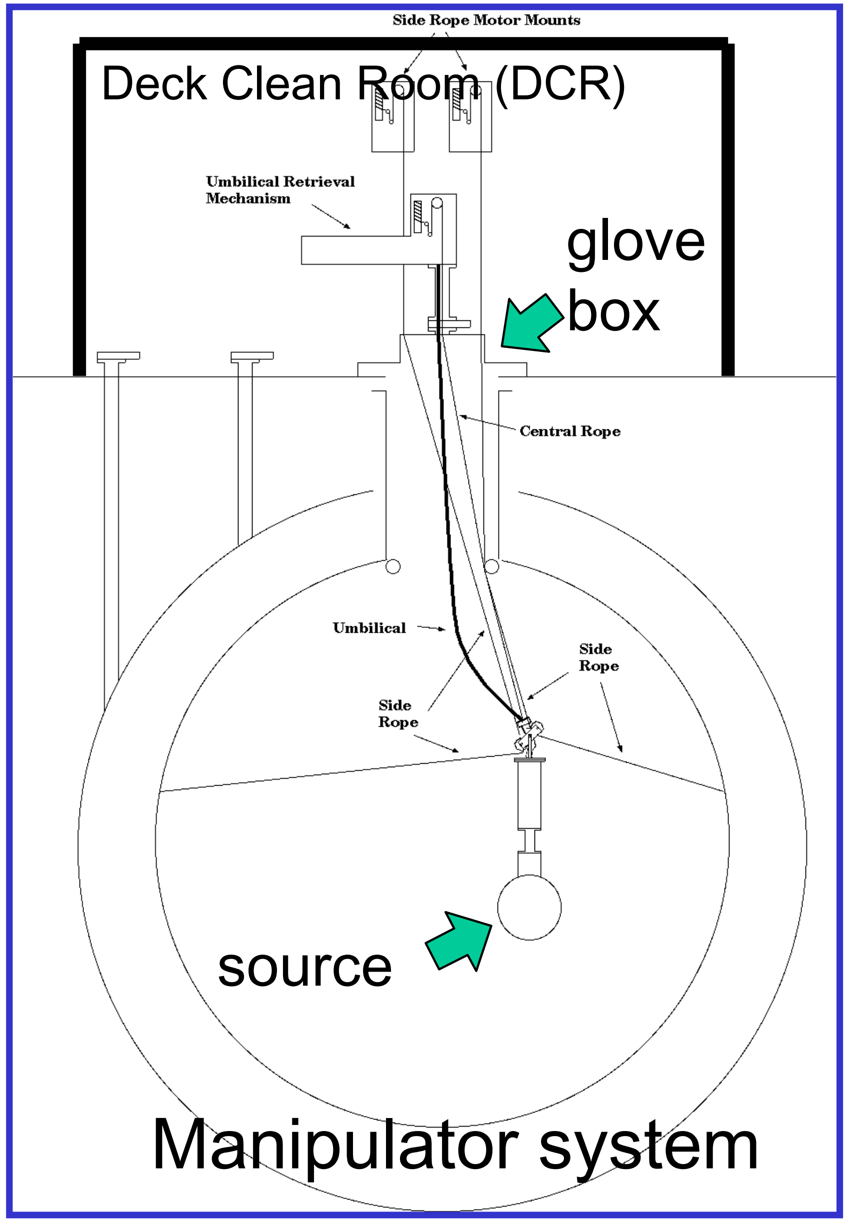
Source	NC uncert. (%)	CC uncert. (%)	ES uncert. (%)
Energy scale	-3.7,+3.6	-1.0,+1.1	±1.8
Energy resolution	±1.2	±0.1	±0.3
Energy non-linearity	±0.0	-0.0,+0.1	±0.0
Radial accuracy	-3.0,+3.5	-2.6,+2.5	-2.6,+2.9
Vertex resolution	±0.2	±0.0	±0.2
Angular resolution	±0.2	±0.2	±2.4
Isotropy mean †	-3.4,+3.1	-3.4,+2.6	-0.9,+1.1
Isotropy resolution	±0.6	±0.4	±0.2
Radial energy bias	-2.4,+1.9	±0.7	-1.3,+1.2
Vertex Z accuracy †	-0.2,+0.3	±0.1	±0.1
Internal background neutrons	-1.9,+1.8	±0.0	±0.0
Internal background γ's	±0.1	±0.1	±0.0
Neutron capture	-2.5,+2.7	±0.0	±0.0
Cherenkov backgrounds	-1.1,+0.0	-1.1,+0.0	±0.0
"AV events"	-0.4,+0.0	-0.4,+0.0	±0.0
Total experimental uncertainty	-7.3,+7.2	-4.6,+3.8	-4.3,+4.5
Cross section [13]	±1.1	±1.2	±0.5

Calibration

Calibration

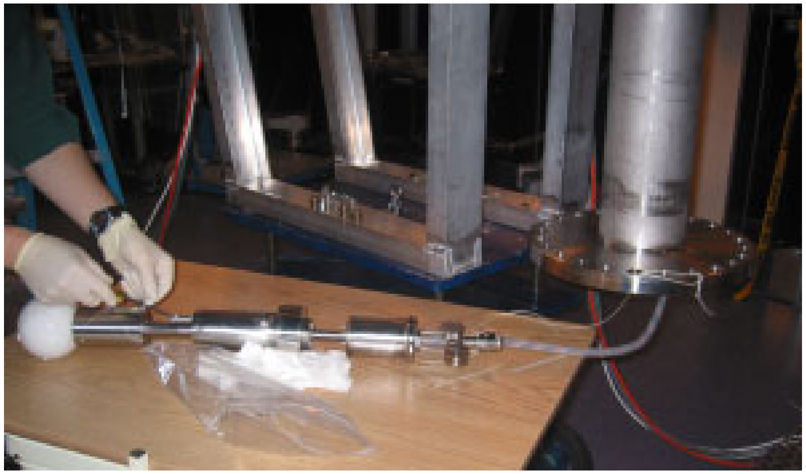
- Use detailed Monte Carlo to simulate events
- Check simulation with large number of calibrations:

Calibration	Simulates...
Pulsed Laser	337-620 nm optics
^{16}N	6.13MeV γ (+4MeV β)
^{252}Cf	neutrons
^{8}Li	<13 MeV β decay
AmBe	4.4 MeV (γ ,n) source
U & Th Sources	^{214}Bi & ^{208}Tl (β,γ)
Radon Spike	Rn backgrounds



Tools for calibration

Manipulator demonstration
@Queen's Univ.



Laser ball

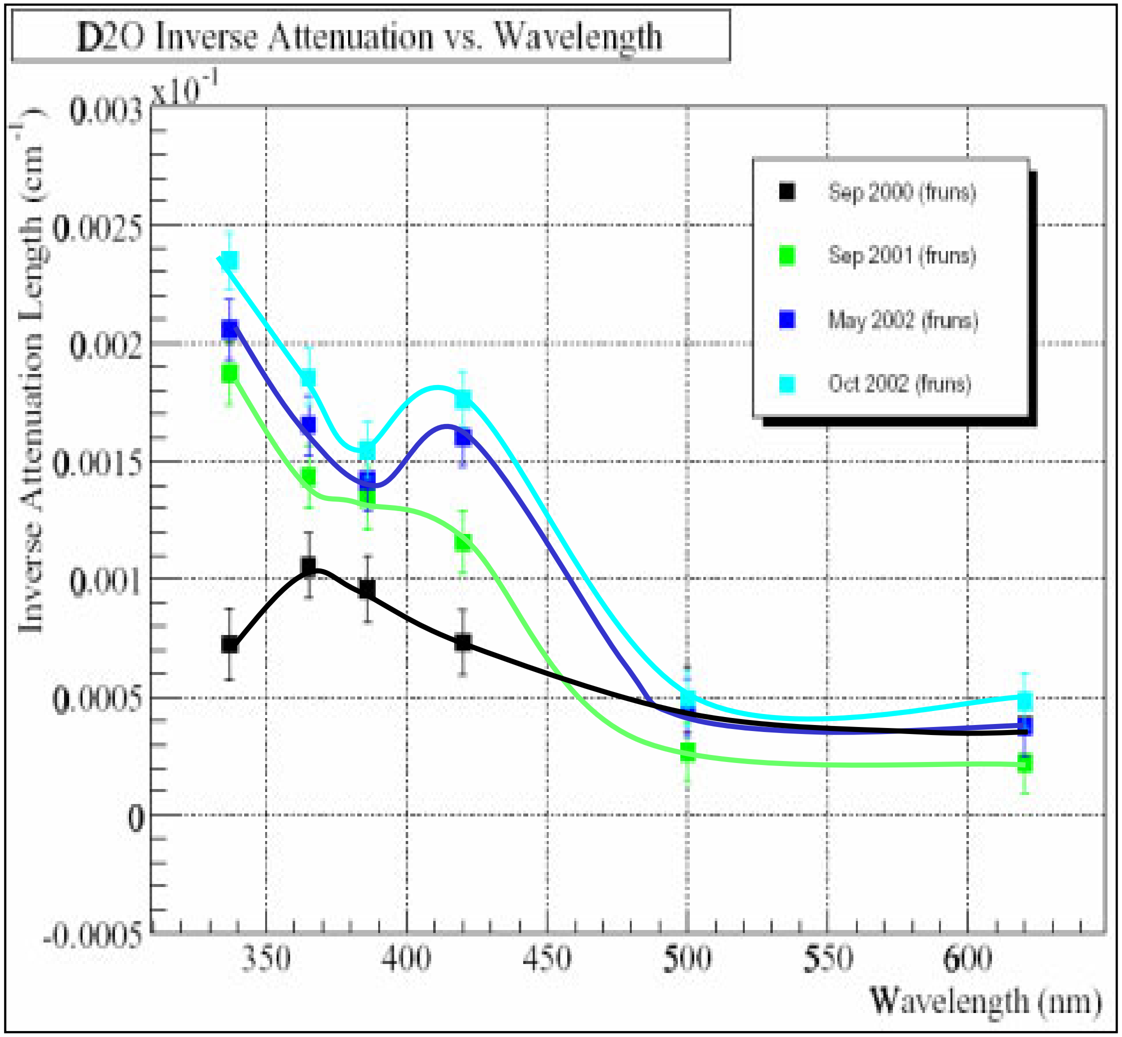
glove box in DCR

Optical Calibration

- The PMT angular response and attenuation lengths of the media are measured directly using laser+diffuser *("laserball")*.

- Attenuation for D_2O and H_2O, as well as PMT angular response, also measured in-situ using radial scans of the laserball.

- Exhibit a change as a function of time after salt was added to the detector.

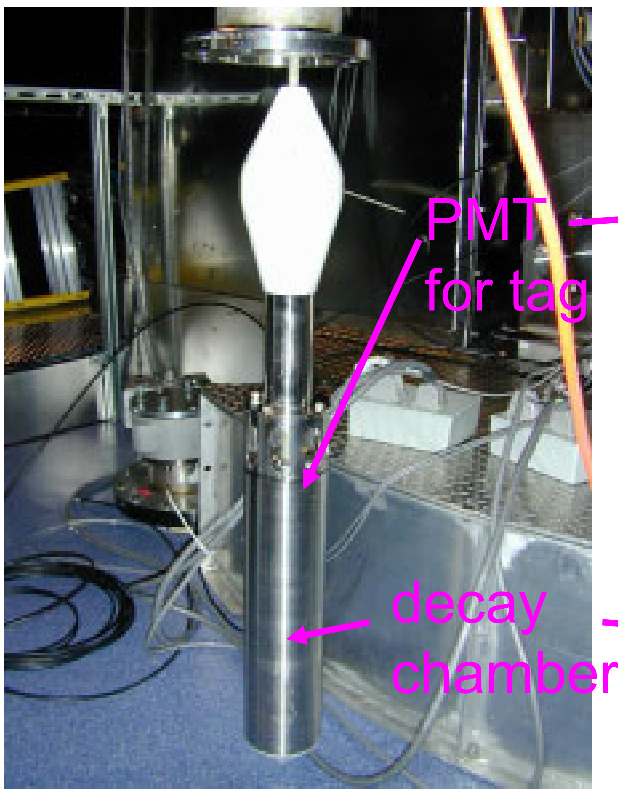


Vertex reconstruction of ^{16}N events

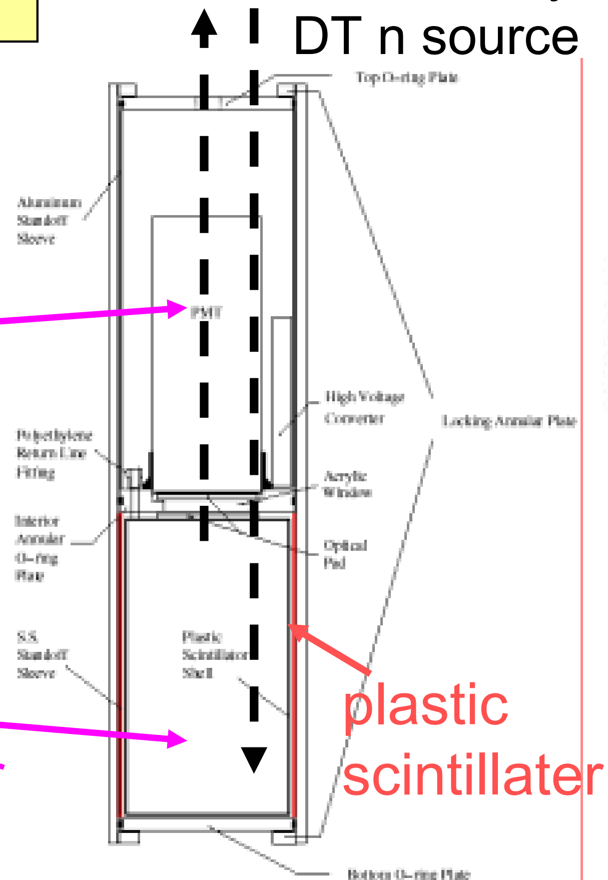
Vertex resolution ~15 cm

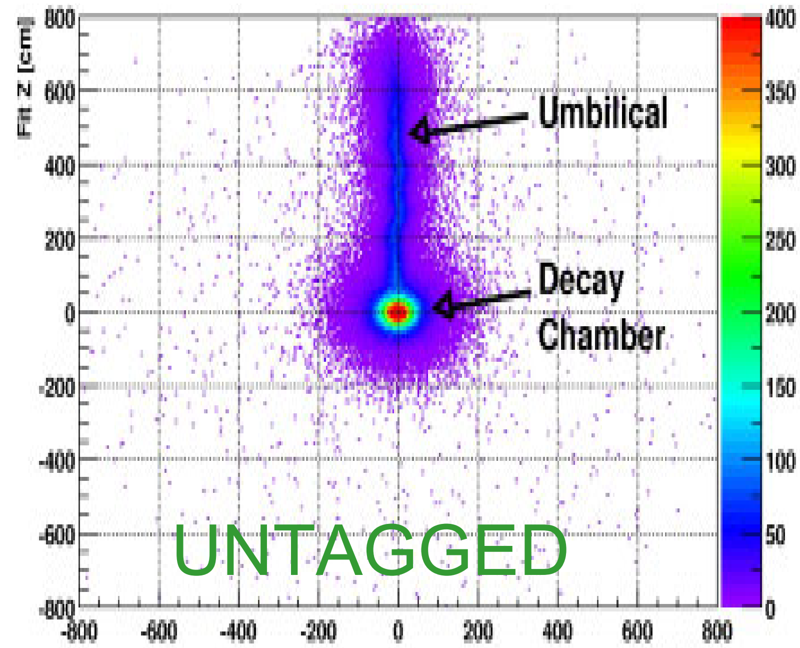
Radial accuracy on neutrino flux

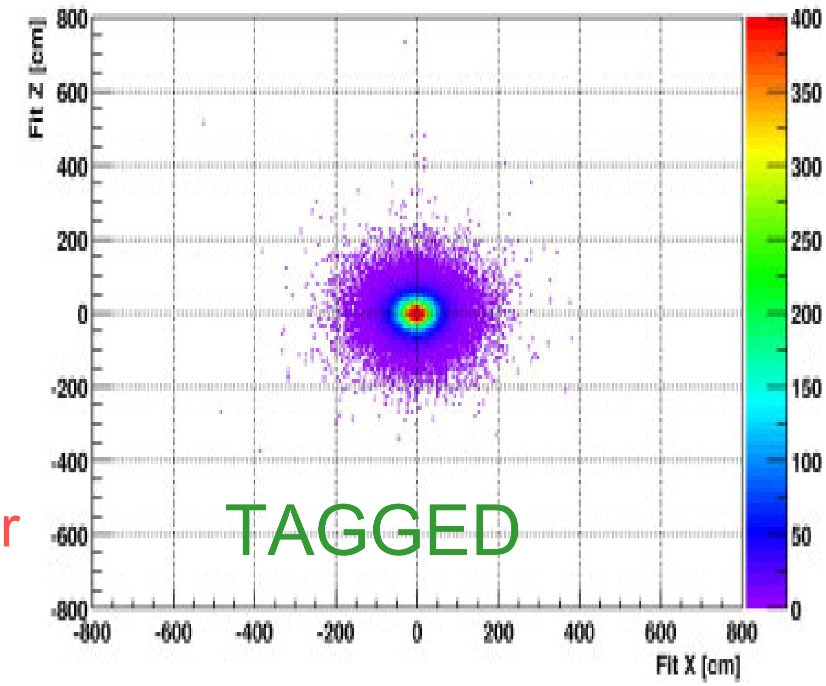
-3.0+3.5%(NC)
-2.6+2.5%(CC)
-2.6+2.9%(ES)



N_2 gas activated by DT n source

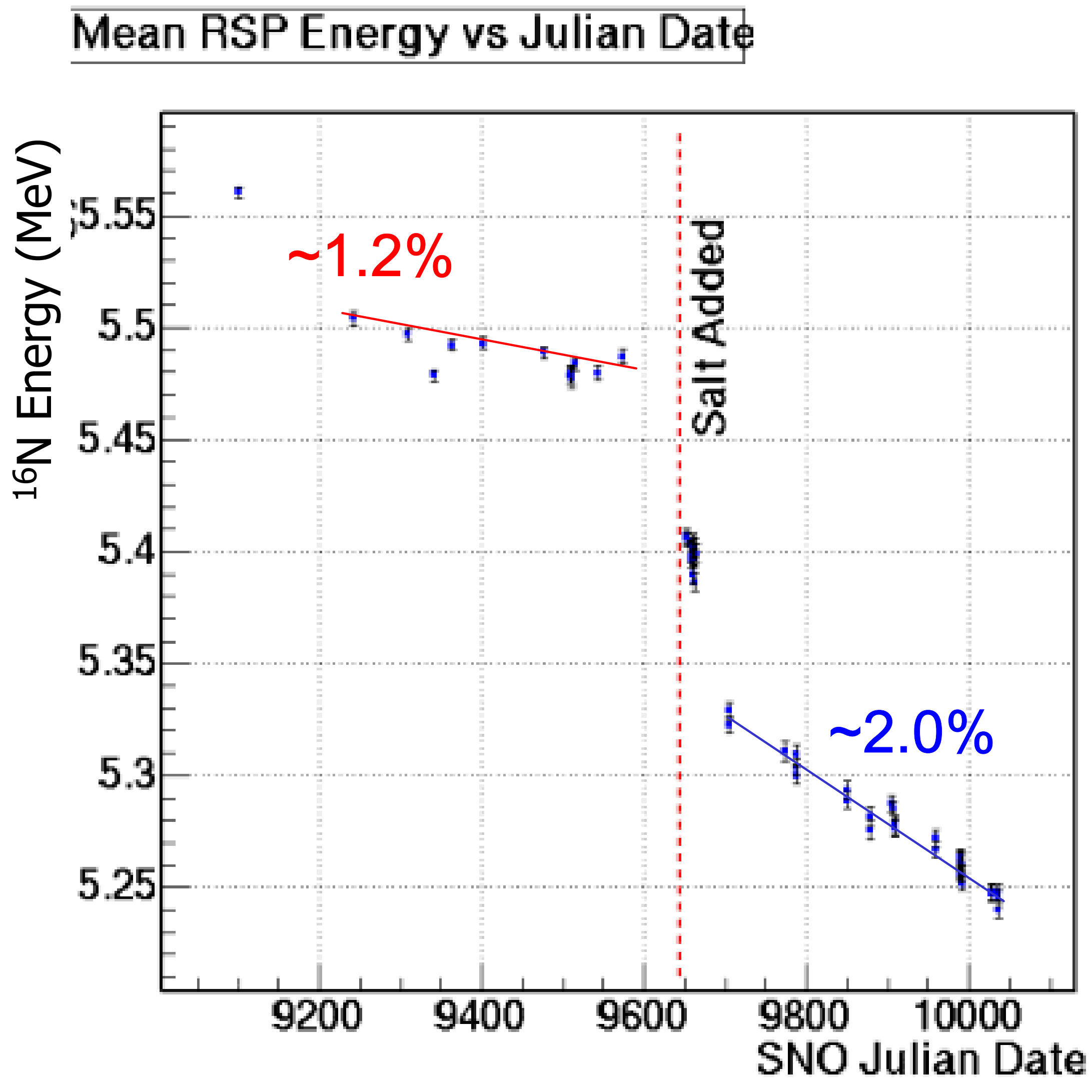






Energy Response from ^{16}N Calibration Source:1

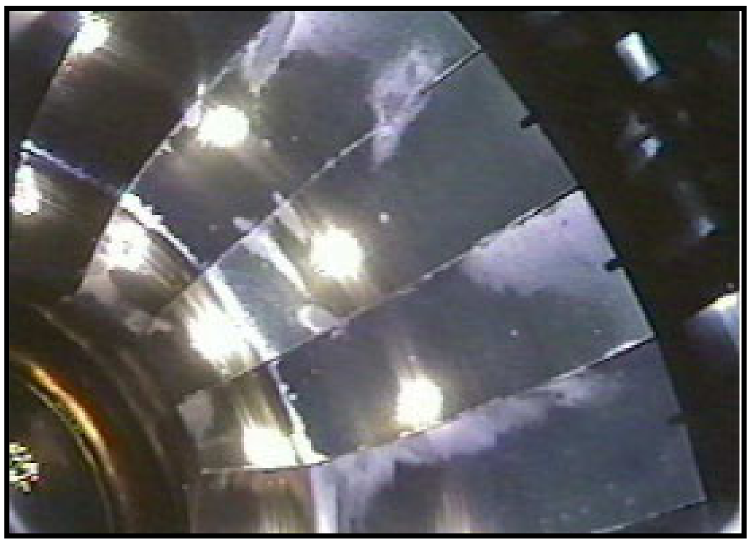
- Energy response of the detector determined from ^{16}N decay.
- Almost mono-energetic γ at 6.13 MeV, accompanied by tagged β decay.
- Provides check on the optical properties of the detector.
- Energy scale is changing

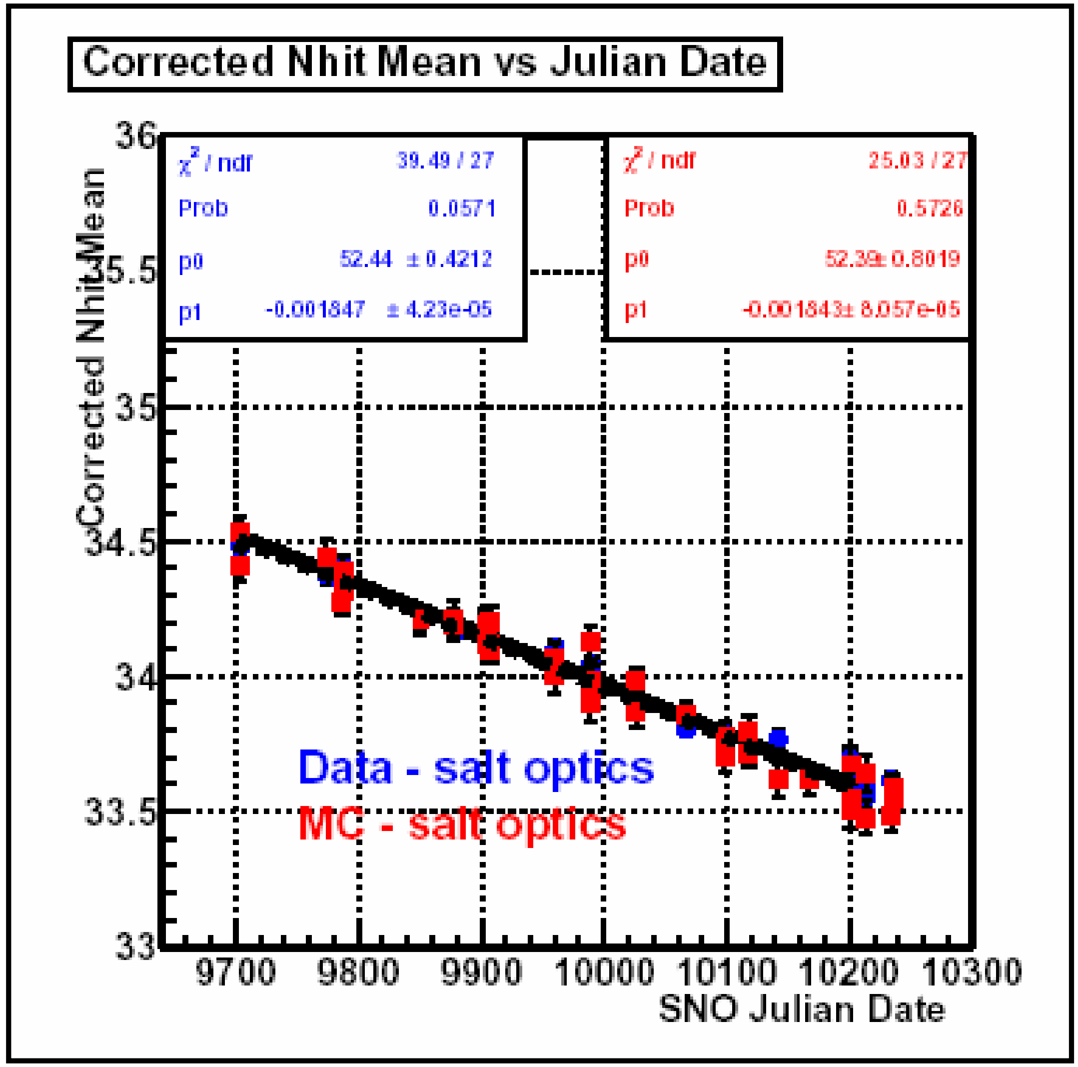


Energy Response from ^{16}N Calibration Source:2

Energy scale drift

- HV drift
- Gain drift
- Threshold drift
- Attenuation changes
- Concentrator degradation



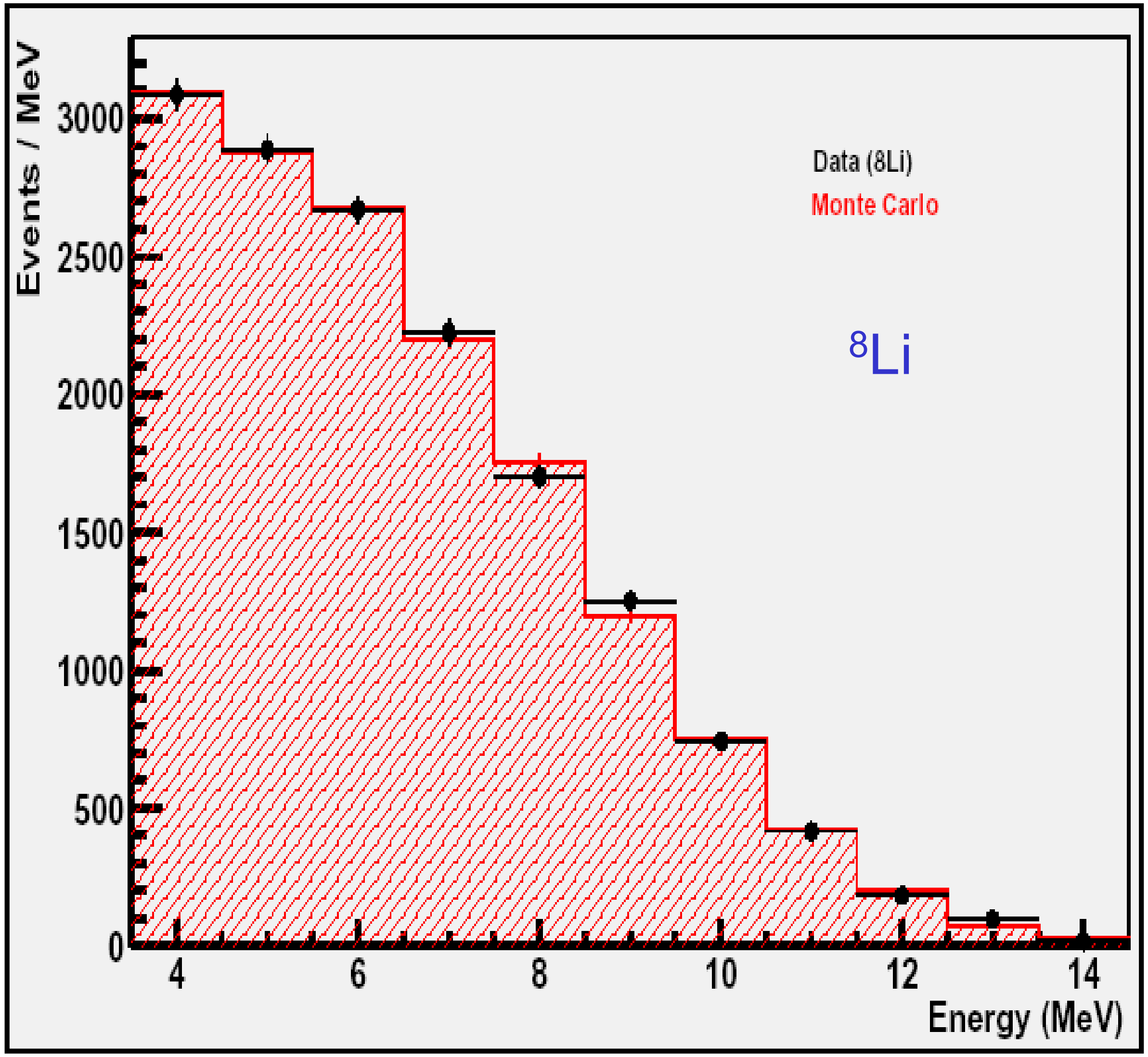


- Radial, temporal, and rate dependencies well modeled by Monte Carlo.

Energy Response

- In addition to ^{16}N (γ), additional calibration sources are employed to understand energy response of the detector.
  - Muon followers (neutron)
  - ^{252}Cf (neutron)
  - ^{8}Li (β)
  - …

  Excellent agreement!



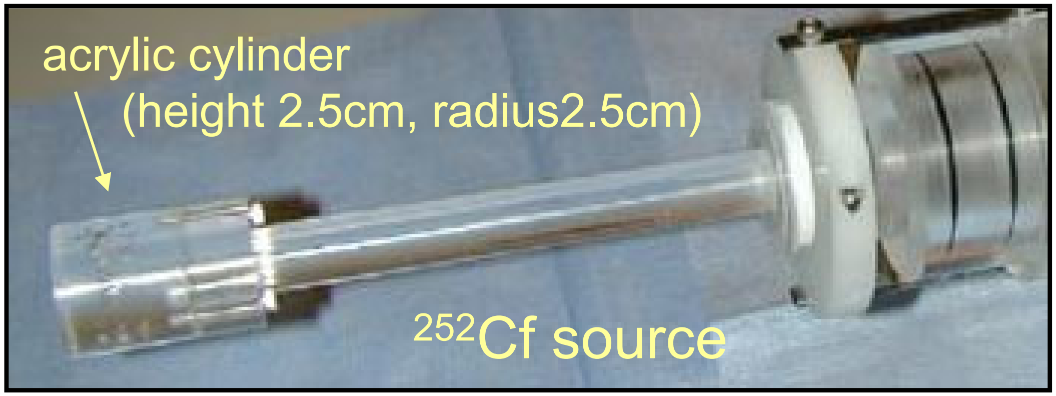
- Systematics dominated by source uncertainties, optical models, and radial/asymmetry distributions

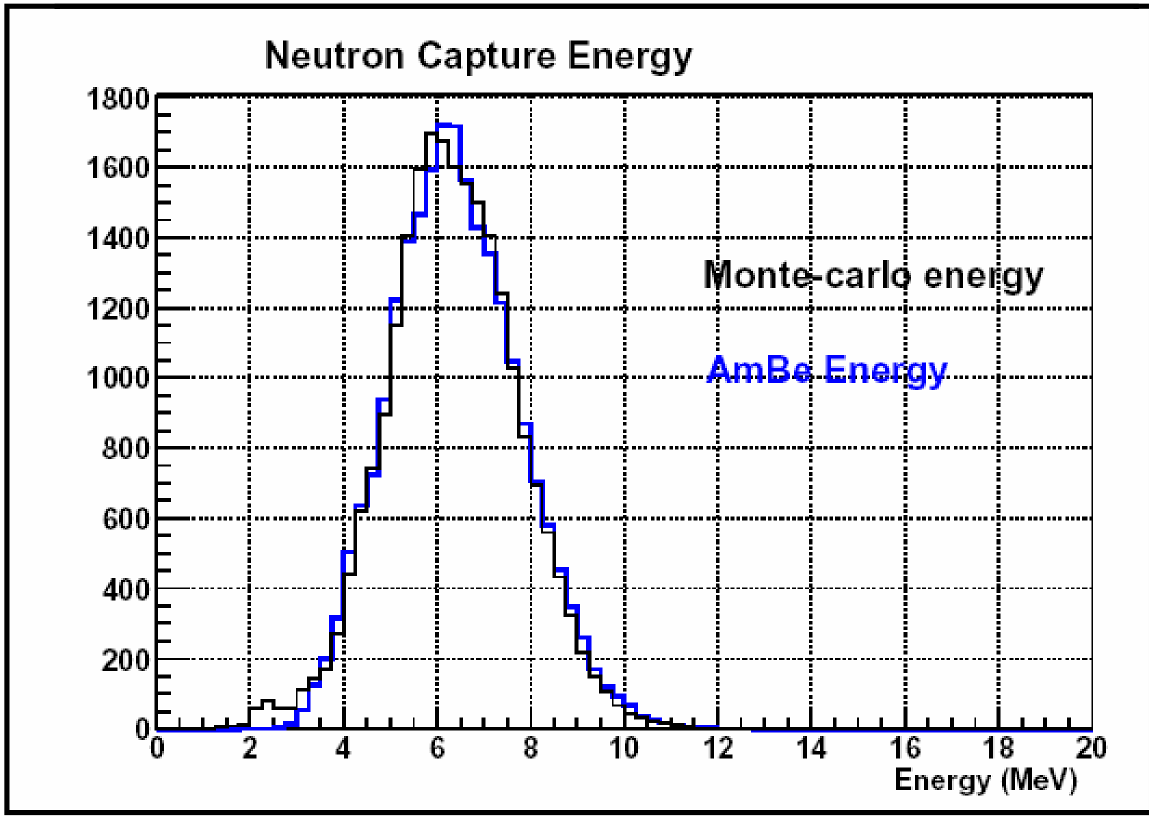
Energy Scale = ± 1.1%

Energy Resolution = ± 3.5%

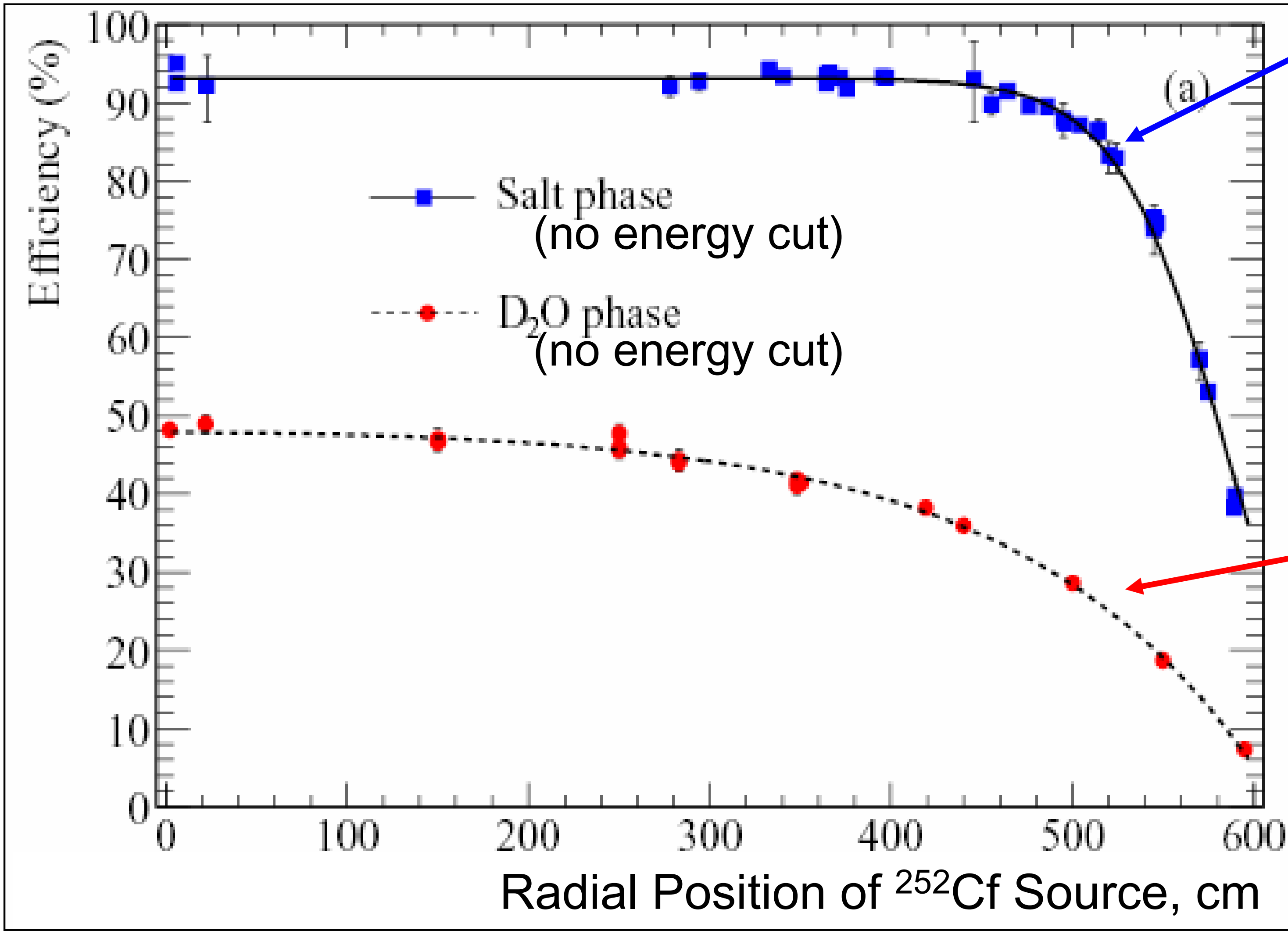
Neutron Response

- Use neutron calibration sources (^{252}Cf and AmBe) to determine capture profile for neutrons.
- ^{252}Cf decays by an emission or spontaneous fission. (3.768 $\pm$ 0.005 neutrons/fission)
- Observe resulting γ cascade from neutron capture on ^{35}Cl.
- γ's accompanying the fission and β's emitted by daughter products are removed using a timing cut.
- Monte Carlo agrees well with observed distributions.





Neutron Capture Efficiency in SNO



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

Average Efficiency
39.9%

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

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

Average Efficiency
14.4%

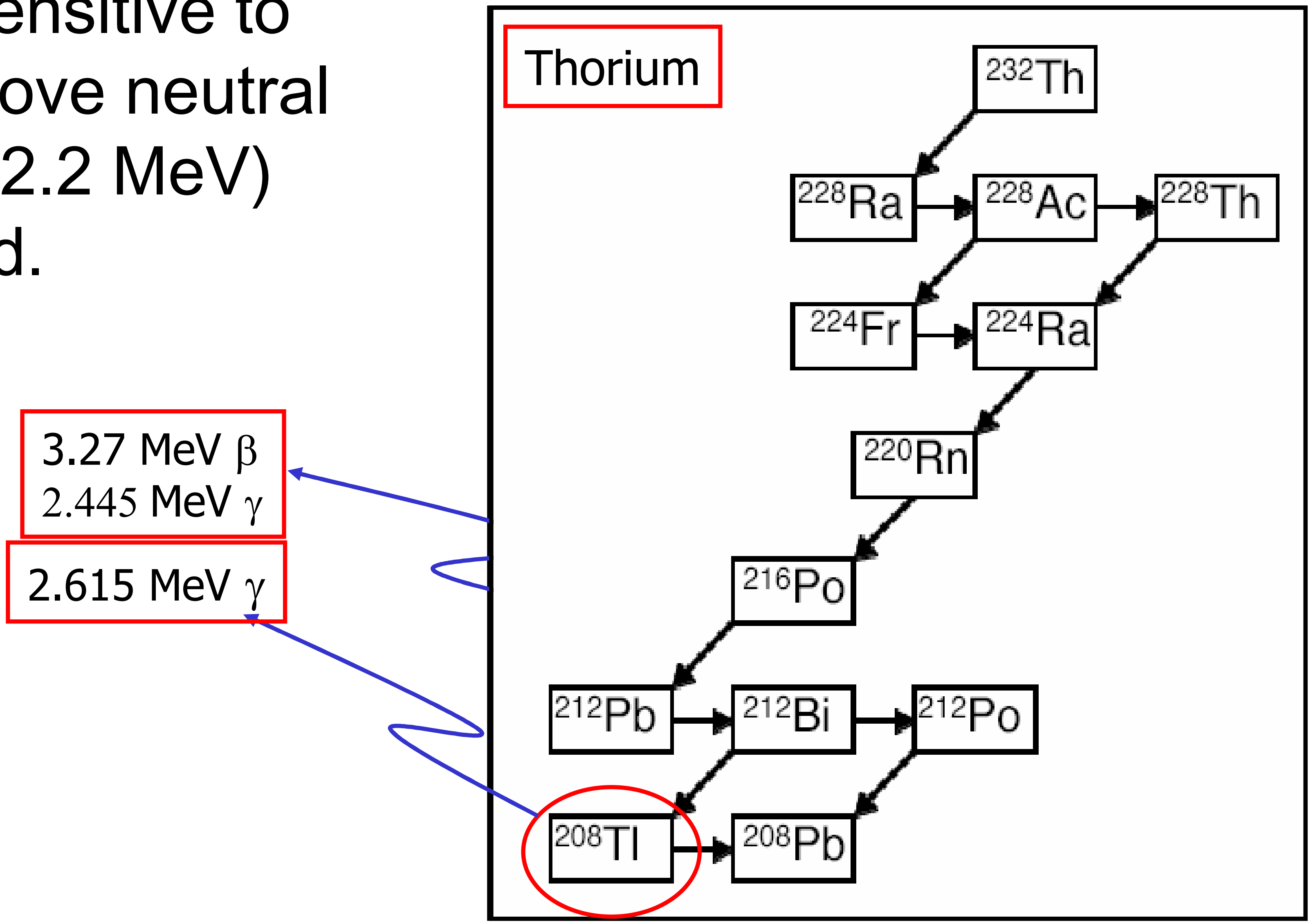
$T_e \geq 5.0$ MeV and
$R_\gamma \leq 550$ cm

Uncertainty of neutron capture efficiency on flux (Salt) = -2.5+2.7%(NC)

Backgrounds

Backgrounds

- Highly sensitive to any γ above neutral current (2.2 MeV) threshold.



Measuring U/Th

- In-situ:

  Low energy data

- Ex-situ:

  Ion exchange (^{224}Ra, ^{226}Ra)

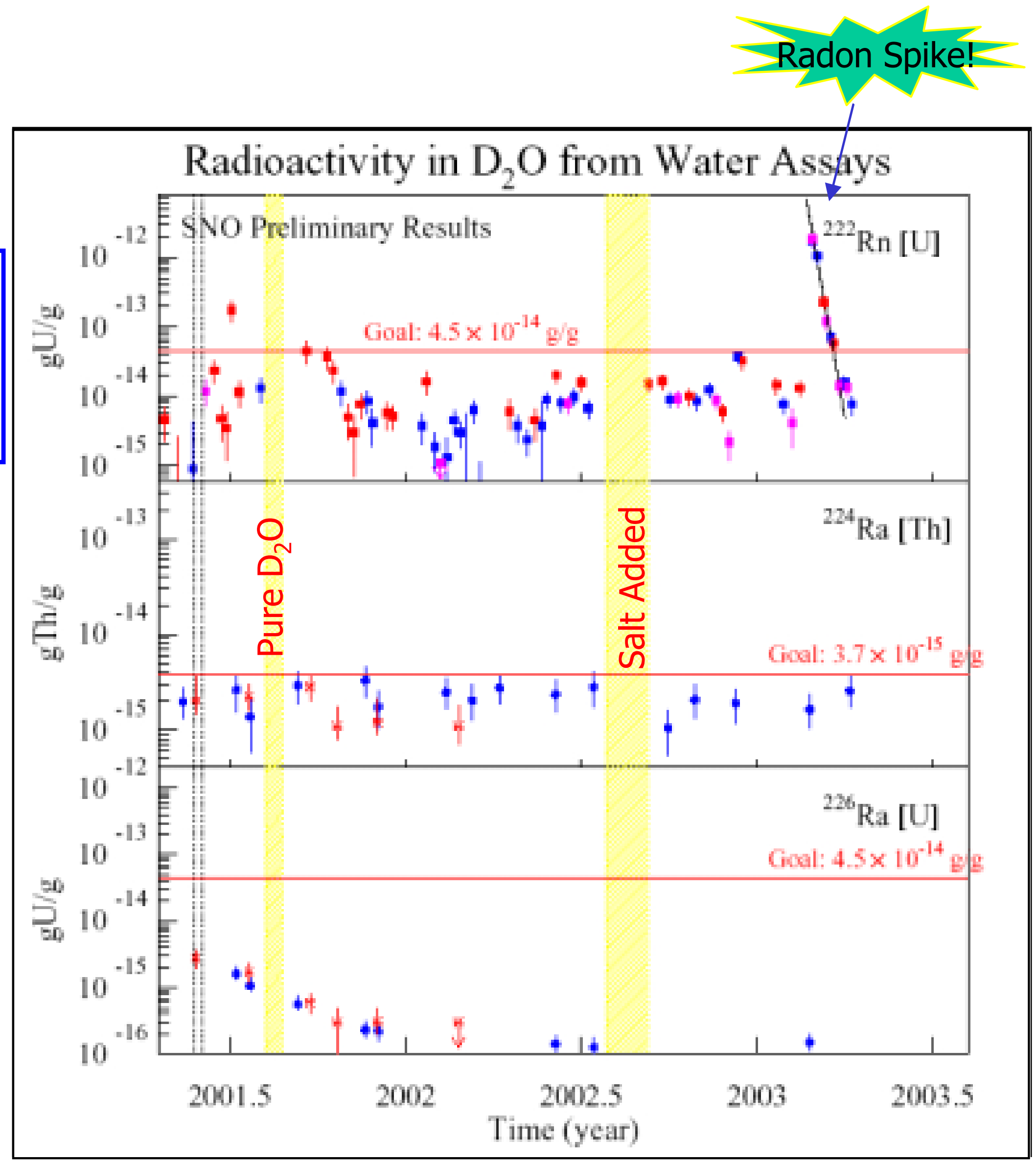
  Membrane degassing

  Count daughter product decays

- Bottom of vessel
- 2/3 way up
- Top of vessel

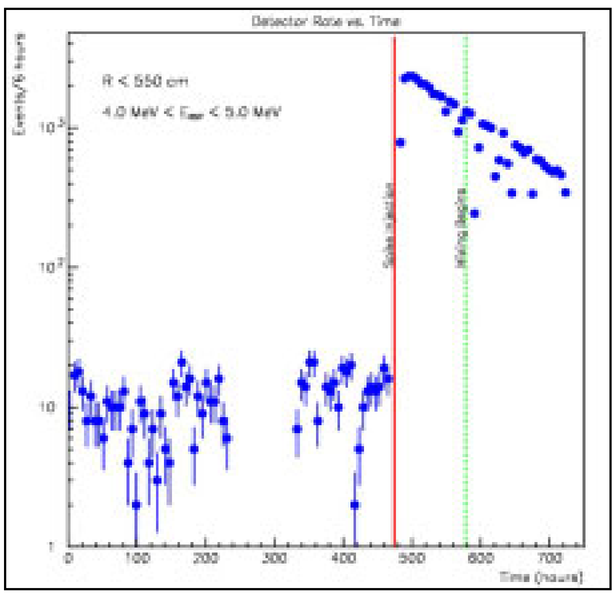
- MnOx
- HTiO

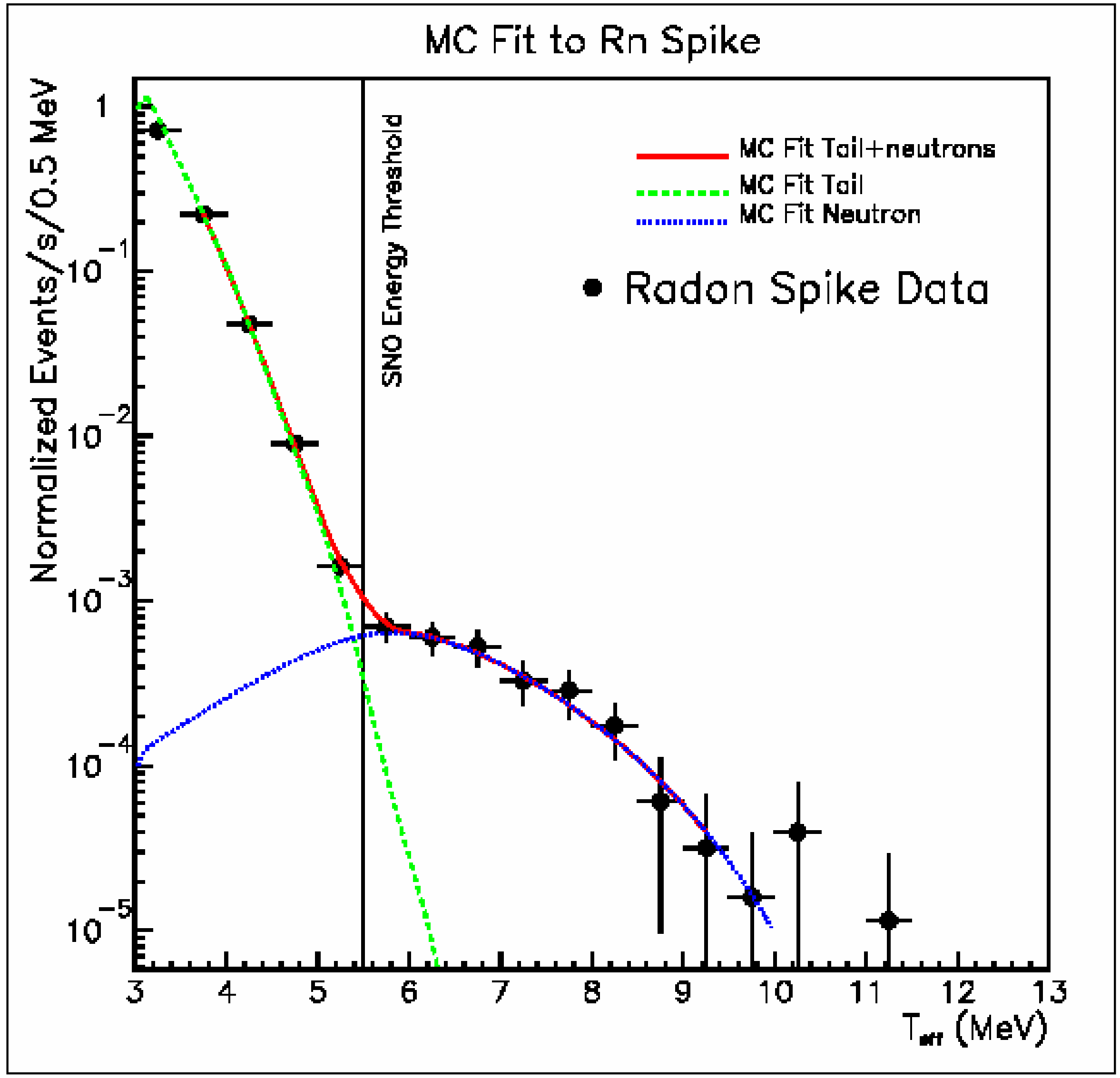
- MnOx
- HTiO



Old Backgrounds, New Technique: Radon `Spikes'

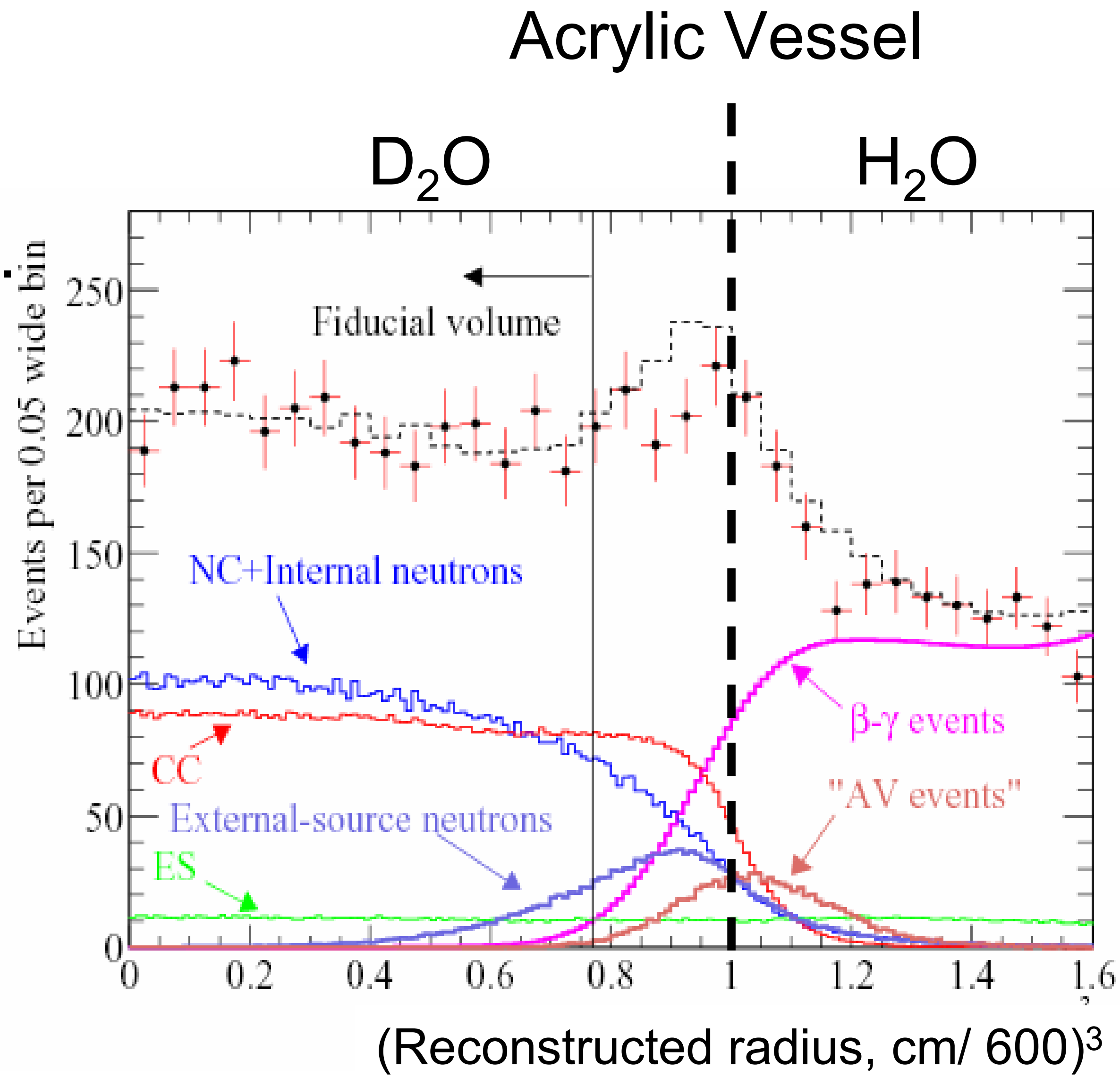
- Controlled radon spike added to D_2O to measure behavior of low-energy backgrounds.
- 80 Bq of Rn slowly mixed in heavy water.





New Backgrounds

- Salt and heightened neutron sensitivity introduces new/increased backgrounds in salt phase.
  - ^{24}Na from neck of vessel.
  - Cosmic rays
  - Atmospheric neutrinos, Fission
  - *"External"* (α,n) reactions on carbon and oxygen in acrylic vessel
- Use radial profile to explicitly fit for external neutron, regardless of source.



Summary of Backgrounds

Source	No. Events
Deuteron photodisintegration	73.1 +24.0,-25.5
$^{2}H(\alpha,\alpha)pn$	2.8 +/- 0.7
$^{17,18}O(\alpha,n)$	1.4 +/- 0.9
Fission, atmospheric ν's	23.0 +/- 7.2
Terrestrial and reactor ν's	2.3 +/- 0.8
Neutrons from rock	<1
^{24}Na activation	8.4 +/- 2.3
Neutrons from CNO ν's	0.3 +/- 0.3
Total internal neutrons	111.3 +/- 25
Internal γ (fission, atm. ν)	5.2 +/- 1.3
^{16}N decays	< 2.5 (68% CL)
External-source neutrons (from fit)	84.5 +/- 34
Cherenkov events from β-γ decays	<14.7 (68% CL)
"AV events"	< 5.4 (68% CL)

Results from Salt Phase

Signal Extraction for Salt

(nucl-ex/0309004)

Data from July 26, 2001 to Oct. 10, 2002

254.2 live days

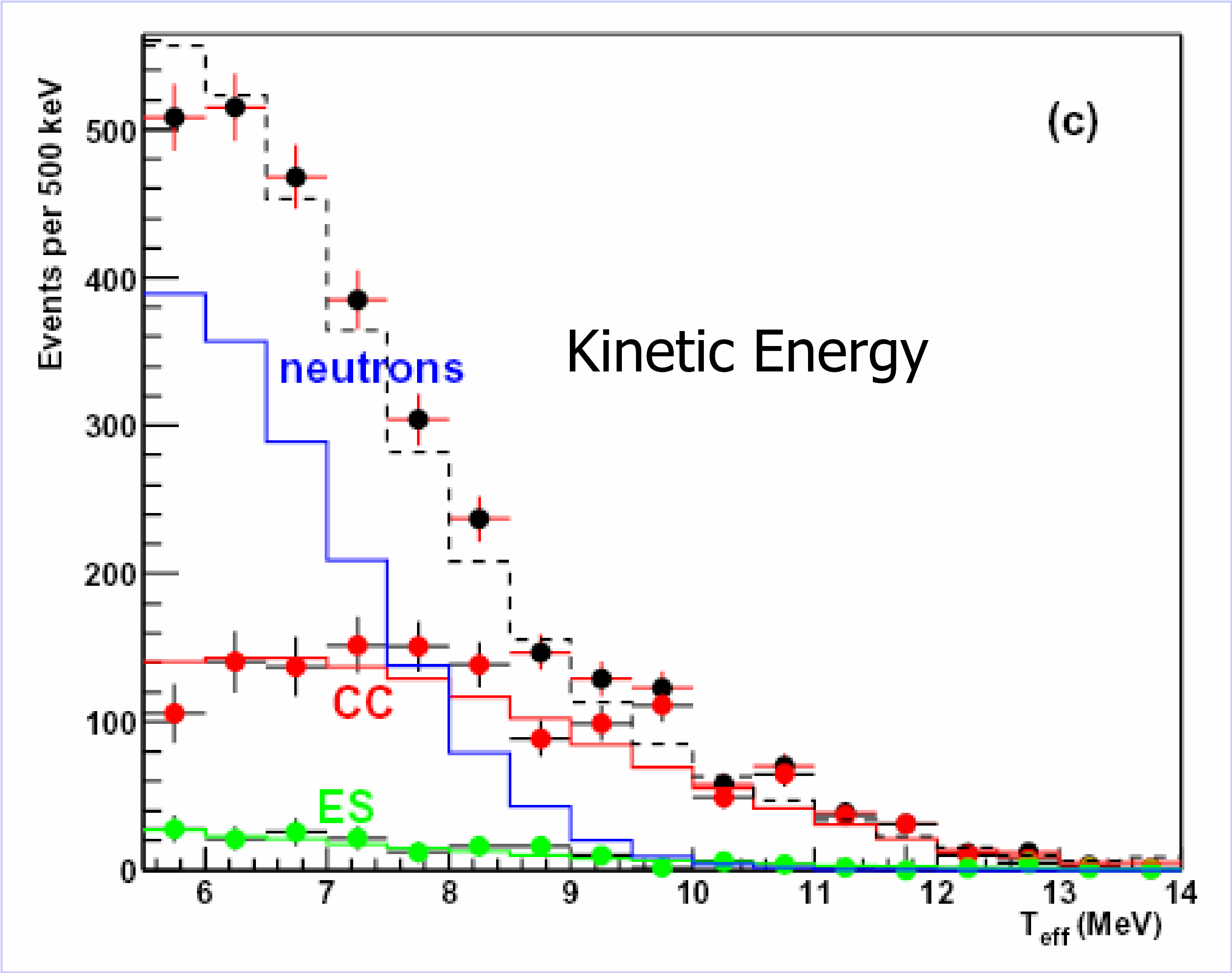
Blind analysis performed

3055 candidate events:

1339.6 $^{+63.8}_{-61.5}$ CC

1344.2 $^{+69.8}_{-69.0}$ NC

170.3 $^{+23.9}_{-20.1}$ ES



Flux Measurements

Unconstrained Flux:

$$\Phi_{cc} = 1.59^{+0.08}_{-0.07} \text{(stat)} {}^{+0.06}_{-0.08} \text{(syst)}$$

$$\Phi_{ES} = 2.21^{+0.31}_{-0.26} \text{(stat)} \pm 0.10 \text{ (syst)}$$

$$\Phi_{NC} = 5.21 \pm 0.27 \text{ (stat)} \pm 0.38 \text{ (syst)}$$

Constrained Flux:

$$\Phi_{cc} = 1.70 \pm 0.07 \text{ (stat)} {}^{+0.09}_{-0.10} \text{(syst)}$$

$$\Phi_{ES} = 2.13^{+0.29}_{-0.28} \text{(stat)} {}^{+0.15}_{-0.08} \text{(syst)}$$

$$\Phi_{NC} = 4.90 \pm 0.24 \text{ (stat)} {}^{+0.29}_{-0.27} \text{(syst)}$$

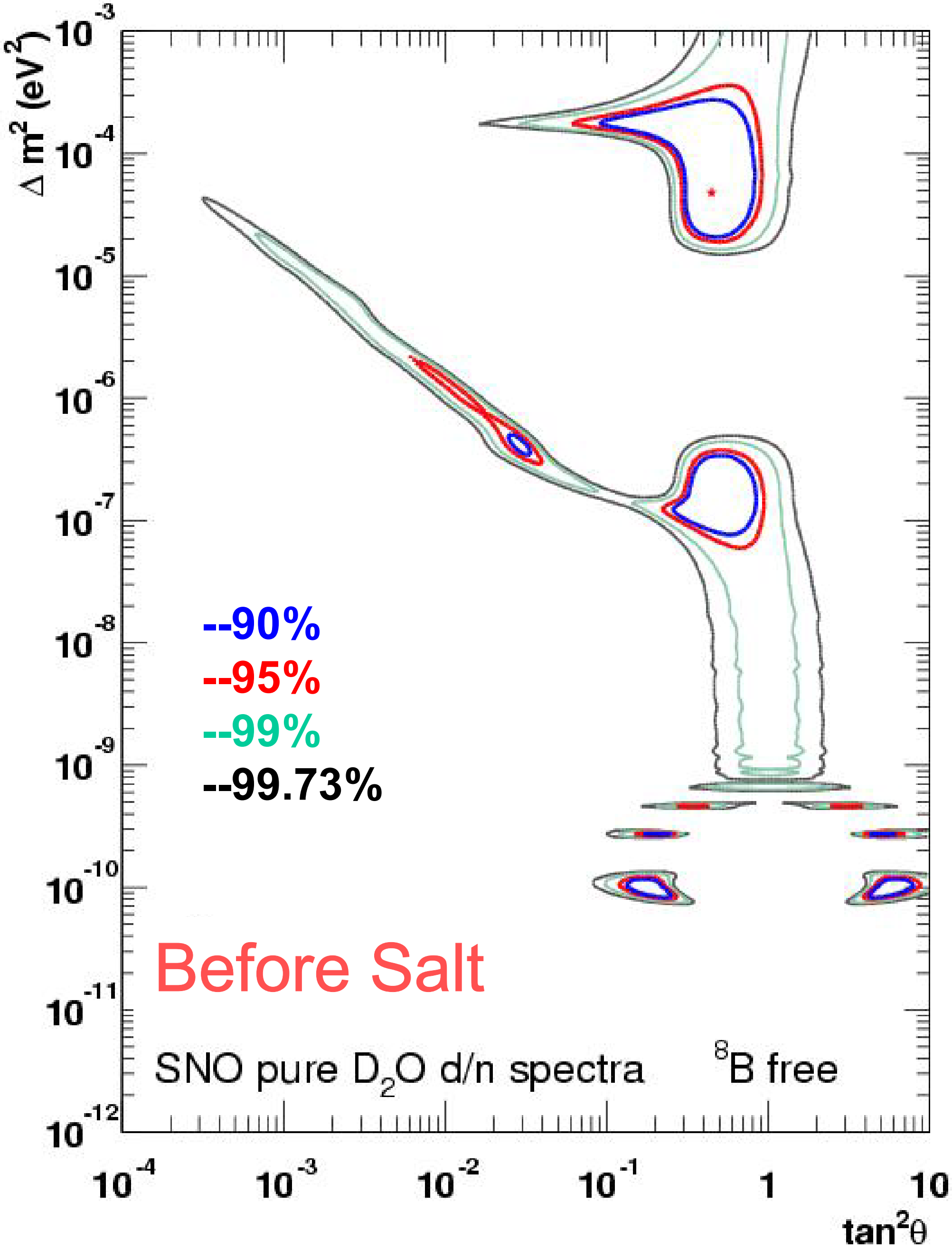
* in units of 10^6 cm^{-2} s^{-1}

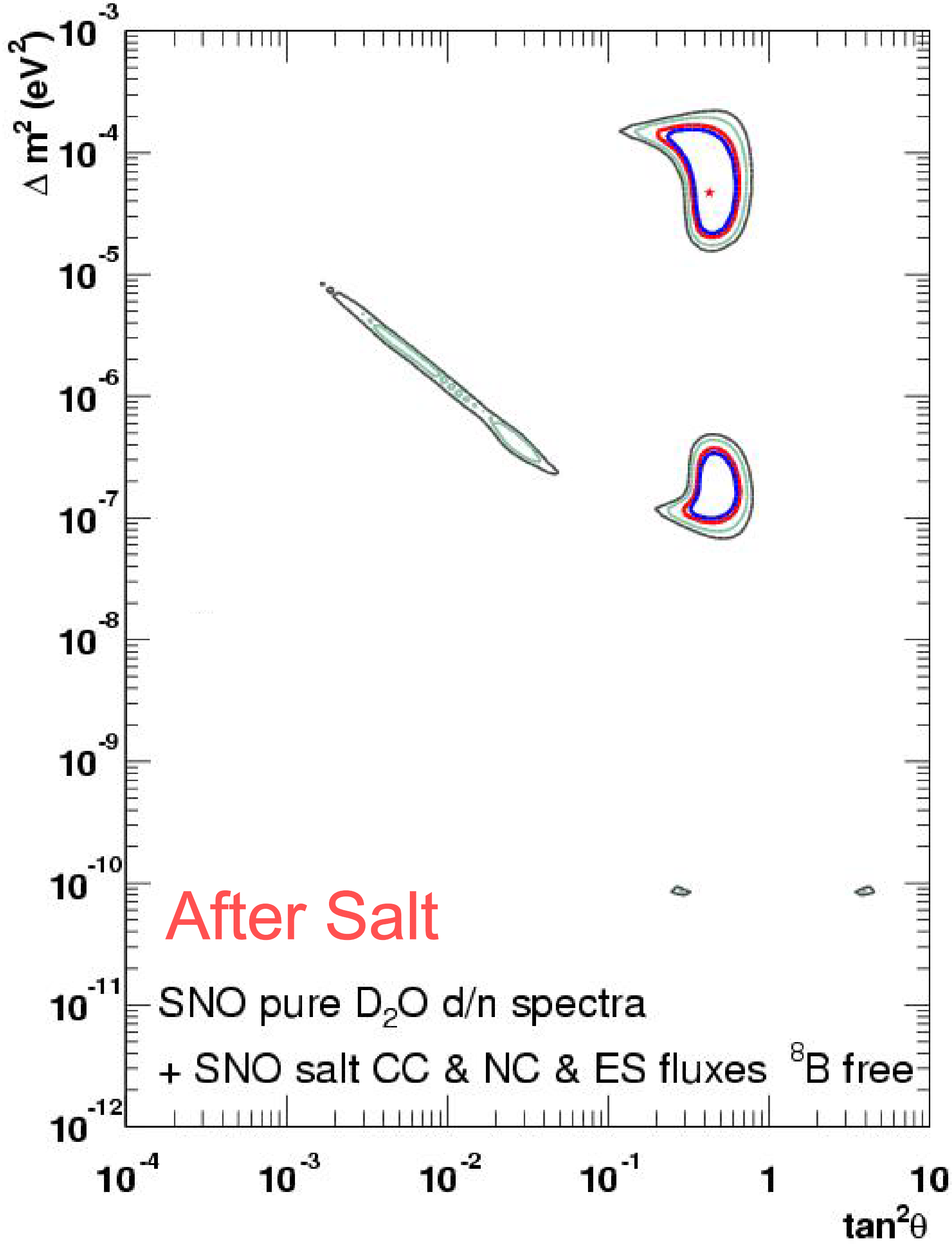
Total Active ^8B Fluxes

^8B BPB01 SSM	$5.05\ (1+0.20-0.16)\times 10^6\ cm^{-2}\ s^{-1}$
NC Pure D_2O Constrained	$5.09\ (1\pm0.13)\times 10^6\ cm^{-2}\ s^{-1}$
NC Salt Unconstrained	$5.21\ (1\pm0.09)\times 10^6\ cm^{-2}\ s^{-1}$

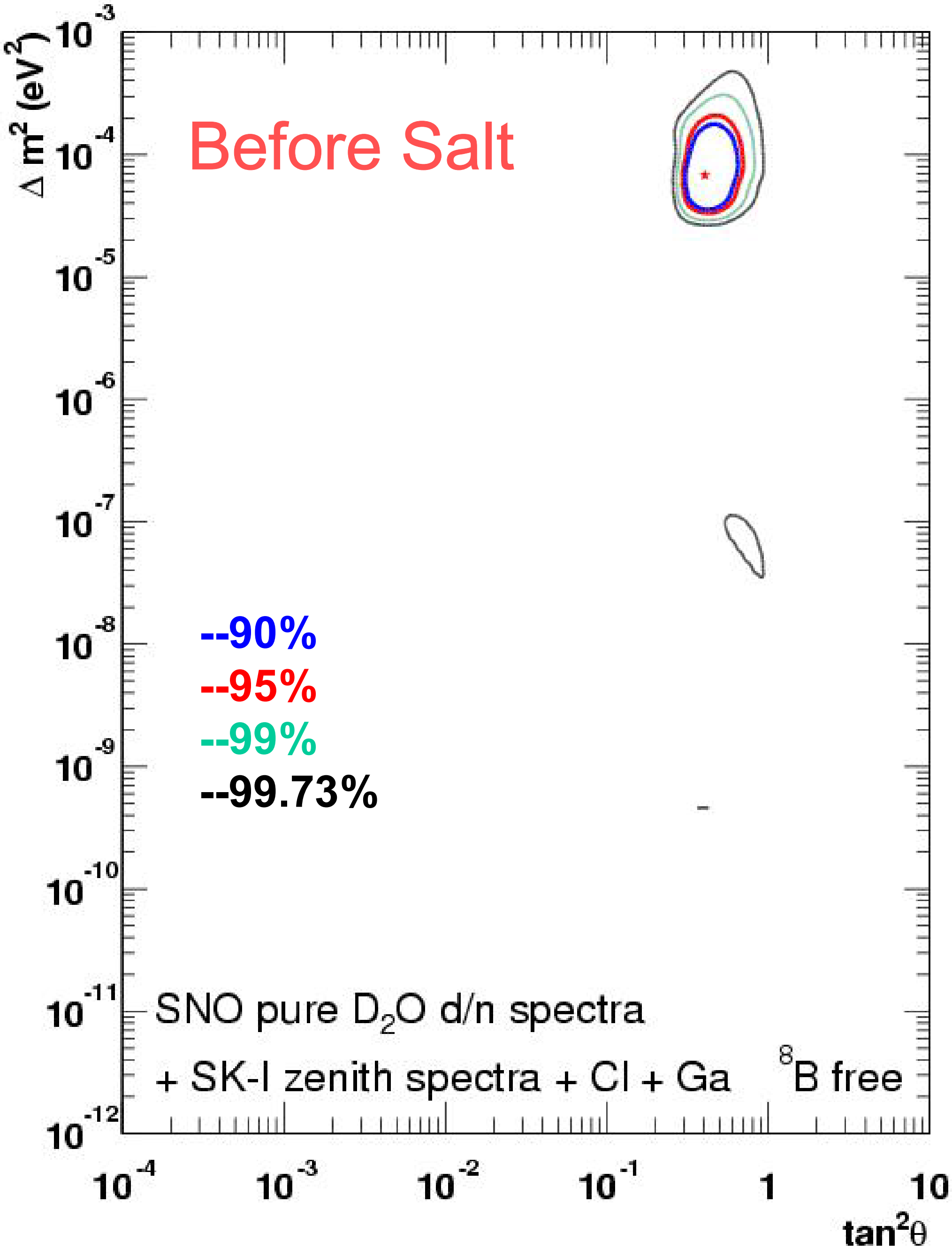
- Consistent with pure D_2O.
- Experimental error on ^8B flux was reduced.

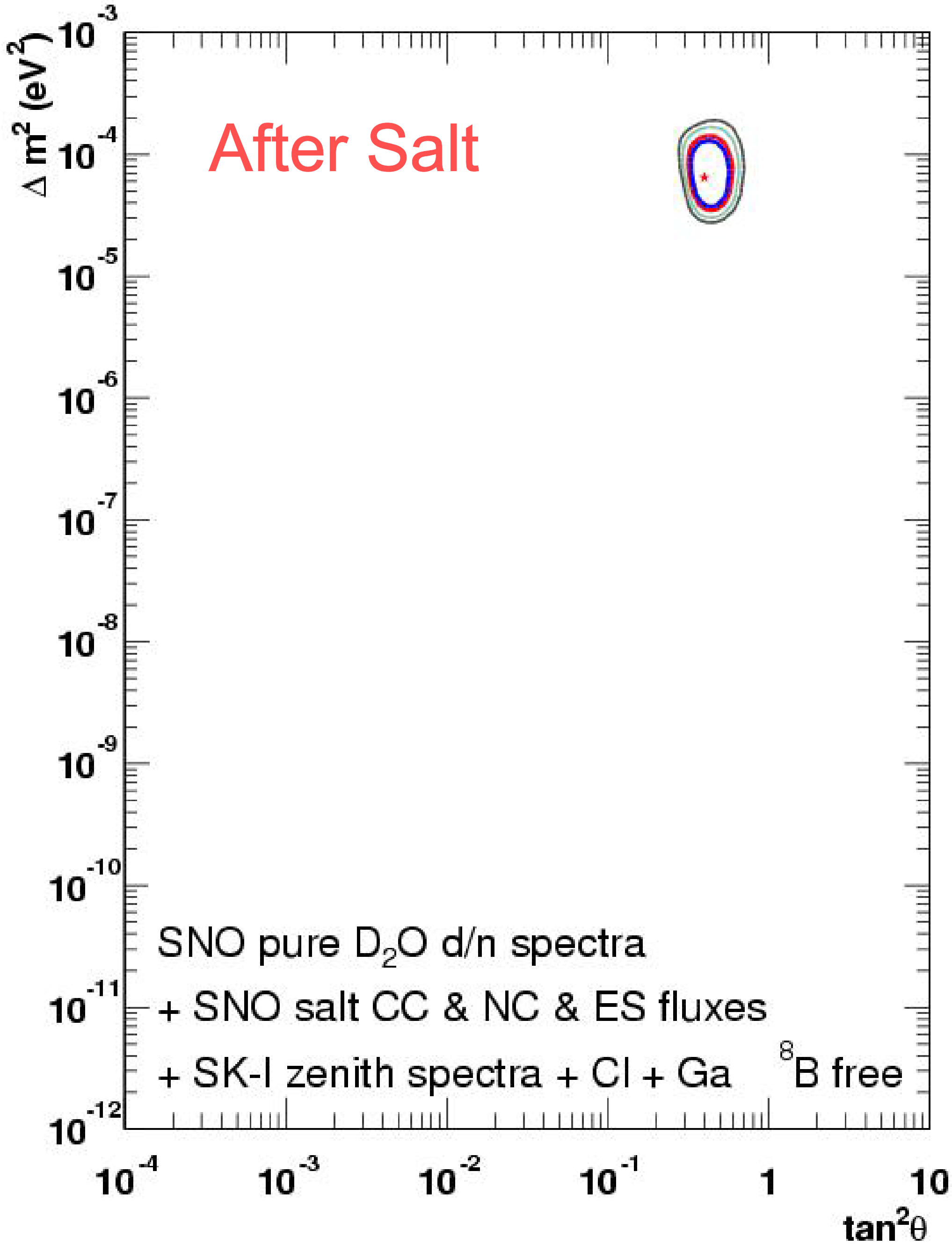
Oscillation Analysis: Only SNO



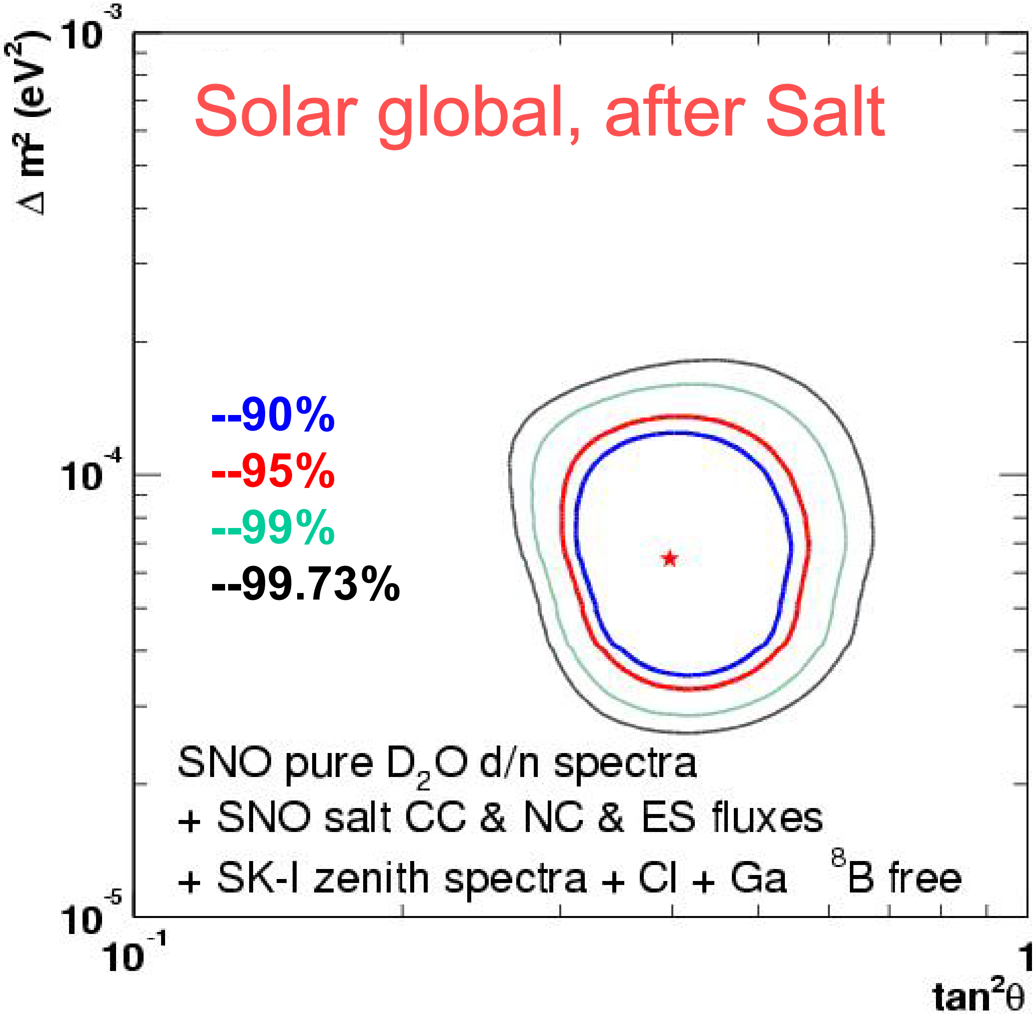


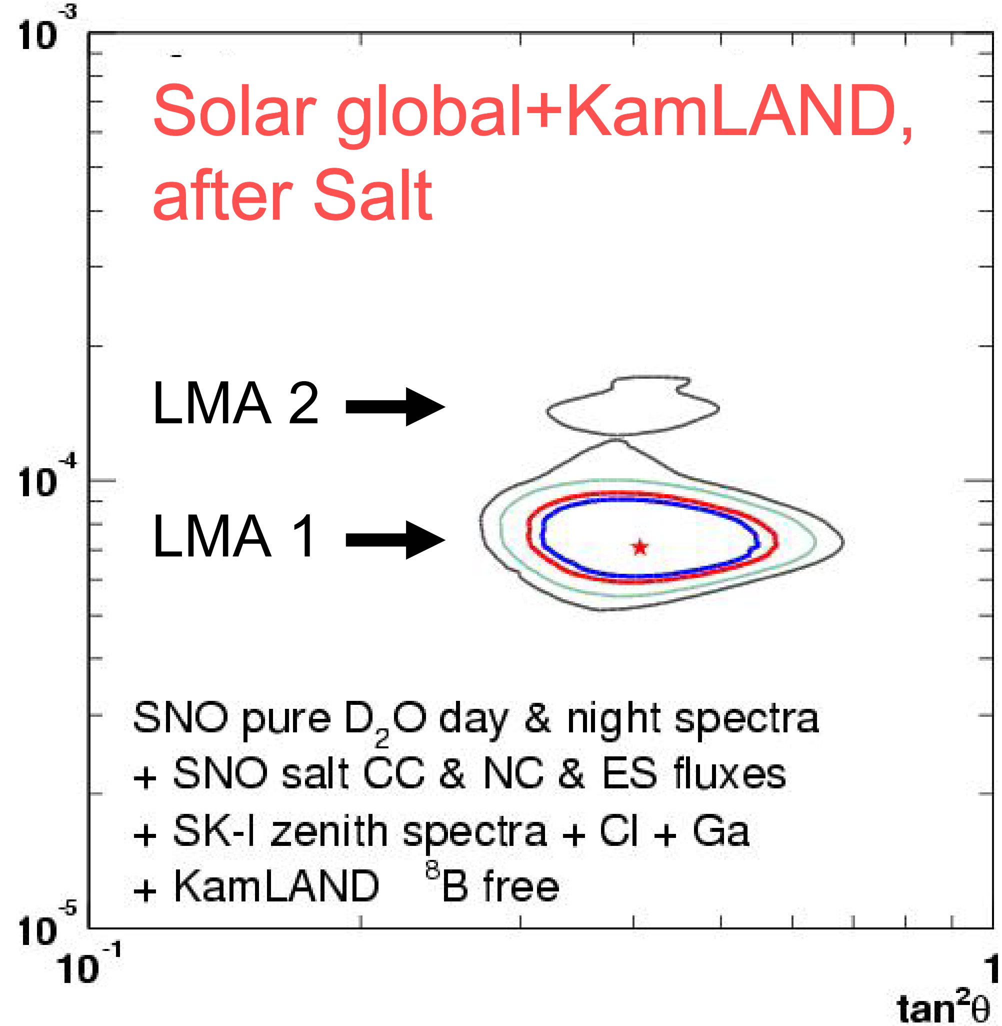
Oscillation Analysis: Solar Global





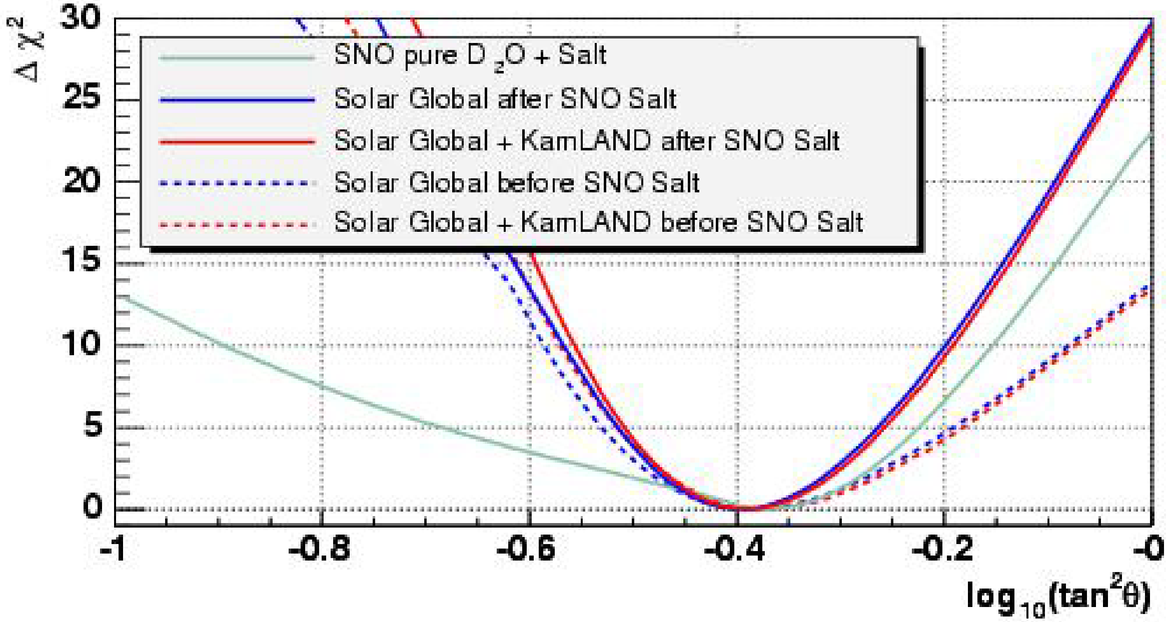
Oscillation Analysis: Solar + KamLAND



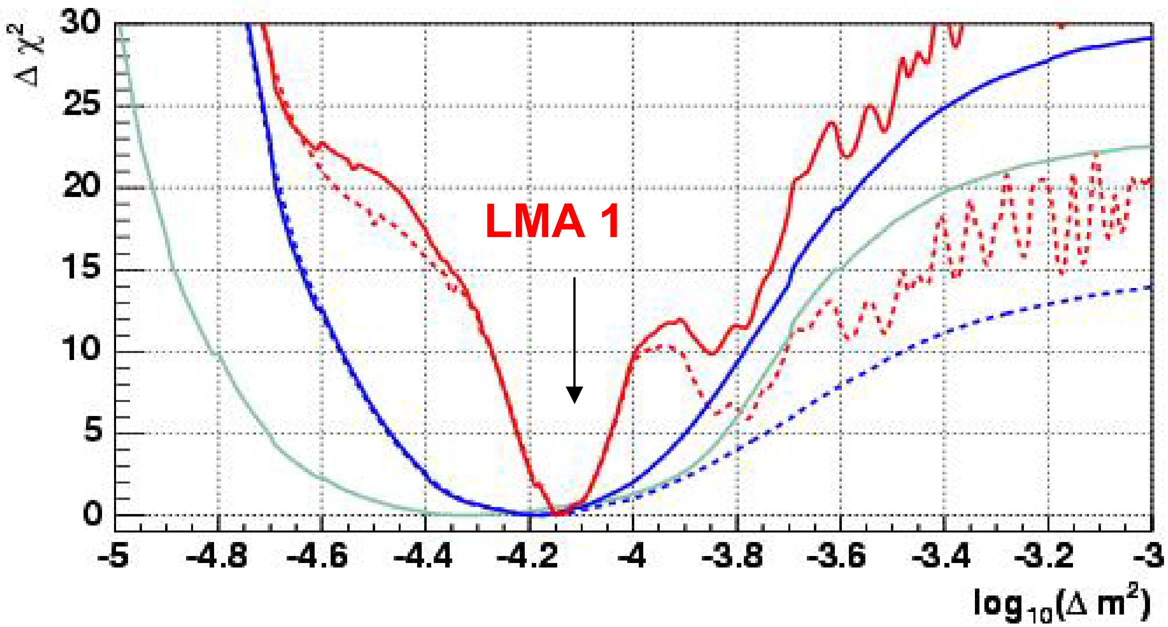


LMA 2 only at > 99% CL

1-D Plots



Maximal mixing rejected at 5.4 σ



Results from SNO -- Salt Phase

Oscillation Parameters,
2-D joint 1-σ boundary

< 1% probability of LMA 2

$$\Delta m^2 = 7.1^{+1.2}_{-0.6} \times 10^{-5}\ \mathrm{eV}^2$$
$$\theta = 32.5^{+2.4}_{-2.3}\ \mathrm{deg}$$

Marginalized 1-D 1-σ errors

Maximal mixing rejected at 5.4 σ

$$\Delta m^2 = 7.1^{+1.0}_{-0.3} \times 10^{-5}\ \mathrm{eV}^2$$
$$\theta = 32.5^{+1.6}_{-1.7}\ \mathrm{deg}$$

Analyses of energy spectrum & day/night with full Salt data set is on going.

Future Plan

Salt Removal (Sept. ~ Oct., 2003)

- Salt was removed using a reverse osmosis unit, which produces a concentrated brine.

- The target is for ~1ppm salt in the D_2O after multiple (3-4) passes through the unit.

- SNO will move to the third phase of the experiment.

Salt removal has been completed.

SNO Phase III (NCD Phase)

- ^{3}He Proportional Counters ("NC Detectors")

40 Strings on 1-m grid

440 m total active length

Detection Principle

$$^2H + \nu_x \rightarrow p + n + \nu_x - 2.22\ MeV \qquad (NC)$$

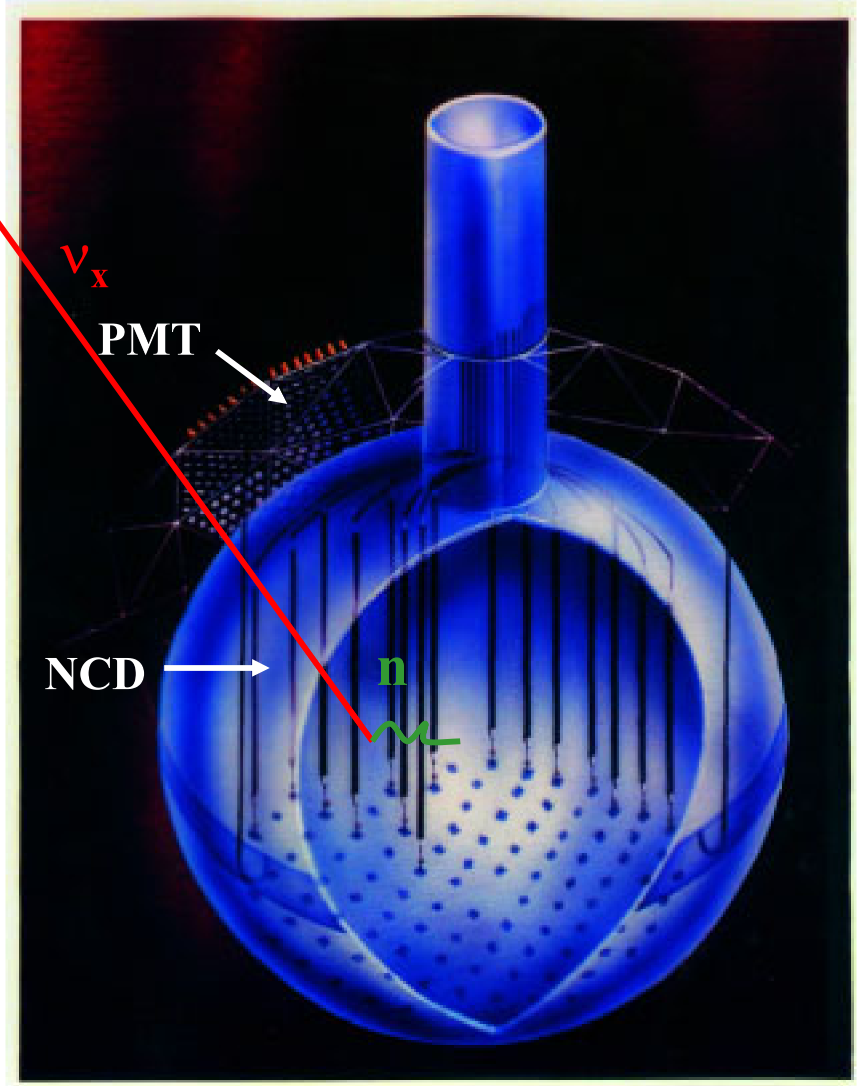
$$^3He + n \rightarrow p + {}^3H + 0.76\ MeV$$

Physics Motivation

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

Different systematic uncertainties than neutron capture on NaCl.

NCD array removes neutrons from CC, calibrates remainder. CC spectral shape.



Why Event-by-Event?

	Phase I		Phase III Projected
Source	ΔCC/CC (%)	ΔNC/NC (%)	ΔNC/NC (%)
Energy Scale ¶	-4.2, +4.3	-6.2, +6.1	0.0
Energy Resolution ¶	-0.9, +0.0	-0.0, +4.4	0.0
Energy Non-linearity ¶	±0.1	±0.4	0.0
Vertex Resolution ¶	±0.0	±0.1	0.0
Vertex Accuracy	-2.8, +2.9	±1.8	0.0
Angular Resolution	-0.2, +0.2	-0.3, +0.3	0.0
Internal Source p-d ¶	±0.0	-1.5, +1.6	3.0
External Source p-d ¶	±0.1	-1.0, +1.0	1.0
D2O Cherenkov ¶	-0.1, +0.2	-2.6, +1.2	0.0
H2O Cherenkov	±0.0	-0.2, +0.4	0.0
AV Cherenkov	±0.0	-0.2, +0.2	0.0
PMT Cherenkov ¶	±0.1	-2.1, +1.6	0.0
Neutron Capture	±0.0	-4.0, +3.6	3.0
Σ Systematic	**-5.2, +5.2**	**-8.5, +9.1**	**4.5**
Σ Statistical	**-2.8, +3.4**	**-8.5, +8.6**	**4**
Σ Uncertainties	**7**	**12**	**6**
¶ CC NC anti-correlation			

Current Status of the NCD Project

Milestones

Counter construction complete	Done
Radio assays complete	April 2001
NCD in-situ background test	Sep 2000

Neutron Background Estimates

From radio assay: < 4.0% SSM

Schedule

Routine data taking+analysis	Ongoing
Training for NCD installation	Complete
Salt removal	Complete
Deployment of NCD array	Ongoing

NCD Phase Begins '04

Summary

- SNO has measured total active ^8B flux precisely, then apply tight constraints on the oscillation parameters.

Total active ^8B flux = 5.21 (1±0.09)x 10^6 cm^{-2} s^{-1}

$$\Delta m^2 = 7.1^{+1.0}_{-0.3} \times 10^{-5}\ \mathrm{eV}^2$$
$$\theta = 32.5^{+1.6}_{-1.7}\ \mathrm{deg}$$
(1D)

- Additional analyses with full Salt data set are on going.
- Neutral Current Detectors are now under deployment.
- SNO Phase-III (NCD) will start in January 2004.