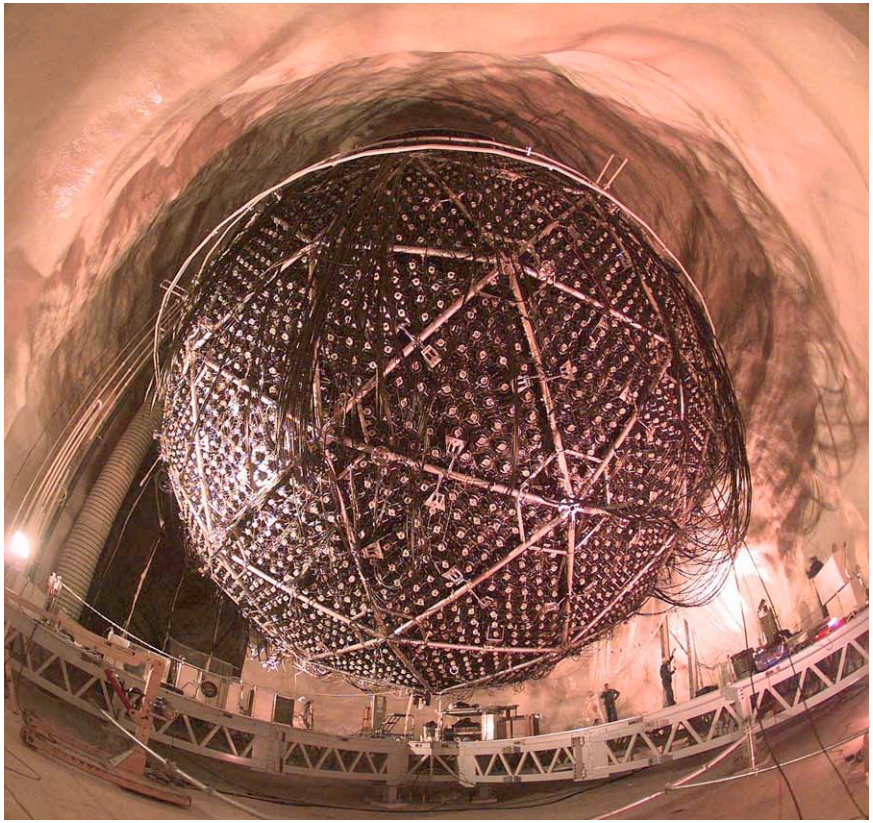
Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory (SNO)



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Outline

1. Introduction — the Solar Neutrino Problem (SNP)
2. Solving the SNP at the Sudbury Neutrino Observatory
3. Physics Implications
4. Summary

pp Chain and the Standard Solar Models

Overall: $4p + 2e \rightarrow {}^{4}He + 2\nu_e + 26.7MeV$

$p+p \rightarrow {}^{2}H+e^{+}+\nu_e$ **[*pp*]**

$p+e+p \rightarrow {}^{2}H+\nu_e$ **[*pep*]**

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

85%

${}^{3}He+{}^{3}He \rightarrow {}^{4}He+2p$

15%

${}^{3}He+p \rightarrow {}^{4}He+ e^{+}+\nu_e$ **[*hep*]**

${}^{3}He+{}^{4}He \rightarrow {}^{7}Be+\gamma$

0.02%

${}^{7}Be+p \rightarrow {}^{8}B+\gamma$
${}^{8}B \rightarrow {}^{8}Be^{*}+e^{+}+\nu_e$
${}^{8}Be^{*} \rightarrow {}^{4}He+{}^{4}He$

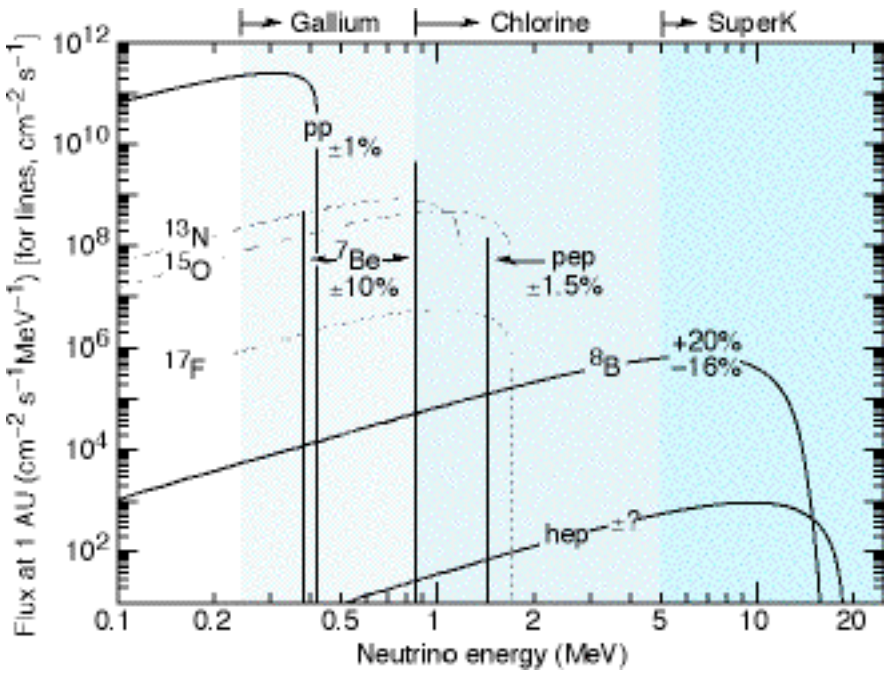
[${}^{8}B$]

${}^{7}Be+ e^{-} \rightarrow {}^{7}Li+\nu_e$
${}^{7}Li+p \rightarrow {}^{4}He+{}^{4}He$

[${}^{7}Be$]

Detailed computer model of solar evolution

Standard Solar Model



Solar ν experiments (pre-SNO)

Experiment	Depth (m.w.e.)	Target	Reaction	Threshold (MeV)
Homestake	4900	615 tons of C_2Cl_4	$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e$	0.814
SAGE	4700	60 tons metallic Ga	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e$	0.233
Gallex + GNO	3300	30.3 tons $GaCl_3$-HCl	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e$	0.233
Kamiokande	2700	3 kt H_2O 680 t fiducial volume	$\nu_x + e \rightarrow \nu_x + e$	7.5
Super-Kamiokande	2700	55 kt H_2O 22.5 kt fiducial volume	$\nu_x + e \rightarrow \nu_x + e$	5.5

$$\text{GALLEX}: \quad \frac{\Phi_{Ga}(\nu_e)}{\Phi_{SSM}(\nu_e)} = 0.58 \pm 0.05$$

$$\text{SAGE}: \quad \frac{\Phi_{Ga}(\nu_e)}{\Phi_{SSM}(\nu_e)} = 0.60 \pm 0.05$$

$$\text{Homestake}: \quad \frac{\Phi_{Cl}(\nu_e)}{\Phi_{SSM}(\nu_e)} = 0.34 \pm 0.03$$

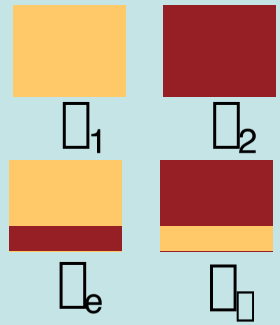
$$\text{Super-K}: \quad \frac{\Phi_{SK}(\nu_x)}{\Phi_{SSM}(\nu_e)} = 0.451^{+0.017}_{-0.015}$$

either
Solar models are
incomplete/incorrect
or
Neutrinos undergo
flavor-changing oscillation

Neutrino Oscillation (2 Flavors)

Mass states (ν_M)
mass: m_1, m_2

Weak states (ν_W)
(participate in weak interactions)

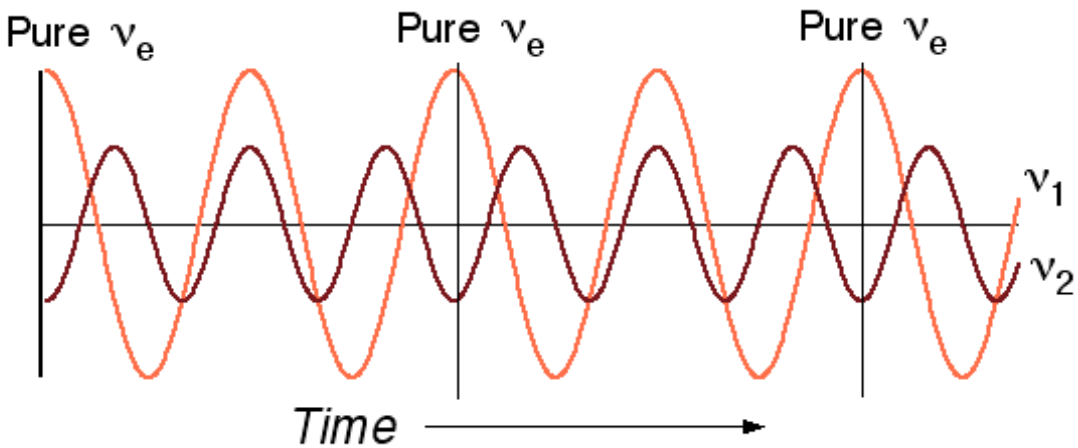


$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Equation of motion in vacuum:

$$i\frac{\partial}{\partial t}\nu_M = \frac{1}{2E} M_M \nu_M \quad \text{where } M_M = \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix}$$

$$i\frac{\partial}{\partial t}\nu_W = \frac{1}{2E} M_W \nu_W \quad \text{where } M_W = \frac{\Delta m^2}{2}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}$$

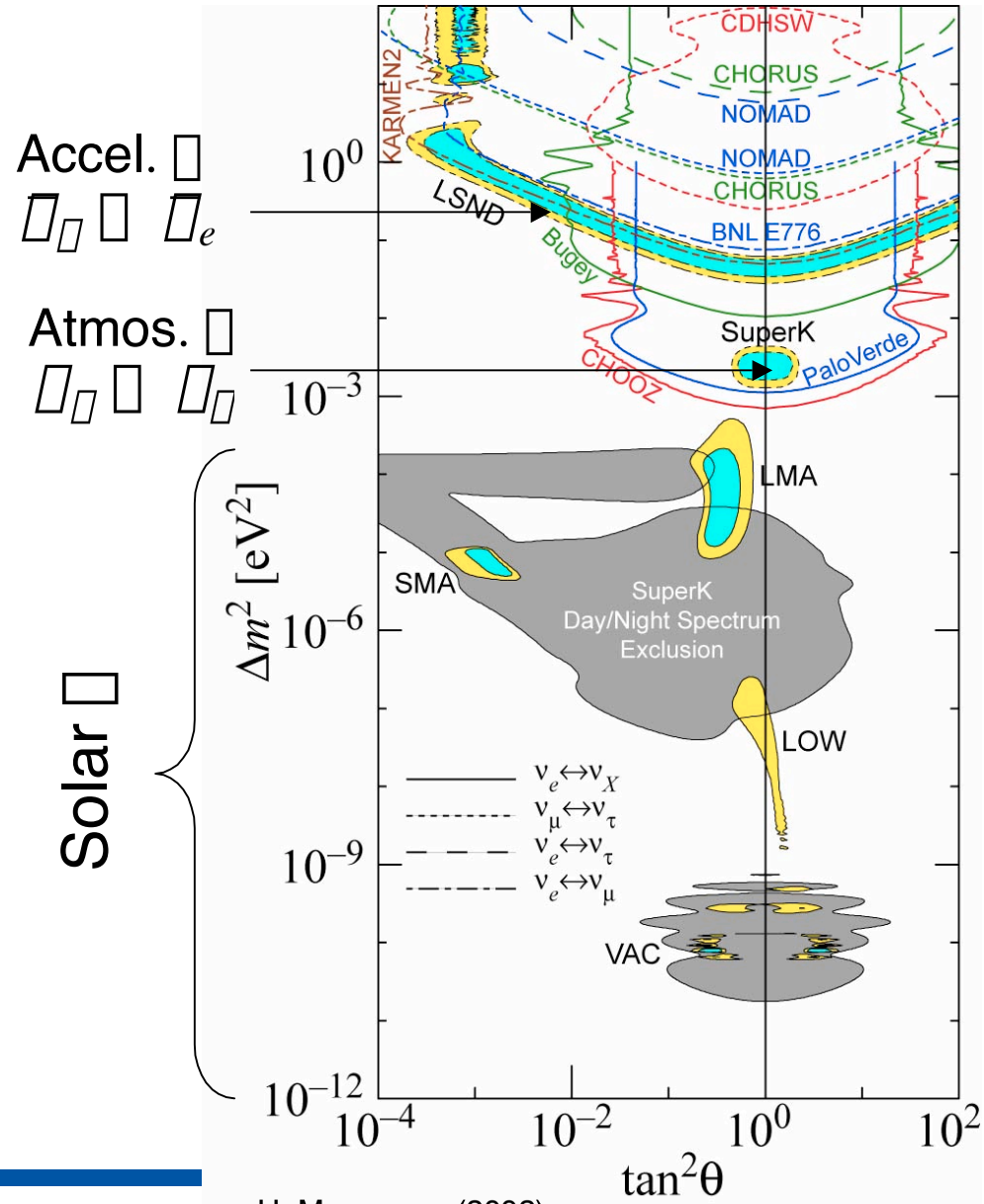


$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2\left(1.27\,\frac{\Delta m^2_{[\mathrm{eV}^2]}\, L_{[\mathrm{m}]}}{E_{[\mathrm{MeV}]}}\right) \quad \text{where } \Delta m^2 = m_2^2 - m_1^2$$

Neutrino Oscillation (Δm^2 vs $\tan^2\theta$)

Different L/E probes different regions in the (Δm^2,$\tan^2\theta$) parameter space.

Solar neutrinos has long baseline L (1 A.U.) and low E (< ~18 MeV) can probe Δm^2 down to 10^{-11}eV^2.



H. Murayama (2002)

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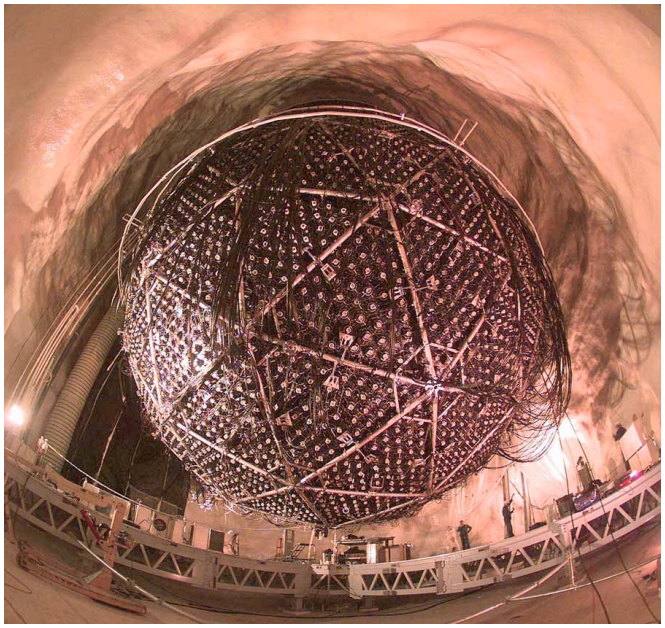
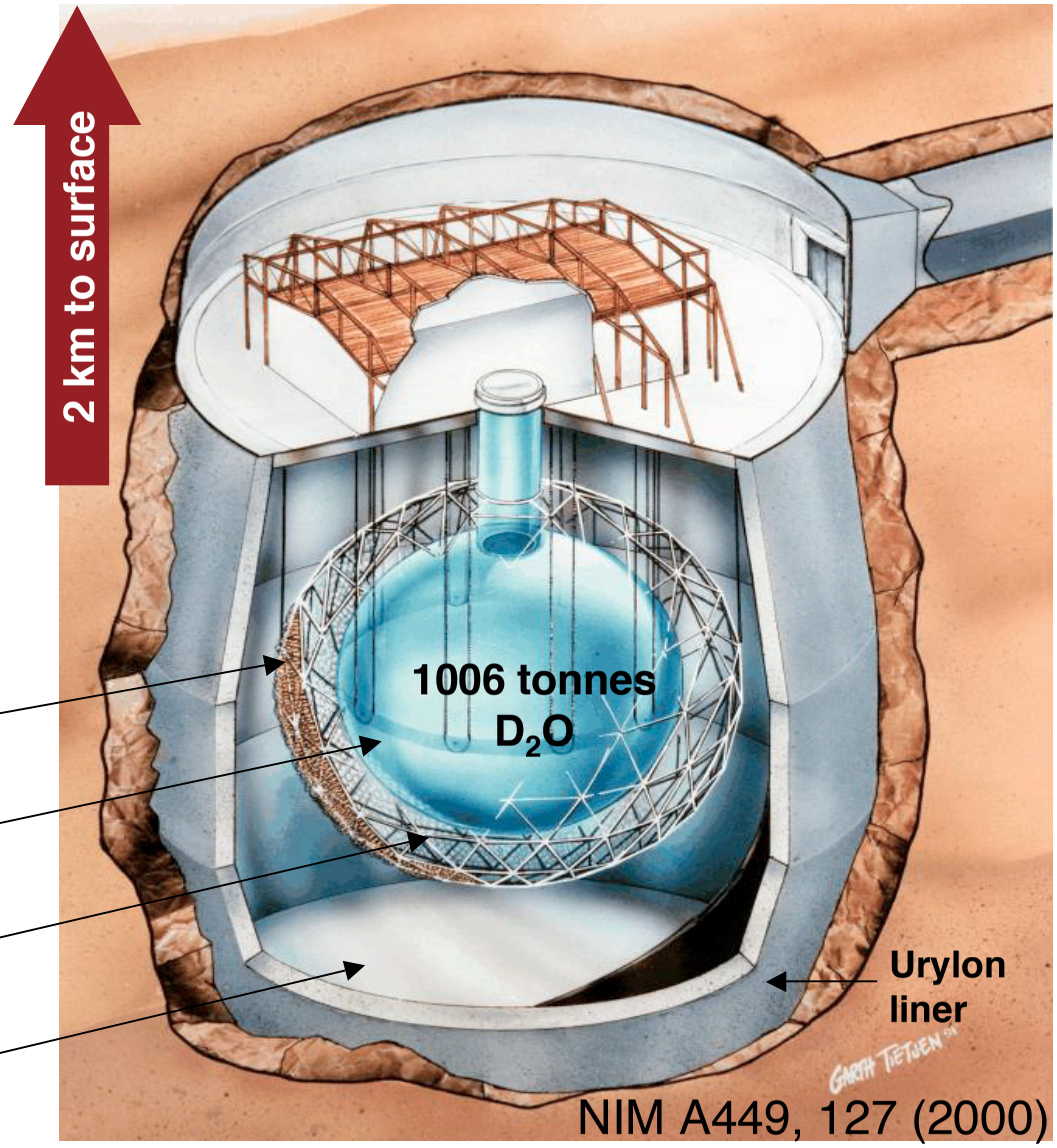
Sudbury Neutrino Observatory





17.8m dia. PMT Support Structure
9456 20-cm dia. PMTs
56% coverage

12.01m dia. acrylic vessel

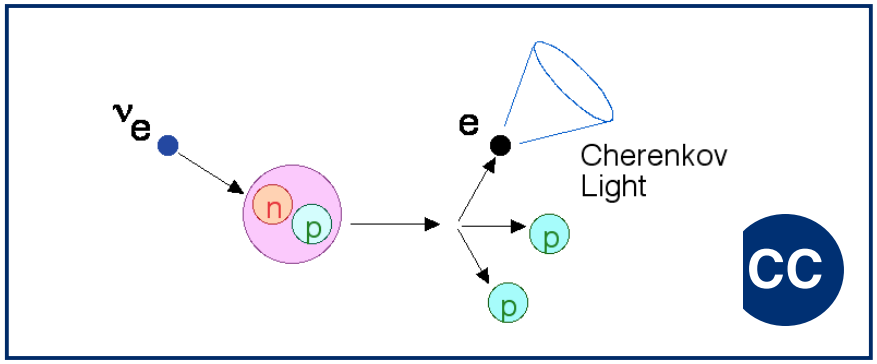
1700 tonnes of inner shielding H_2O

5300 tonnes of outer shielding H_2O

Detecting ν in SNO

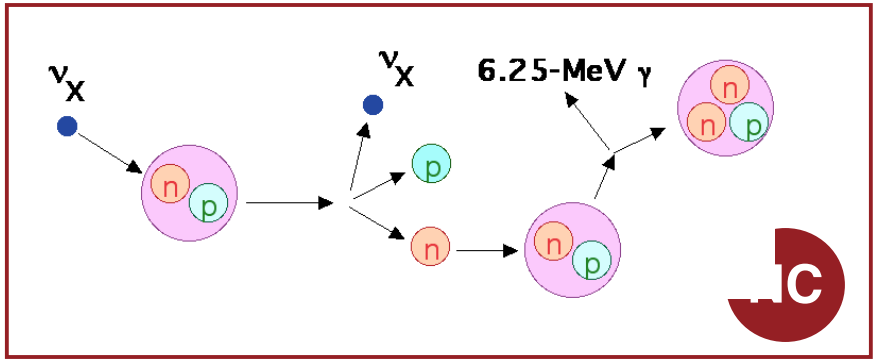
CC $\nu_e + d \rightarrow p + p + e^-$

- Measurement of ν_e energy spectrum
- Weak directionality: $1 - 0.340\cos\theta$



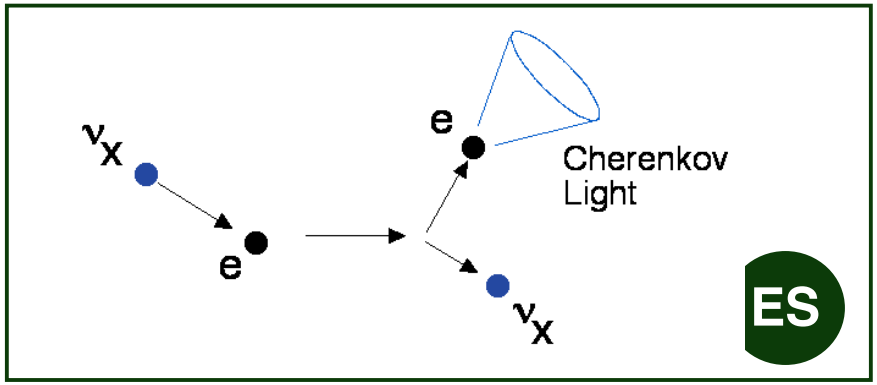
NC $\nu_x + d \rightarrow p + n + \nu_x$

- Measure total ^{8}B ν flux from the sun
- $\Phi(\nu_e) = \Phi(\nu_\mu) = \Phi(\nu_\tau)$

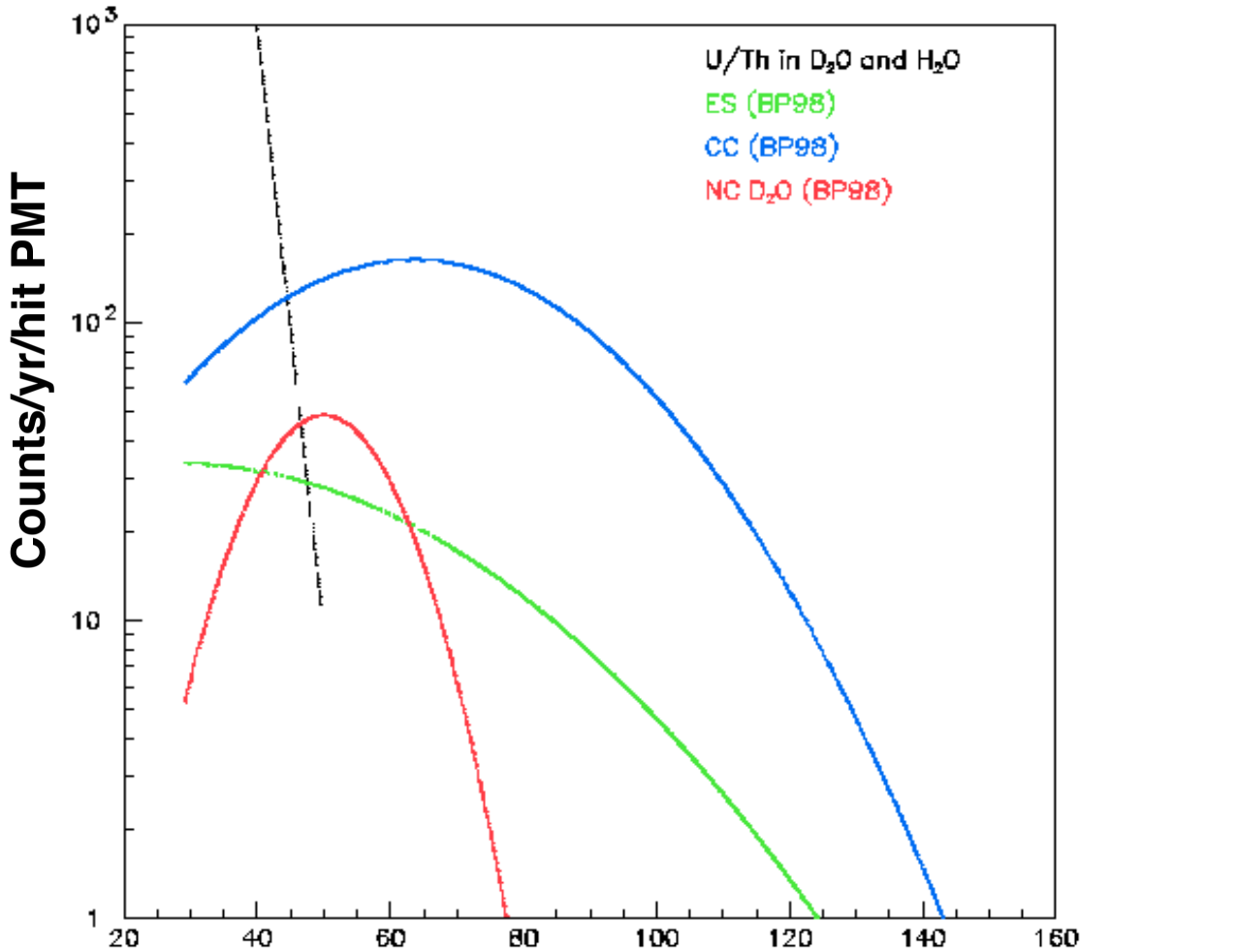


ES $\nu_x + e^- \rightarrow \nu_x + e^-$

- Low Statistics
- $\Phi = \Phi(\nu_e) + 0.154\,\Phi(\nu_\mu + \nu_\tau)$
- Strong directionality: $\theta_e \sim 18^\circ$ (T_e = 10 MeV)



Cherenkov Signals in SNO (Pure D_2O)



Energy

Number of Hit PMTs

~ 9 PMT Hits/MeV

Smoking Guns for Flavor Changing Oscillation

Measure: **Oscillation to active flavor if:**

$$\frac{\phi^{CC}}{\phi^{ES}} = \frac{\phi_e}{\phi_e + 0.15(\phi_\mu + \phi_\tau)} \Rightarrow \phi^{CC}(\nu_e) < \phi^{ES}(\nu_x)$$

June 2001 : $\phi^{CC}_{SNO}(\nu_e) < \phi^{ES}_{SK}(\nu_x)$ (3.3σ) [PRL 87, 071301]

THIS TALK

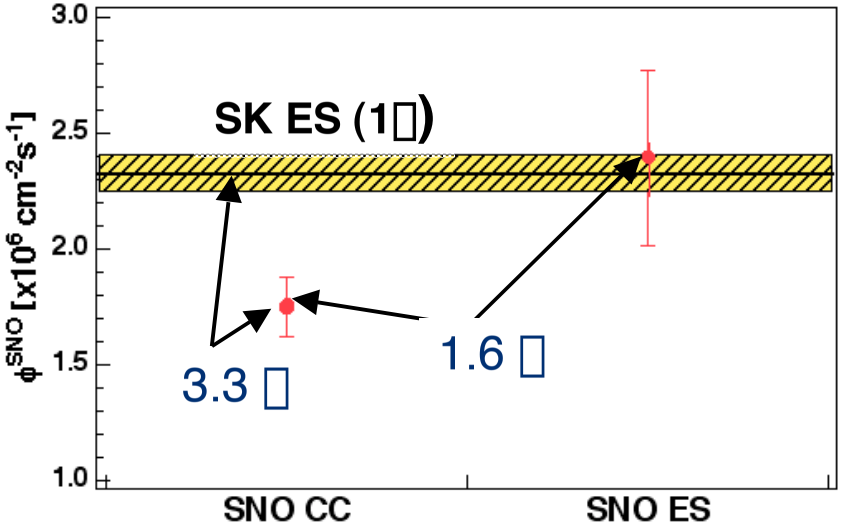
$$\frac{\phi^{CC}}{\phi^{NC}} = \frac{\phi_e}{\phi_e + \phi_\mu + \phi_\tau} \Rightarrow \phi^{CC}(\nu_e) < \phi^{NC}(\nu_x)$$

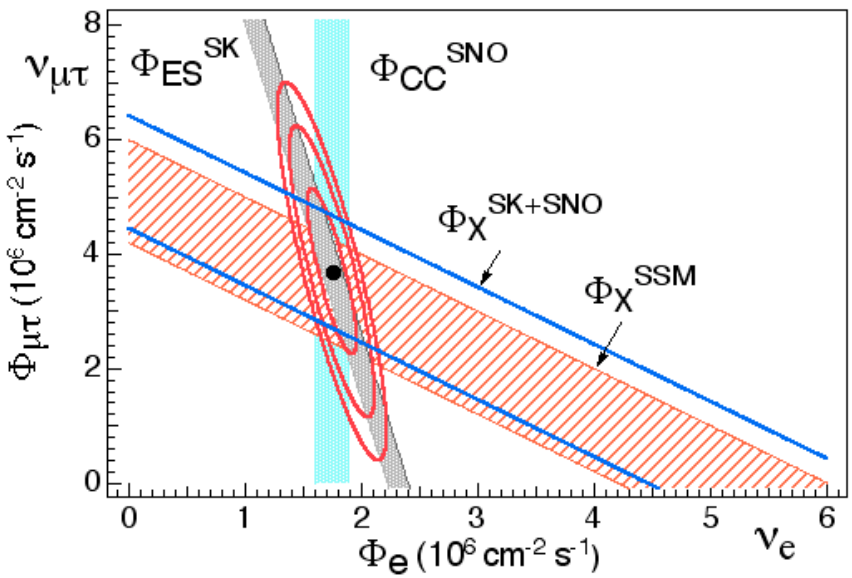
April 2002 : $\phi^{CC}_{SNO}(\nu_e), \phi^{NC}_{SNO}(\nu_x), \phi^{ES}_{SNO}(\nu_x)$ [nucl-ex/0204008]

$$\phi^{CC(ES)}_{Night} \neq \phi^{CC(ES)}_{Day} \Rightarrow \phi^{CC(ES)}_{Night} > \phi^{CC(ES)}_{Day}$$

April 2002 : Day and Night fluxes [nucl-ex/0204009]

Recap [T_e > 6.75 MeV]





Result 1: $\nu_e \rightarrow \nu_{\mu,\tau}$

Excludes:
pure $\nu_e \rightarrow \nu_{sterile}$ at 3.1 σ

Result 2:

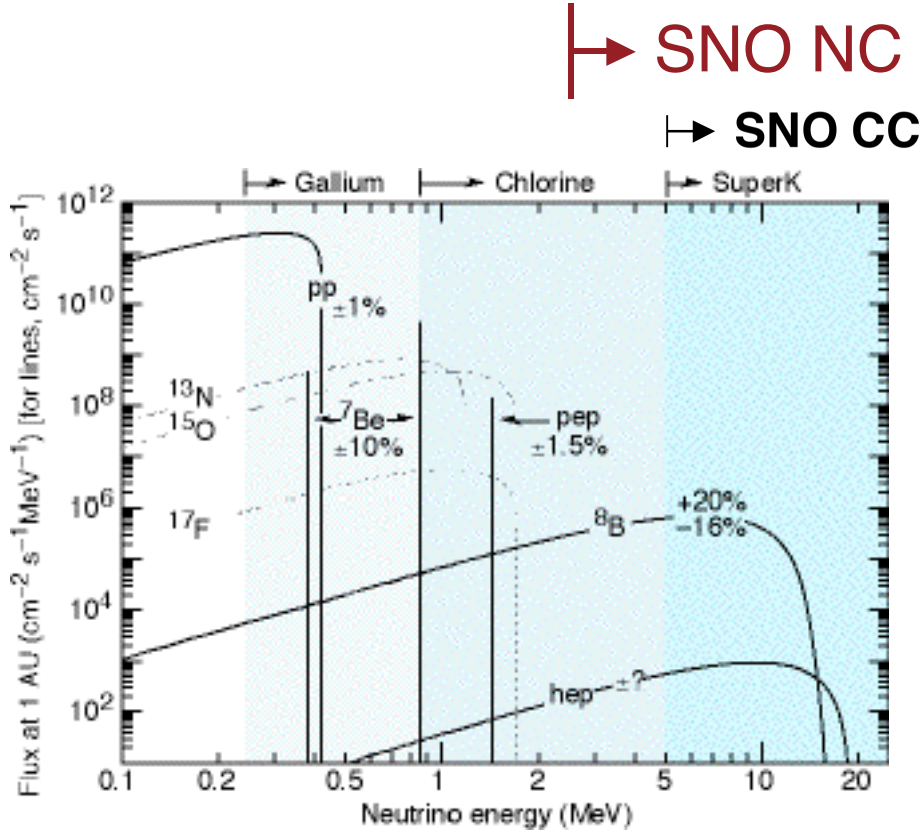
Solar model predictions are verified

What else can NC tell us?

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

1. ν_e disappearance and $\nu_{\mu/\tau}$ appearance in one experiment:
   - Direct measurement of the total active ^8B ν flux
   - No ambiguity in combining results from experiments with different systematics (e.g. energy resolution)

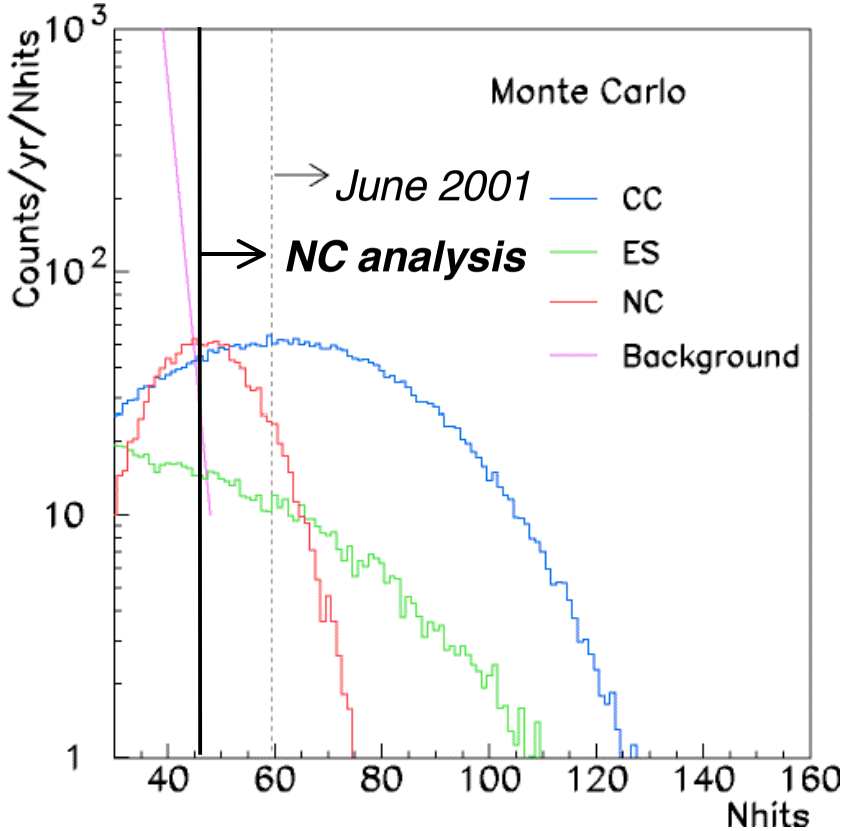
2. Lowest E_ν threshold (2.2 MeV) for real time experiments
   [No energy spectral information]



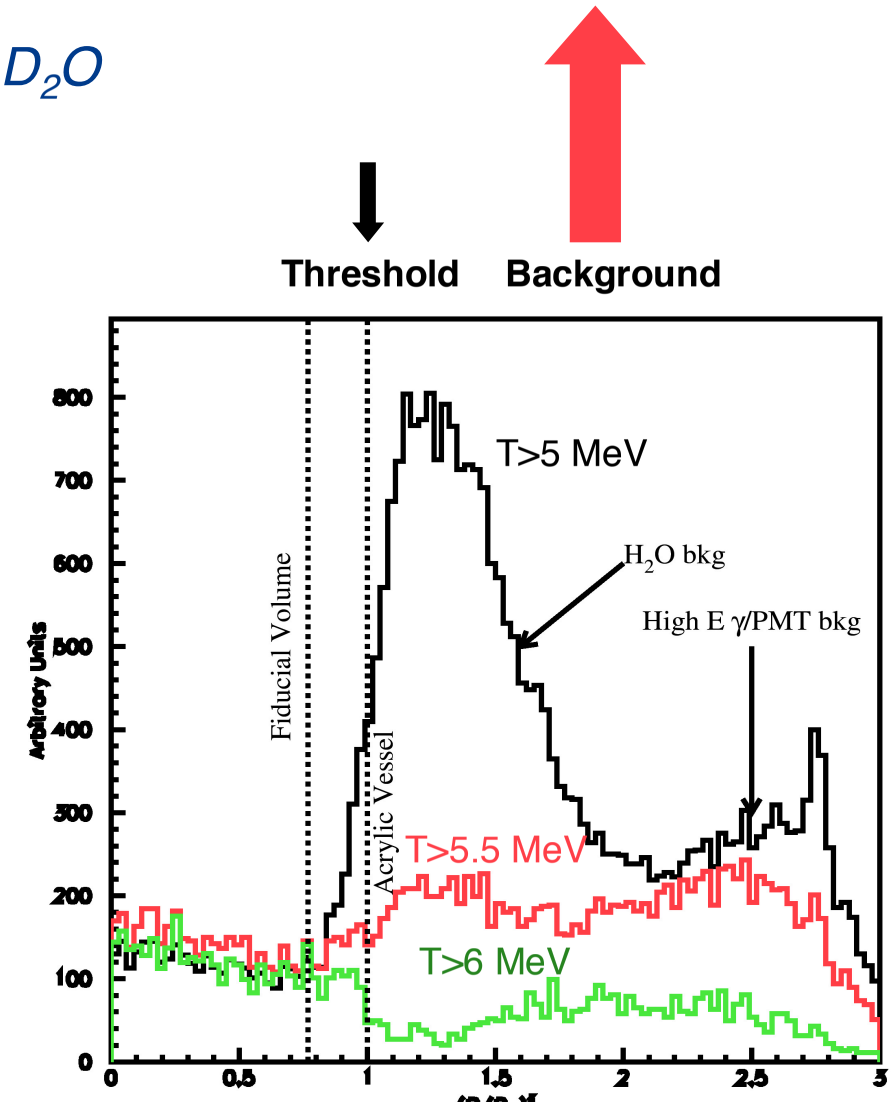
Solar Neutrino Analysis (NC+CC+ES)

NC and Day-Night Analysis in Pure D_2O

- Energy: $T_{eff} > 5$ MeV
- Fiducial vol.: $R < 550$ cm

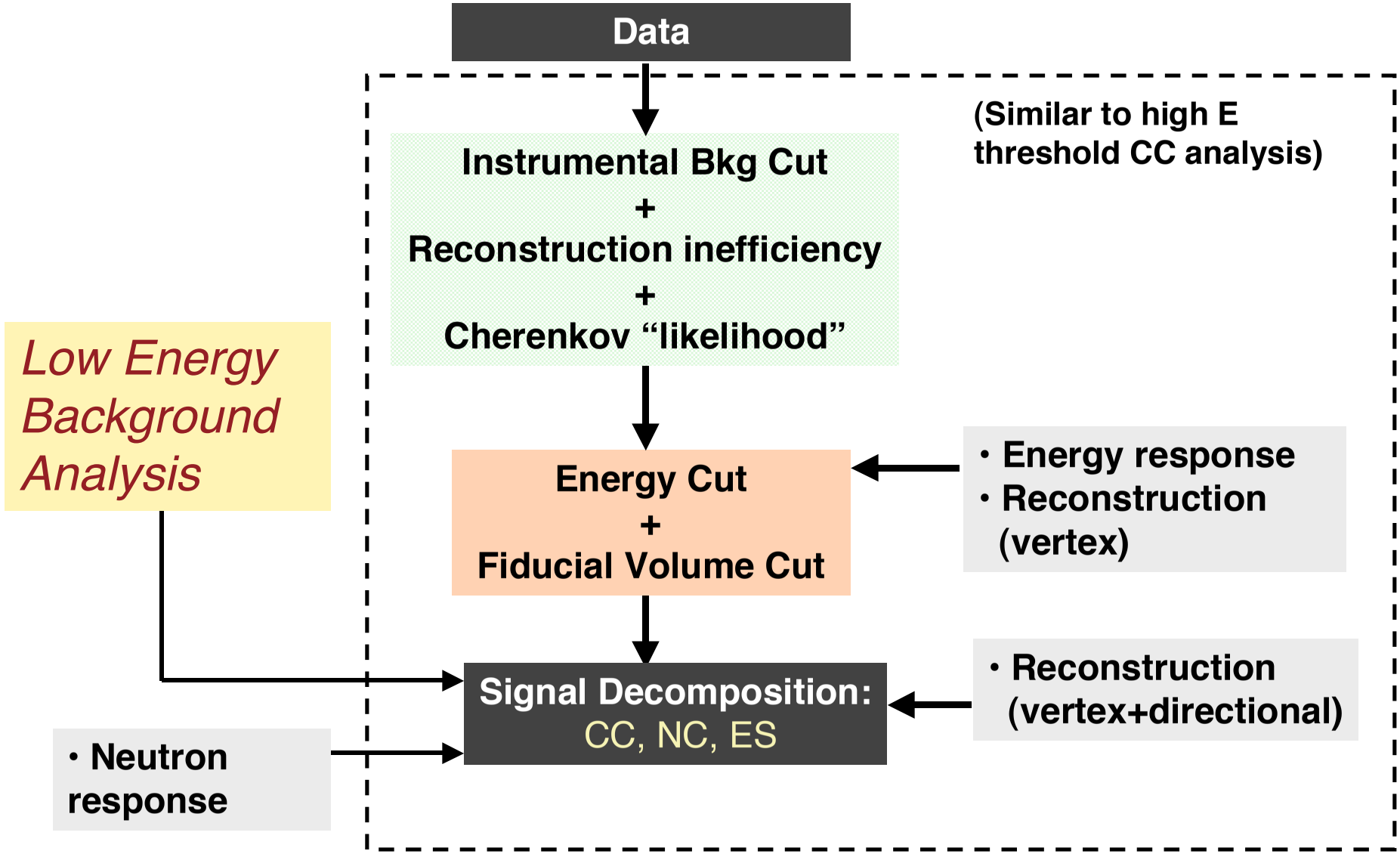


Energy



Radius $(R/R_{AV})^3$

NC Data Analysis



Data Reduction

Nov 2, 1999 to May 28, 2001
306.4 live days *Day*=128.5 days, *Night*=177.9 days

Analysis Step	*Events*
Total Event Triggers	450,188,649
Neutrino Data Trigger	191,312,560
NHIT ≥30	10,088,842
Instrumental Background	7,805,238
Cherenkov "likelihood"	3,418,439
Fiducial Volume (R<550cm)	67,343
Energy Threshold (T>5 MeV)	3440
Muon Follower	2981
Residual Cosmic Background	2928
Candidate Event Set	**2928**

[c.f. High energy CC paper: 240.9 live days, 1169 candidate events]

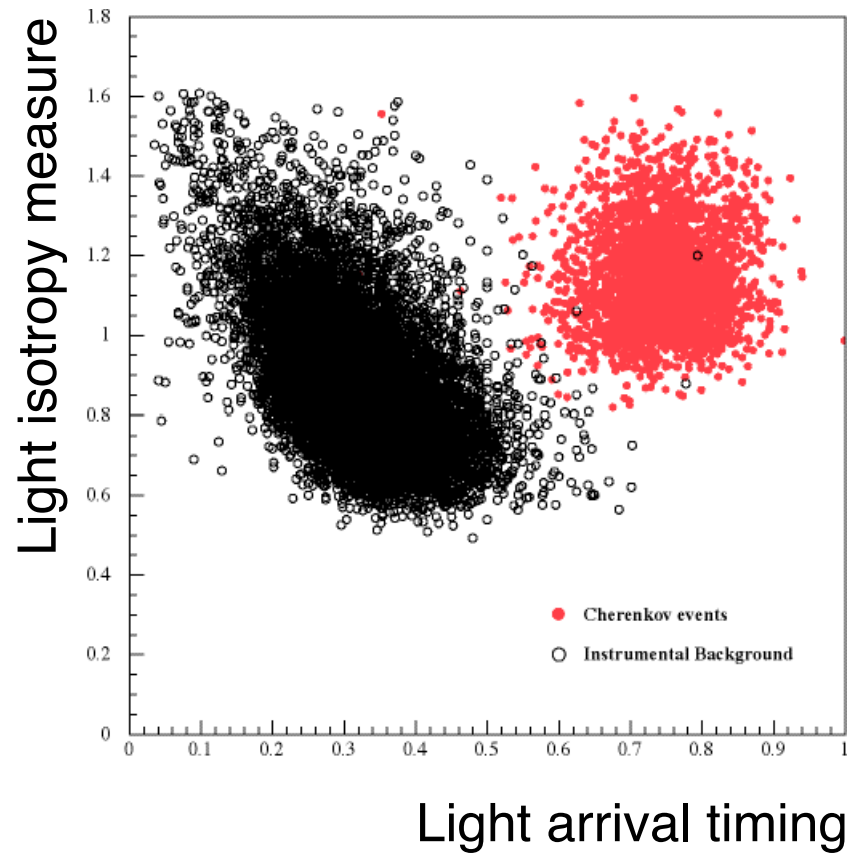
Data Reduction Cuts

Pass 0 Cuts — Instrumental background removal using:

- PMT time distribution
- PMT charge distribution
- Veto PMT tag
- Event time correlation

"Cherenkov likelihood" — Residual instrumental background removal using:

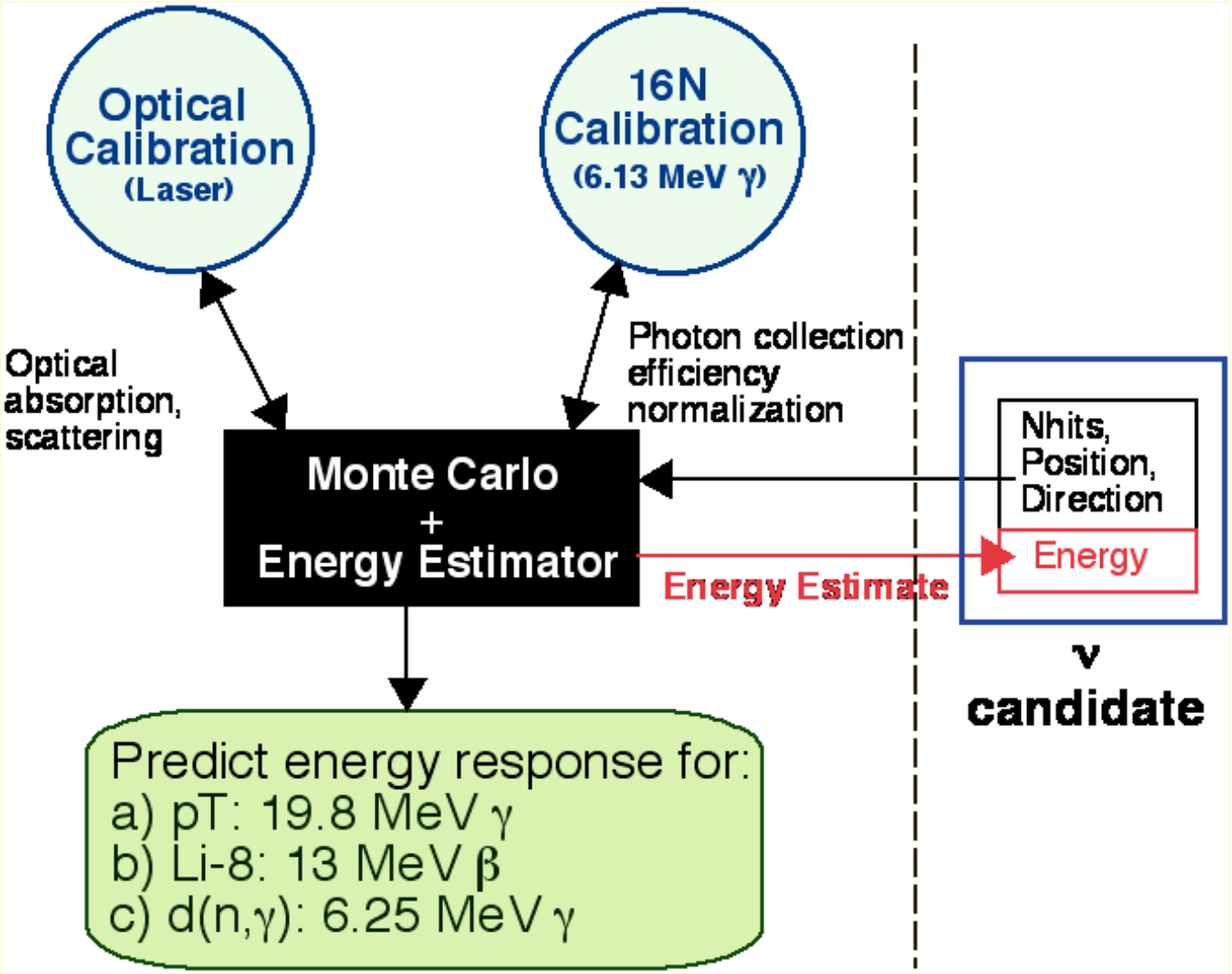
- Reconstruction information
- Light isotropy
- Light arrival timing



signal loss: $CC: 1.43^{+0.39}_{-0.21}\%$ $ES: 1.46^{+0.40}_{-0.21}\%$ $NC: 2.28^{+0.41}_{-0.23}\%$

Residual instrumental bkg. contamination: < 3 events (95% CL)

SNO Energy Calibration

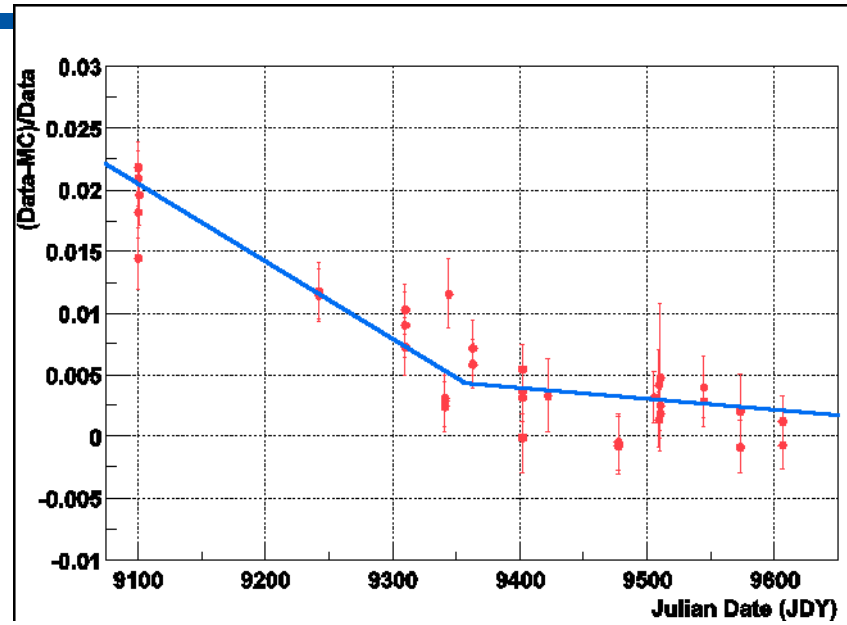


Energy Response

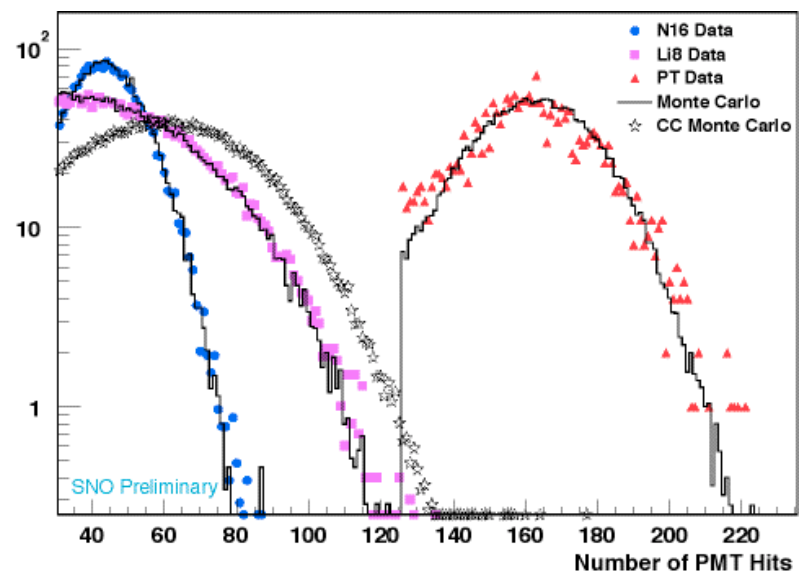
Calibration:

- PMT & Optics
- Normalized to ^{16}N
- Linearity check with pT

□E/E = ± 1.21%
□□/□ = + 4.5%
Linearity = ±0.23% @ E=19.1 MeV

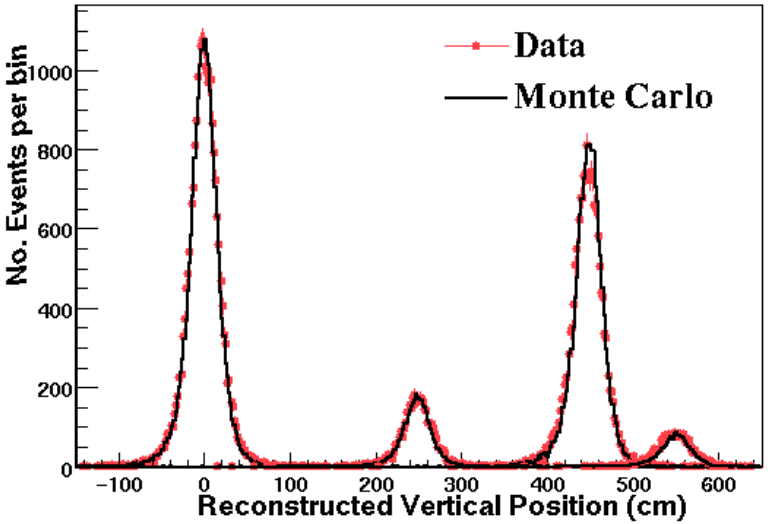


	□□^{CC}/□^{CC}	□□^{NC}/□^{NC}
□E	$^{+4.3}_{-4.2}$ %	$^{+6.1}_{-6.2}$ %
□□	$^{+0.0}_{-0.9}$ %	$^{+4.4}_{-0.0}$ %
Linearity	±0.1%	±0.4%
Total	$^{+4.3}_{-4.3}$ %	$^{+7.5}_{-6.2}$ %

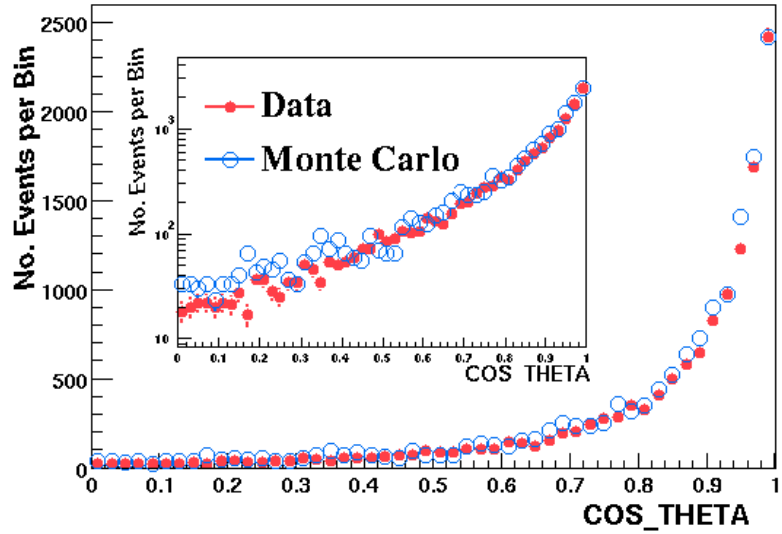


Reconstruction

Vertex: ^{8}Li at different locations



Angular Resolution: ^{16}N far from source



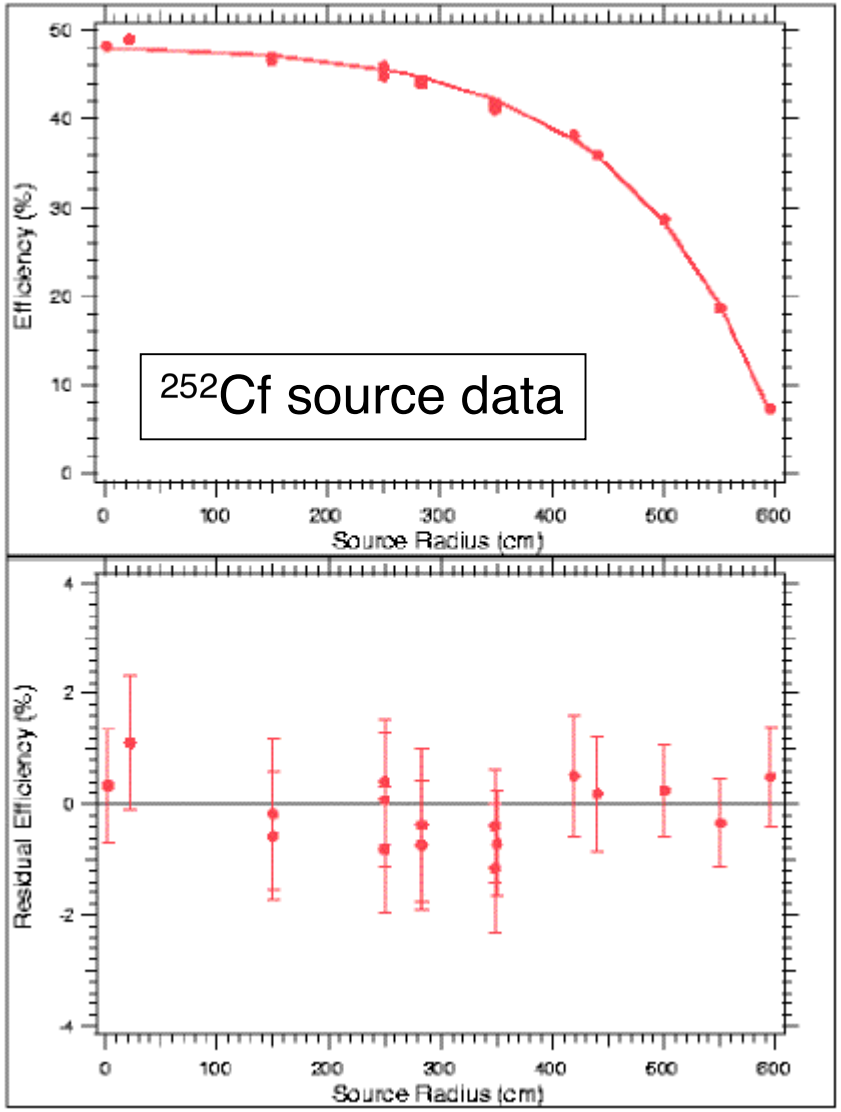
	$\Delta\Delta^{CC}/\Delta^{CC}$	$\Delta\Delta^{NC}/\Delta^{NC}$
Vertex Accuracy	$^{+2.9}_{-2.8}$ %	$^{+1.8}_{-1.8}$ %
Vertex Resolution	$^{+0.0}_{-0.0}$ %	$^{+0.1}_{-0.1}$ %
Angular Resolution	$^{+0.2}_{-0.2}$ %	$^{+0.3}_{-0.3}$ %
Total	$^{+2.9}_{-2.8}$ %	$^{+1.8}_{-1.8}$ %

Neutron Capture Efficiency

Analytic Prediction n capture efficiency			
Isotope	**Abundance**	**Point Source at Center**	**Uniform Source**
D	99.9176%	49.11%	29.34%
H	0.0824%	29.76%	17.79%
16-O	99.9195%	9.20%	5.49%
17-O	0.0485%	5.36%	3.20%
18-O	0.0320%	0.02%	0.00%
Escape		6.55%	44.15%
Total		**100%**	**100%**

Measured:

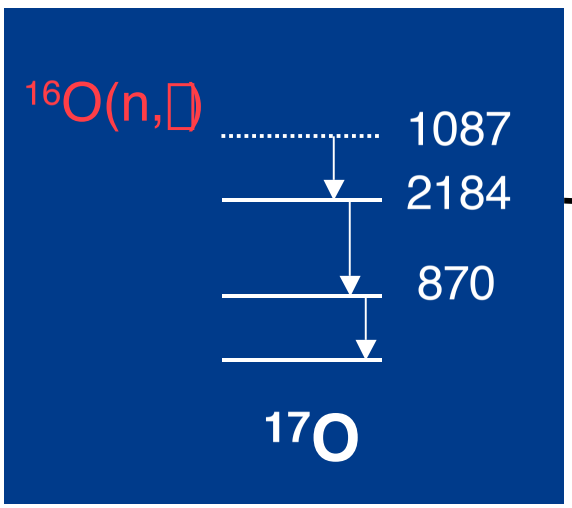
n capture on d (uniform source)
29.9 ± 1.1 %

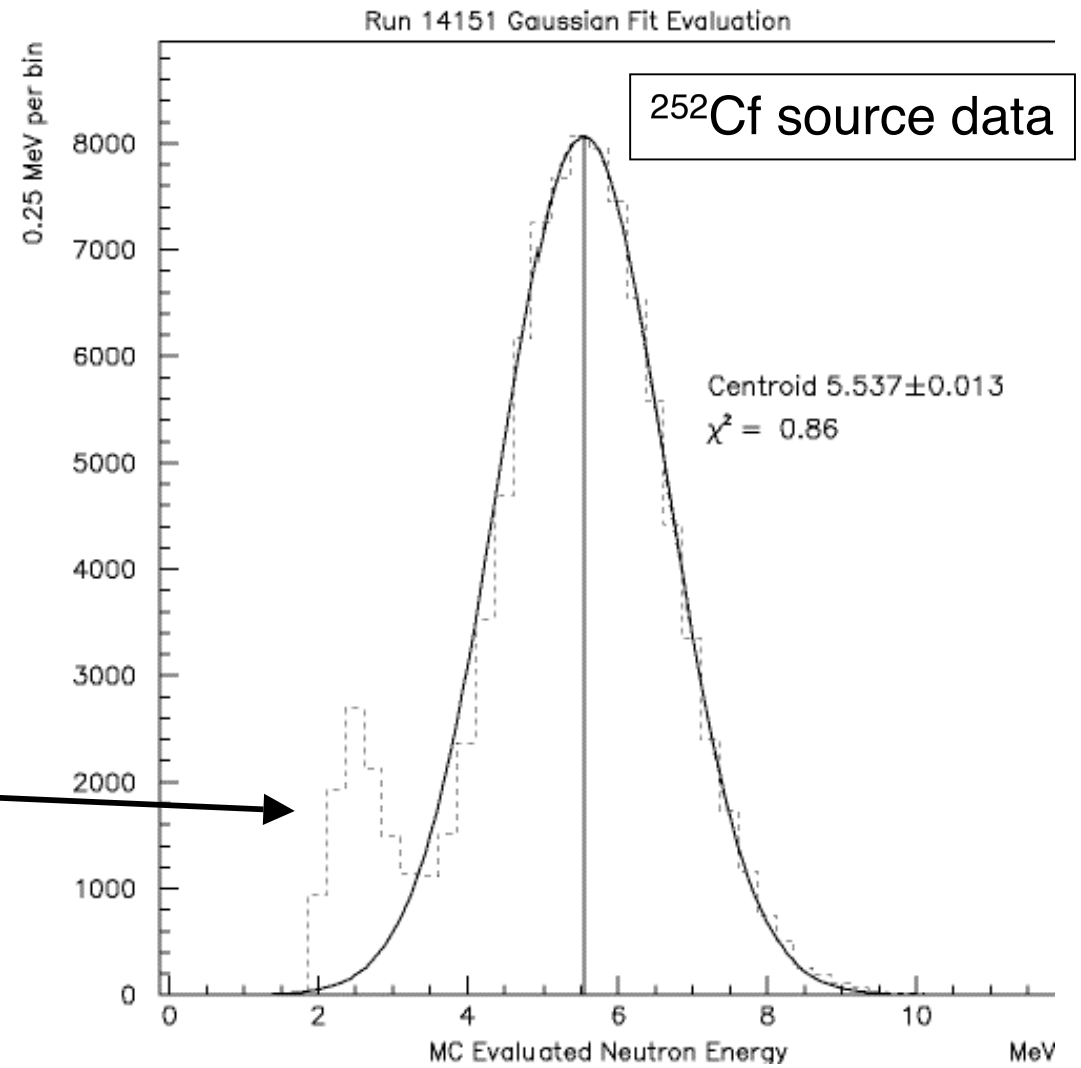


Neutron Detection Efficiency

- Given a 5-MeV e^- kinetic energy (T_e) analysis threshold, what is the probability of observing the Cherenkov signal from the 6.25 MeV □in n+d□ t+□?

→ 14.4 ± 0.5 %





Low Energy Background (Overview)

Daughters in U or Th chain
- [illegible] decays
- [illegible] decays

"Photodisintegration"

[illegible] + d [illegible] n + p

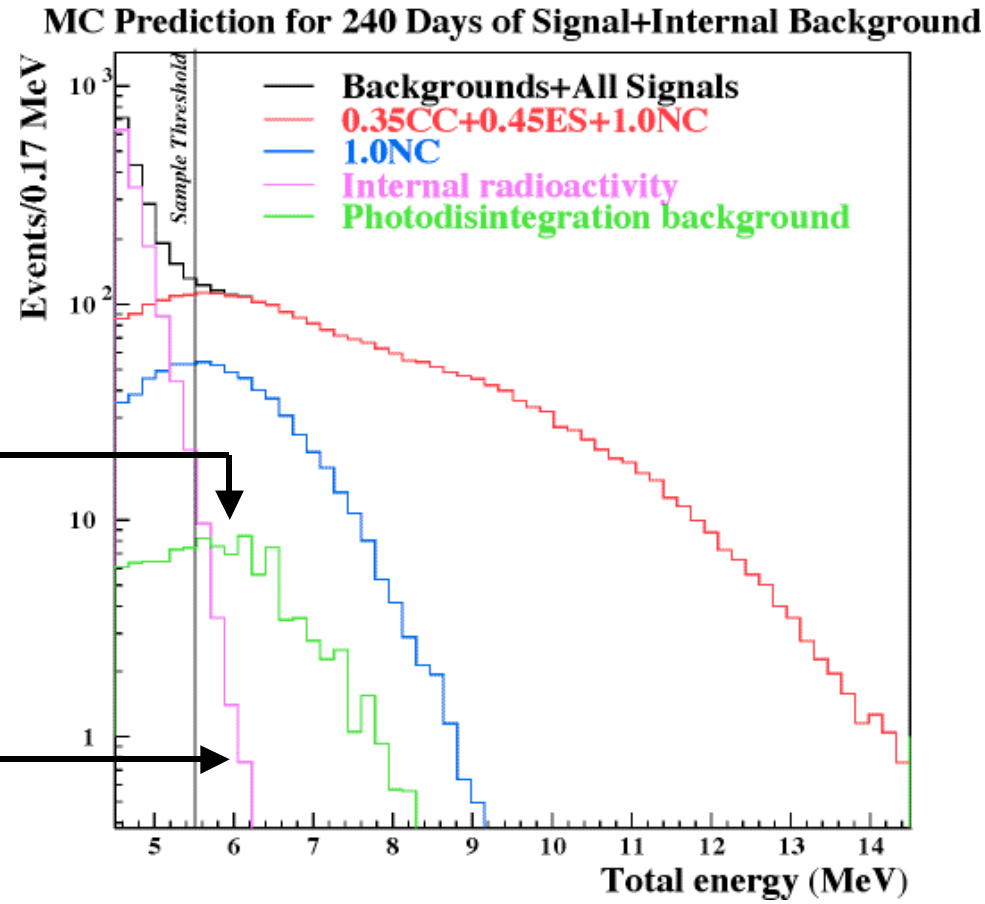
Indistinguishable from NC !

Technique: [illegible] Radiochemical assay
[illegible] Light isotropy study

"Cherenkov Tail"

Cause: [illegible] Tail of resolution, or
[illegible] Mis-reconstruction

Technique: [illegible] U/Th calib. source
[illegible] Monte Carlo



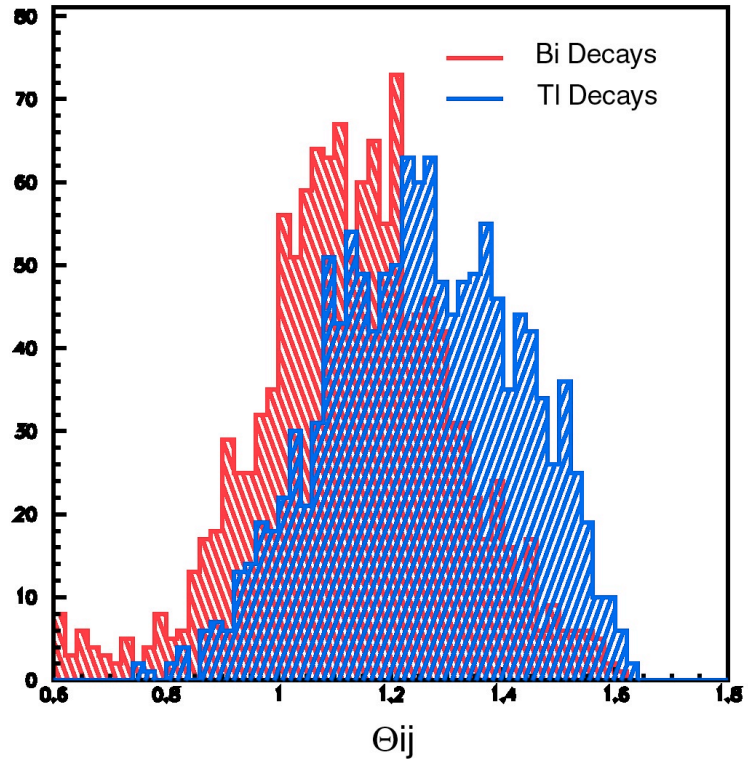
Must know U and Th concentration in D_2O

Measuring the U and Th Concentration in "Water"

1. **Ex-situ:** Radiochemical assays of the D_2O and H_2O
   - Extract ^{226}Ra and ^{224}Ra in the U and Th chain using **MnOx** and **HTiO** ion exchanger. Measure U and Th concentration by:
     - **MnOx**: α spectroscopy on Po daughters
     - **HTiO**: Bi-Po βαα coincidence
   - Extract ^{222}Rn in the U chain by **degassing**. Measure Rn concentration by direct γ counting in a Lucas cell.

2. **In-situ:**

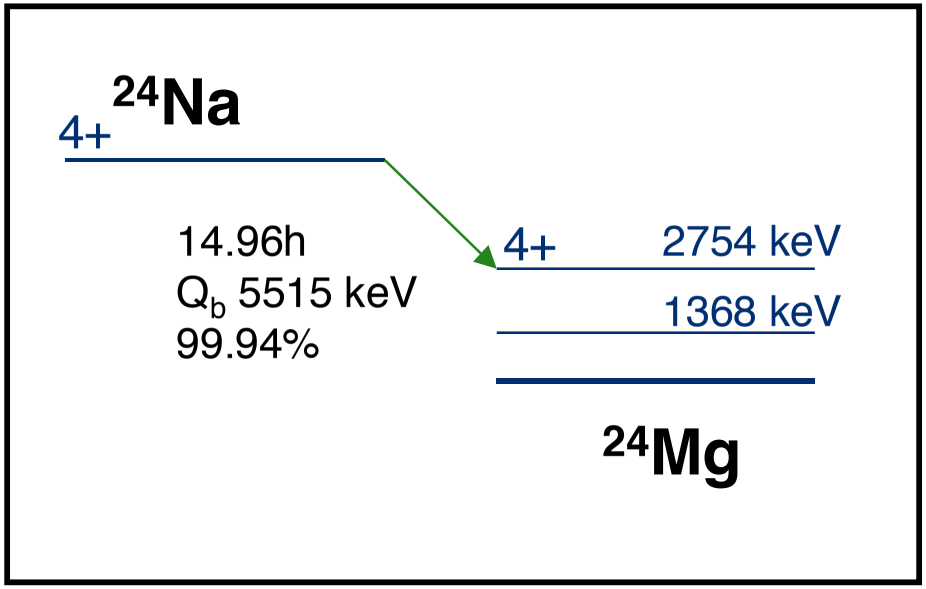
   Light isotropy:
   - ^{214}**Bi** (U chain) mostly **single** β
   - more ***anisotropic*** light pattern
   - ^{208}**Tl** (Th chain) mostly β + γ
   - more ***isotropic*** light pattern

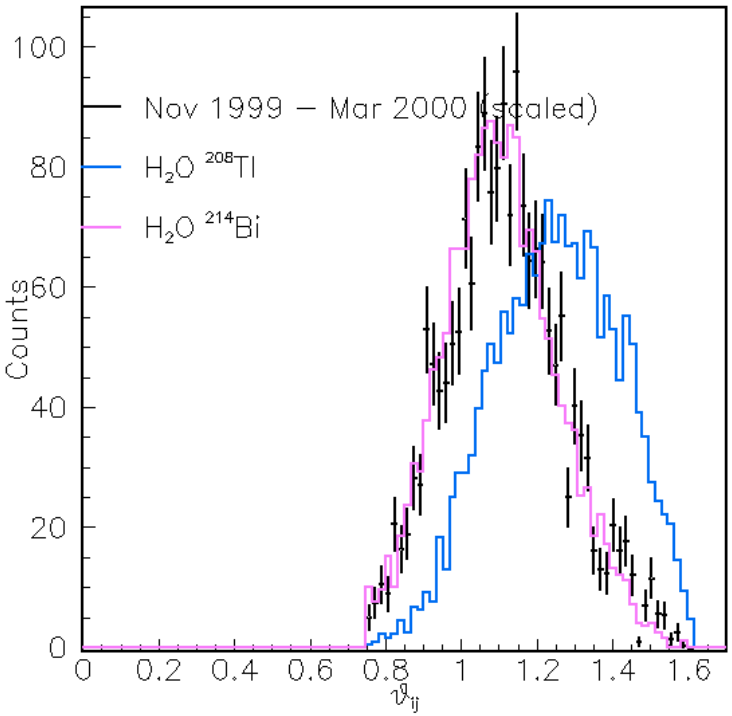


Calibrating the In-situ Technique

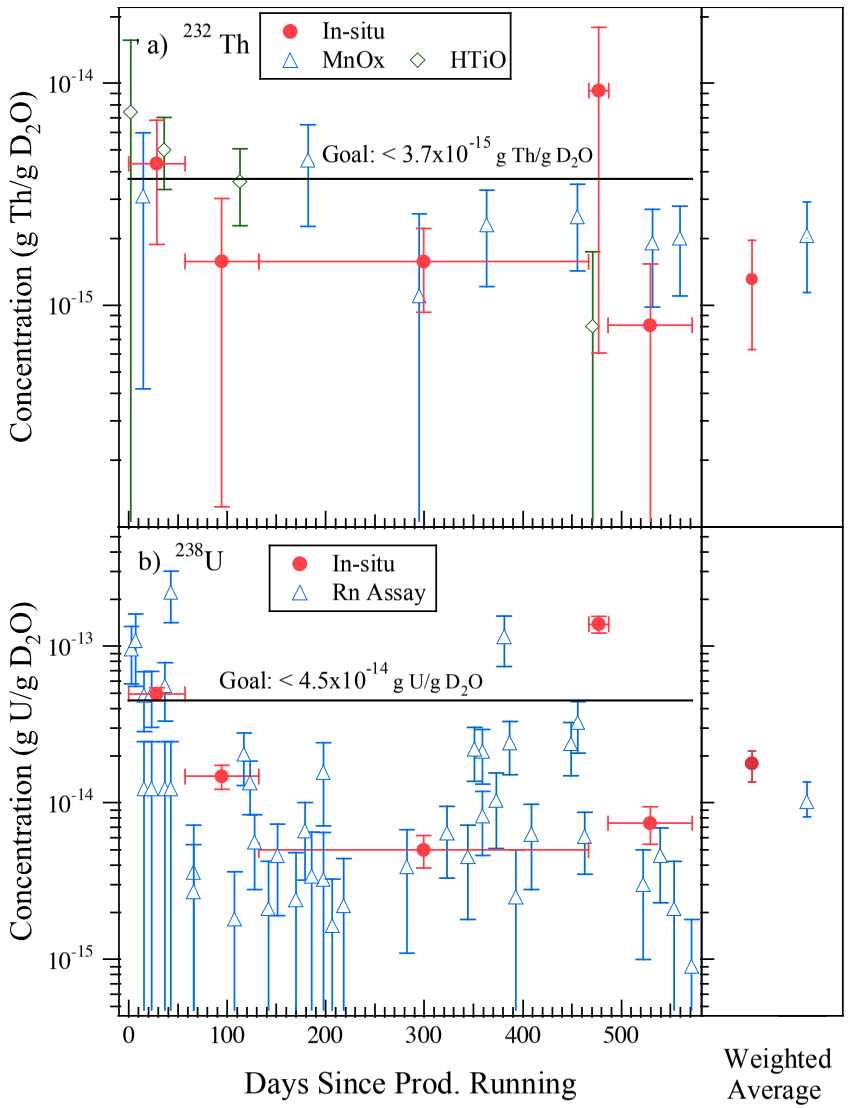
1. Activated salt water in storage tanks & with “hot” Th source in the AV

2. Date from high Rn period





Measuring the U and Th Concentration in "Water"



In-situ and ex-situ measurements give consistent results

	D_2O (10^{-15} g/g D_2O)	H_2O (10^{-14} g/g H_2O)
[Th]	1.63 ± 0.58	9.1 ± 2.7
[U]	$17.8^{+3.5}_{-4.3}$	75.5 ± 33.0

Monte Carlo

pd n produced	$1.0 \pm 0.2\ d^{-1}$	$0.5 \pm 0.2\ d^{-1}$
pd n detected (306.4 d)	44^{+8}_{-9} counts	11^{+6}_{-4} counts

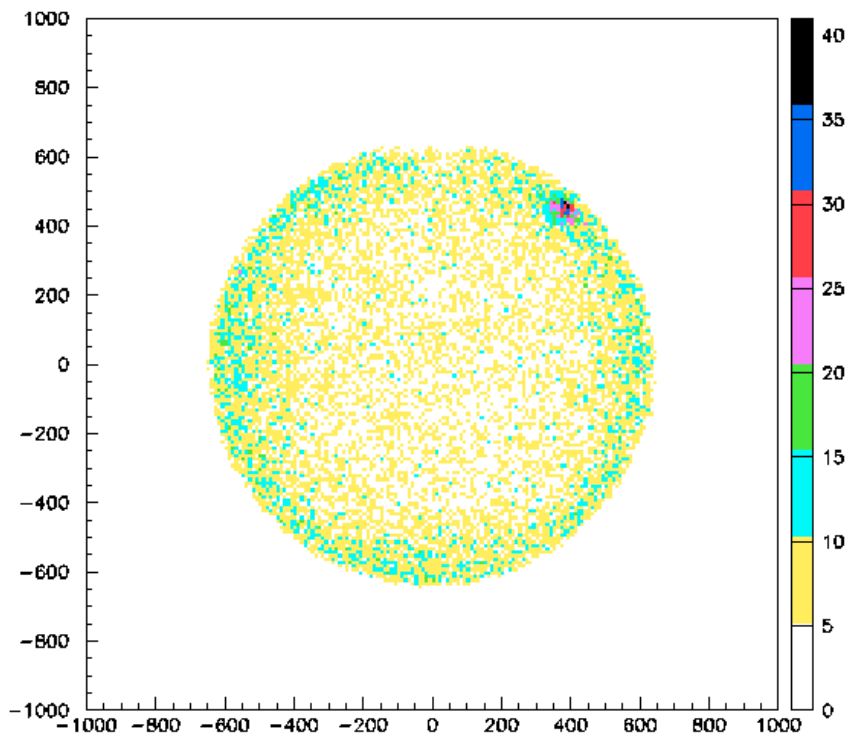
[c.f. SSM ~ 2 detected n d^{-1}]

U and Th in/on the Acrylic Vessel

- Original Target (2 ppt): 60 μg Th or U
- Bulk acrylic assayed (NAA)
- Dust concentration on inner and outer surfaces measured prior to filling
- Hot spot ("Berkeley Blob") found in Cherenkov data

	U (μg)	Th (μg)
Bulk	$7.5^{+1.7}_{-1.3}$	15 ± 15
Outer surface	0.18 ± 0.04	0.96 ± 0.19
Inner surface	0.16 ± 0.04	0.87 ± 0.17
Blob	–	10^{+9}_{-4}
Total	8^{+2}_{-1} μg	27^{+18}_{-16} μg
***pd* n detected** (306.4 d)	2 ± 2 counts	14^{+6}_{-7} counts

[c.f. SSM ~ 2 detected n d^{-1}]



Z vs X projection

Neutron Background Summary

For $T_e \geq 5$ MeV
$R < 550$ cm

	neutron bkg. (counts)
D_2O	44^{+8}_{-9}
H_2O+AV	27^{+8}_{-8}
Atmospheric ν	4 ± 1
^{235}U spont. fission	$<< 1$
$^{2}H(\alpha,\gamma)pn$	2.0 ± 0.4
$^{17}O(\alpha,n)$	$<< 1$
Terrestrial & reactor ν	1^{+3}_{-1}
External neutrons	$<< 1$
Total	**78 ± 12**

12% of the number of observed NC neutrons assuming standard solar model ν flux

Cherenkov Tail — D_2O

- Monte Carlo of detector response well calibrated in the D_2O region

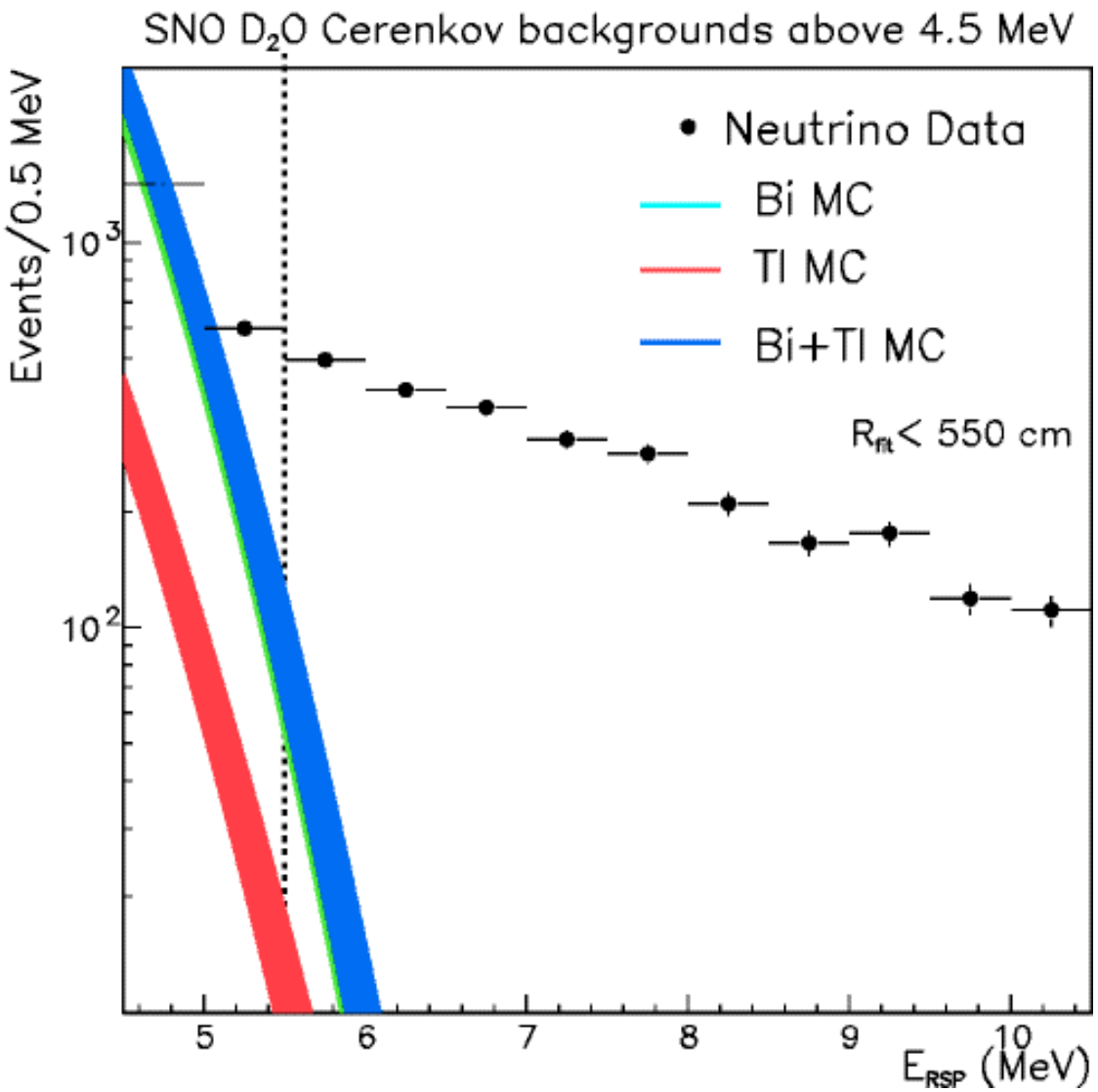
  Determine Cherenkov tail background due to D_2O radioactivity by Monte Carlo, using the U and Th concentration obtained above.

- MC predictions cross checked with a Th calibration source

T>5 MeV, R<550cm:

Th : 3^{+2}_{-1} counts

U : 17^{+12}_{-5} counts



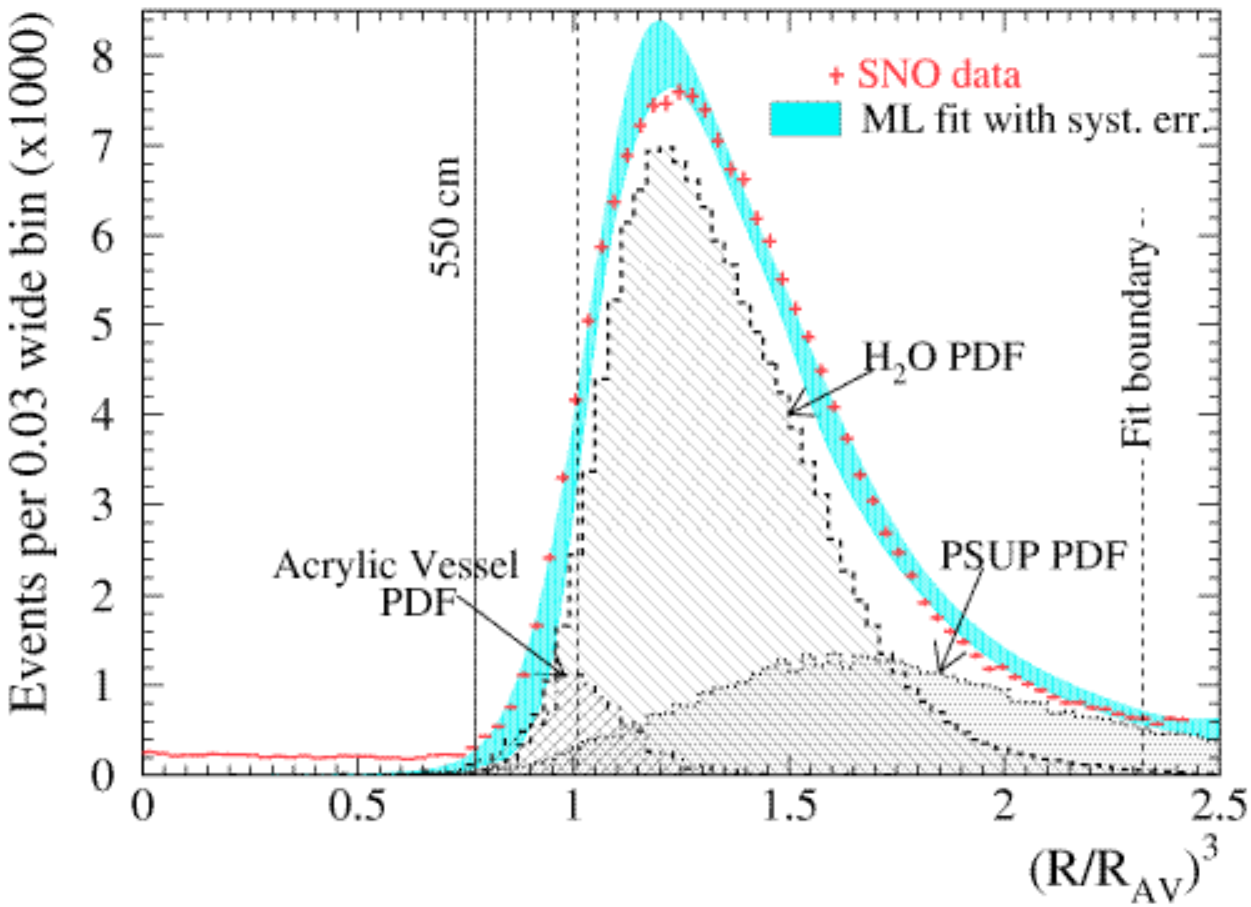
Cherenkov Tail — AV, H_2O, PMT+Rock

- Deployed an encapsulated Th calibration source in the detector. Measured the Cherenkov tail inside the fiducial volume above the energy threshold
- Agree with Monte Carlo predictions based on radioactivity (last few slides)

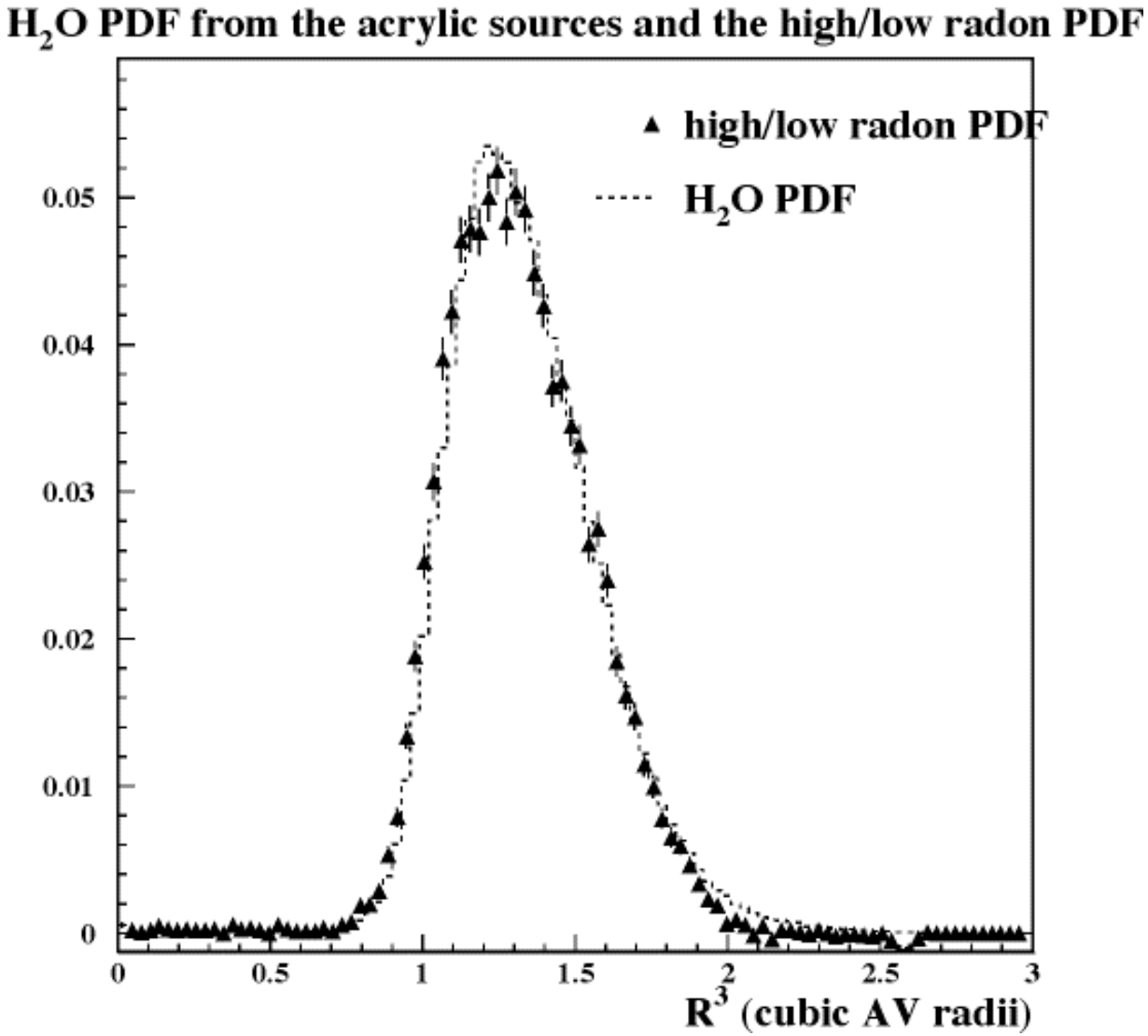
For $T_e \geq 5$ MeV, R<550cm

	Tail Bkg (counts)
D_2O	20^{+13}_{-6}
H_2O	3^{+4}_{-3}
AV	6^{+3}_{-6}
PMT	16^{+11}_{-8}
Total	45^{+17}_{-11}

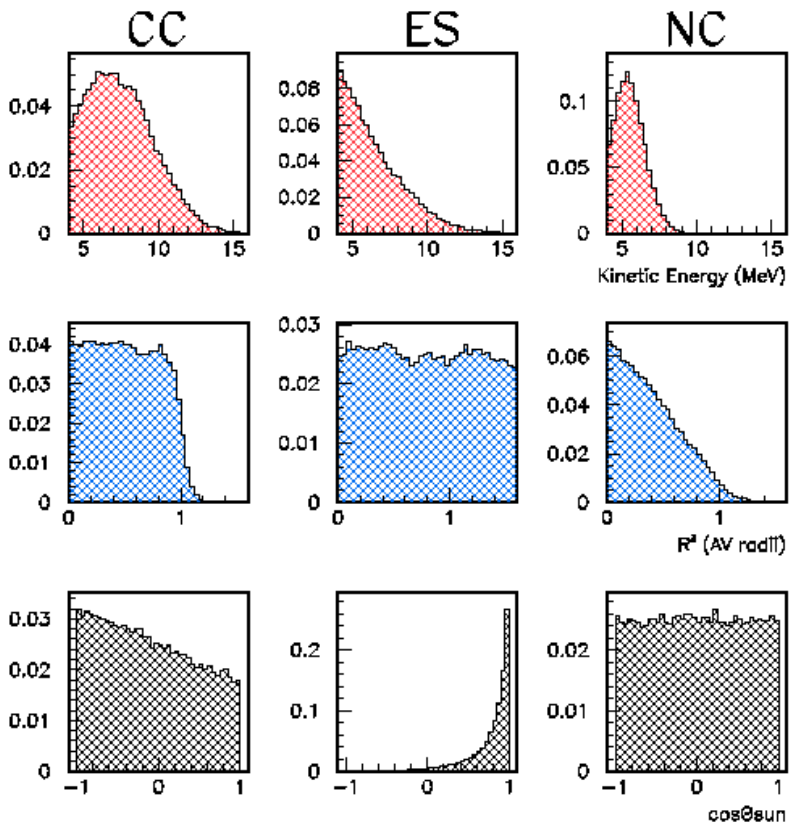
[c.f.: 2928 candidates]



Cherenkov Tail (PDF Check)



Extracting the □ Signals



Signal PDFs: T, R^3, cos $\theta_\odot$

Shape Constraint

Max. Likelihood Fit

□ Signals	Cherenkov tail & neutron background
Amplitudes Free	Amplitudes Fixed
Perturb Observables: $\vec{R}, \vec{u}, T$	Shift amplitudes (±1 □)

□^{CC} □^{NC} □^{ES}

OR

□$_e$ □$_{\mu\tau}$

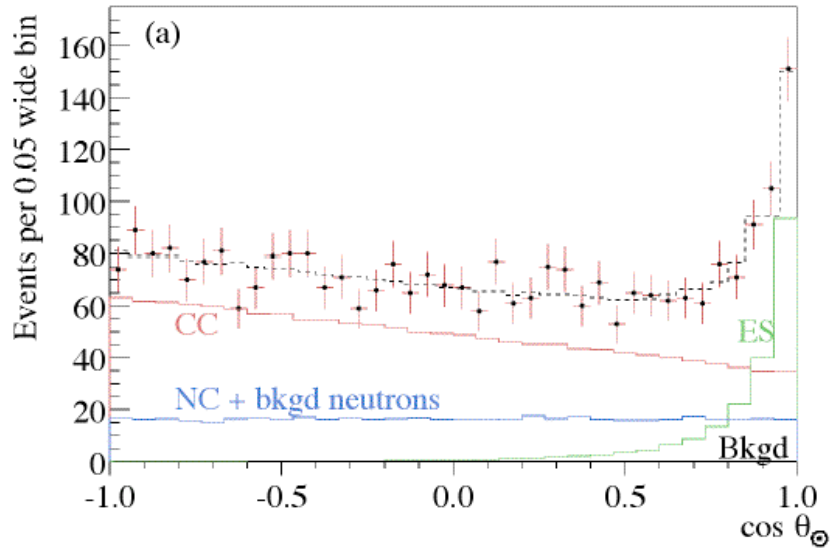
+ □□

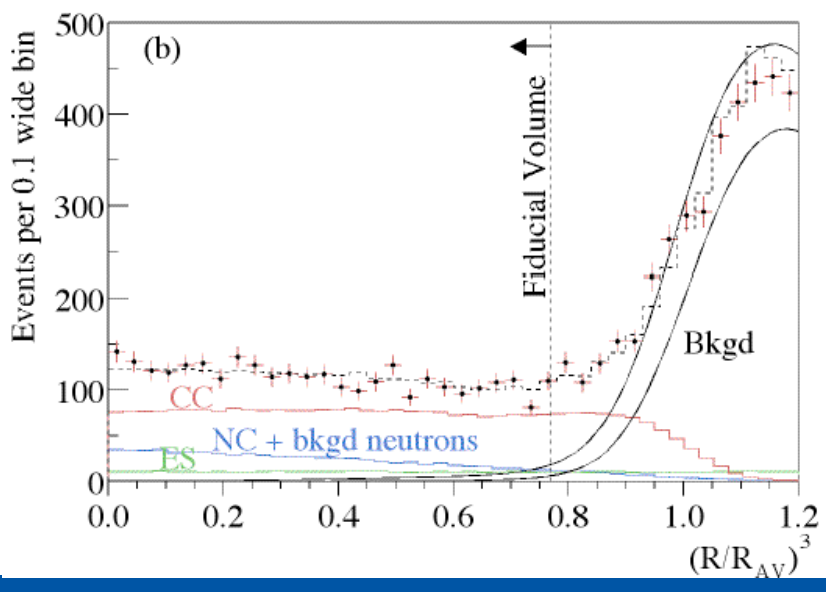
Signal Extraction Results

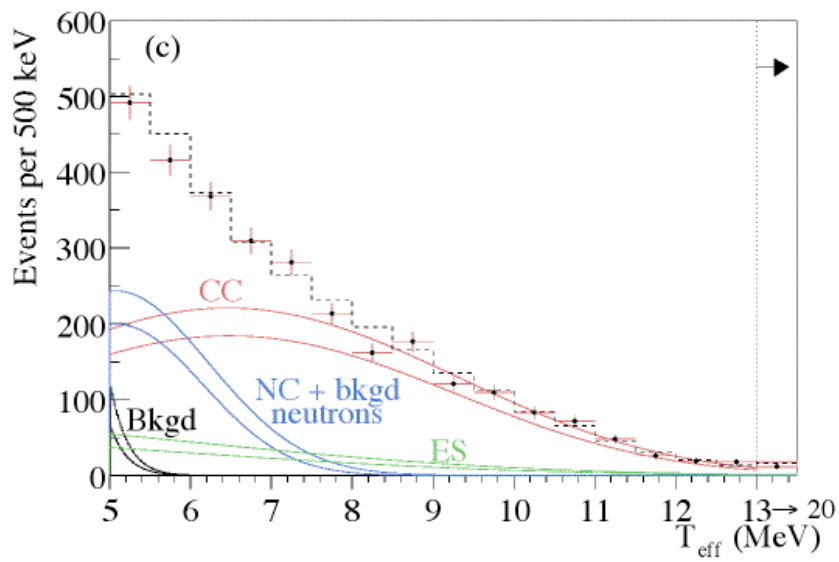
Assume standard ^{8}B spectrum

***Null hypothesis*:**
no neutrino flavor mixing

CC	1967.7	$^{+61.9}_{-60.9}$	events
NC	576.5	$^{+49.5}_{-48.9}$	events
ES	263.6	$^{+26.4}_{-25.6}$	events







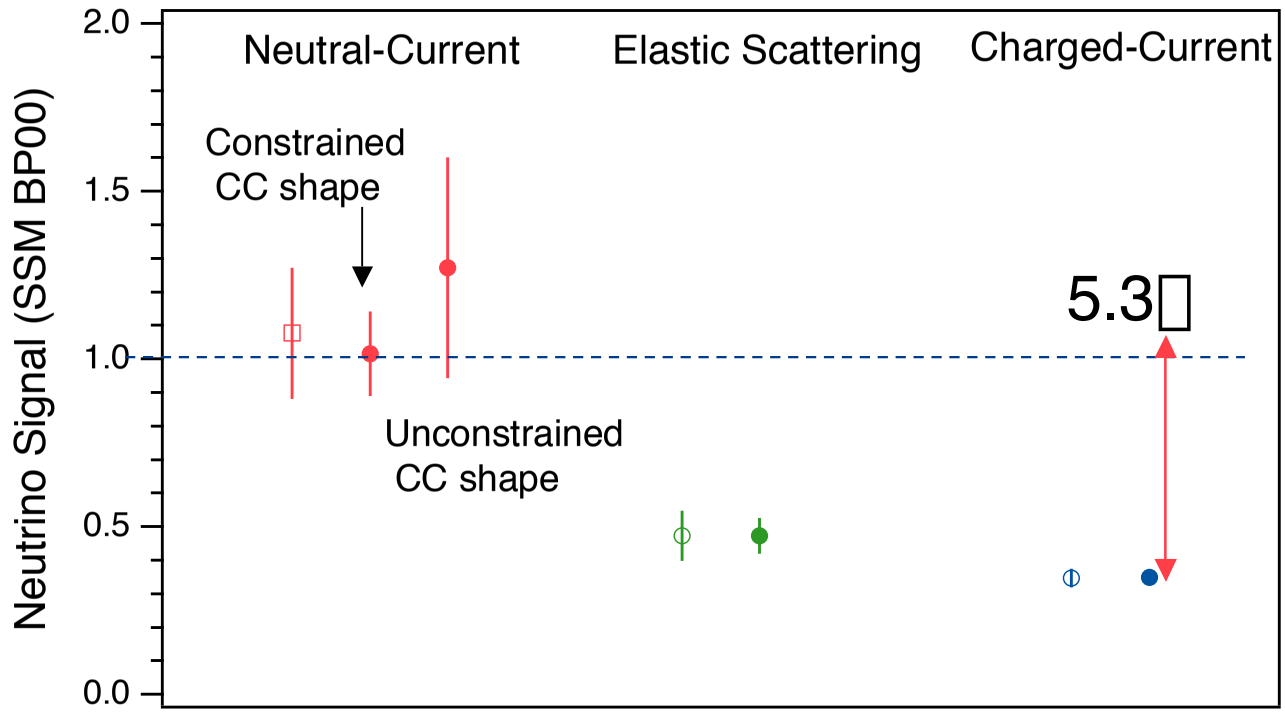
Systematic Uncertainties (Shape constrained)

Source	□CC/CC (%)	□NC/NC (%)	□□□/□□□ (%)
Energy Scale ¶	-4.2, +4.3	-6.2, +6.1	-10.4, +10.3
Energy Resolution ¶	-0.9, +0.0	-0.0, +4.4	-0.0, +6.8
Energy Non-linearity ¶	±0.1	±0.4	±0.6
Vertex Resolution ¶	±0.0	±0.1	±0.2
Vertex Accuracy	-2.8, +2.9	±1.8	±1.4
Angular Resolution	-0.2, +0.2	-0.3, +0.3	-0.3, +0.3
Internal Source p-d ¶	±0.0	-1.5, +1.6	-2.0, +2.2
External Source p-d ¶	±0.1	-1.0, +1.0	±1.4
D2O Cherenkov ¶	-0.1, +0.2	-2.6, +1.2	-3.7, +1.7
H2O Cherenkov	±0.0	-0.2, +0.4	-0.2, +0.6
AV Cherenkov	±0.0	-0.2, +0.2	-0.3, +0.3
PMT Cherenkov ¶	±0.1	-2.1, +1.6	-3.0, +2.2
Neutron Capture	±0.0	-4.0, +3.6	-5.8, +5.2
Cut Acceptance	-0.2, +0.4	-0.2, +0.4	-0.2, +0.4
□ Experimental	**-5.2, +5.2**	**-8.5, +9.1**	**-13.2, +14.1**
Cross Section §	±1.8	±1.4	±1.2

¶ CC NC anti-correlation

Solar □ Flux Summary

□ ^{8}B from $CC_{SNO}+ES_{SK}$ (2001)
○ ES_{SNO} (2001)
○ CC_{SNO} (2001)
● NC_{SNO} (2002)
● ES_{SNO} (2002)
● CC_{SNO} (2002)



□ (□e+□□+□□) □ (□e)+0.15□ (□□+□□) □ (□e)

Null hypothesis rejected at 5.3□

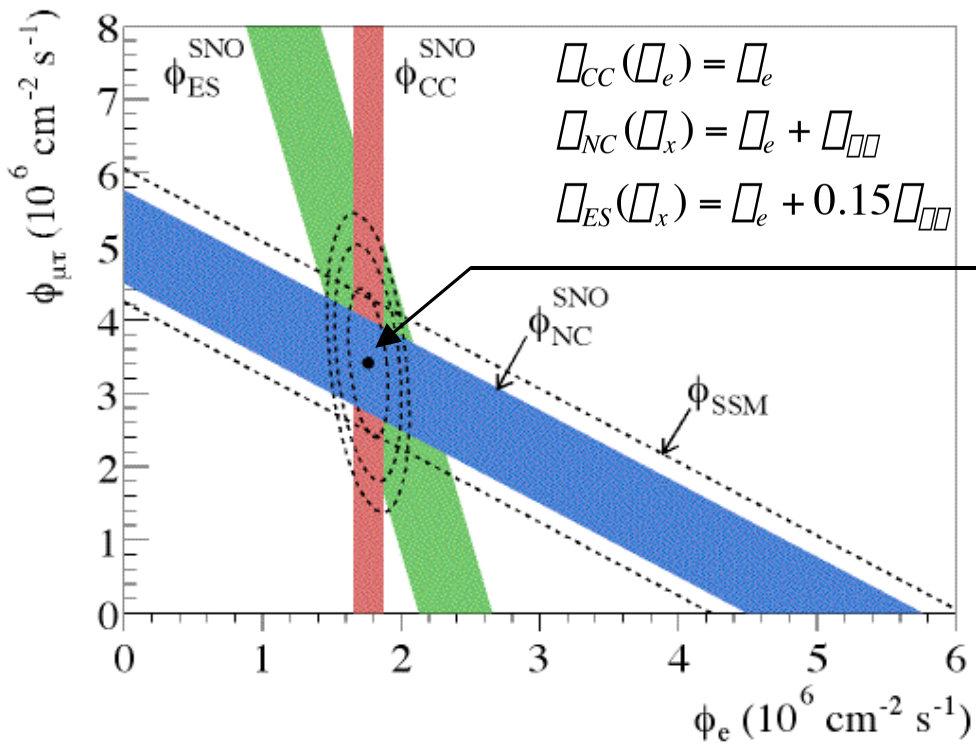
STRONG Evidence for □e □ □□ and/or □□

$$\Phi_{CC}(\nu_e) = 1.76^{+0.06}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}(\text{syst.}) \times 10^{6}\,\text{cm}^{-2}\text{s}^{-1}$$

$$\Phi_{ES}(\nu_x) = 2.39^{+0.24}_{-0.23}(\text{stat.})^{+0.12}_{-0.12}(\text{syst.}) \times 10^{6}\,\text{cm}^{-2}\text{s}^{-1}$$

$$\Phi_{NC}(\nu_x) = 5.09^{+0.44}_{-0.43}(\text{stat.})^{+0.46}_{-0.43}(\text{syst.}) \times 10^{6}\,\text{cm}^{-2}\text{s}^{-1}$$

Disappearance and Reappearance



$$\phi_{CC}(\phi_e) = \phi_e$$

$$\phi_{NC}(\phi_x) = \phi_e + \phi_{\mu\tau}$$

$$\phi_{ES}(\phi_x) = \phi_e + 0.15\phi_{\mu\tau}$$

$$\phi_e = 1.76^{+0.05}_{-0.05}\,(\text{stat.})\,^{+0.09}_{-0.09}\,(\text{syst.})\times 10^6\,\text{cm}^{-2}\text{s}^{-1}$$

$$\phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}\,(\text{stat.})\,^{+0.48}_{-0.45}\,(\text{syst.})\times 10^6\,\text{cm}^{-2}\text{s}^{-1}$$

Solar Model predictions are verified:
[in 10^6 cm^{-2} s^{-1}]

$$\phi_{SSM} = 5.05^{+1.01}_{-0.81}$$

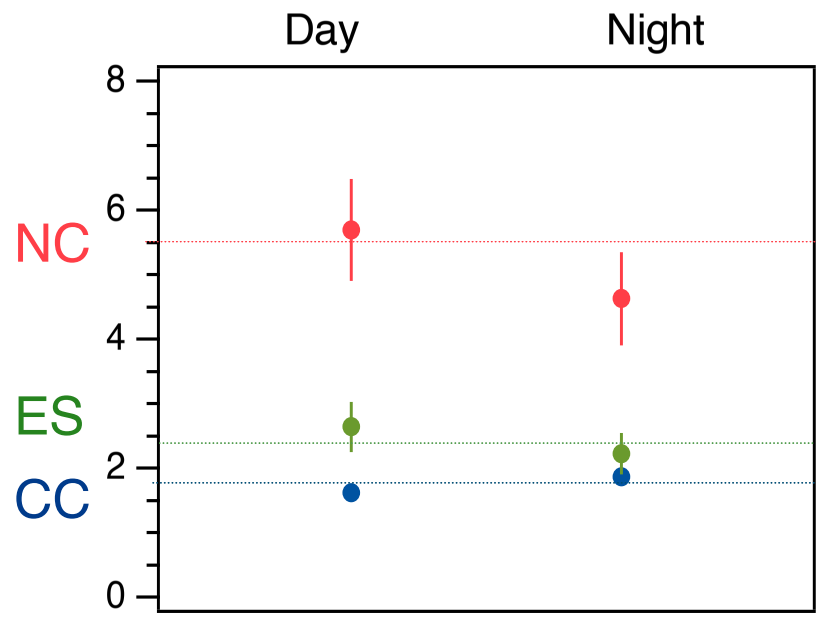
$$\phi_{SNO}^{constrained} = 5.09^{+0.44}_{-0.43}\,(\text{stat.})\,^{+0.46}_{-0.43}\,(\text{syst.})$$

$$\phi_{SNO}^{unconstrained} = 6.42^{+1.57}_{-1.57}\,(\text{stat.})\,^{+0.55}_{-0.58}\,(\text{syst.})$$

Day Flux vs Night Flux

- Data divided into two sets (to test statistical bias)
- Sub-divide into 2 zenith angle bins:
  Day: cos θ_z>0 (128.5 days)
  Night: cos θ_z<0 (177.9 days)
- ^{8}B shape constrained extraction

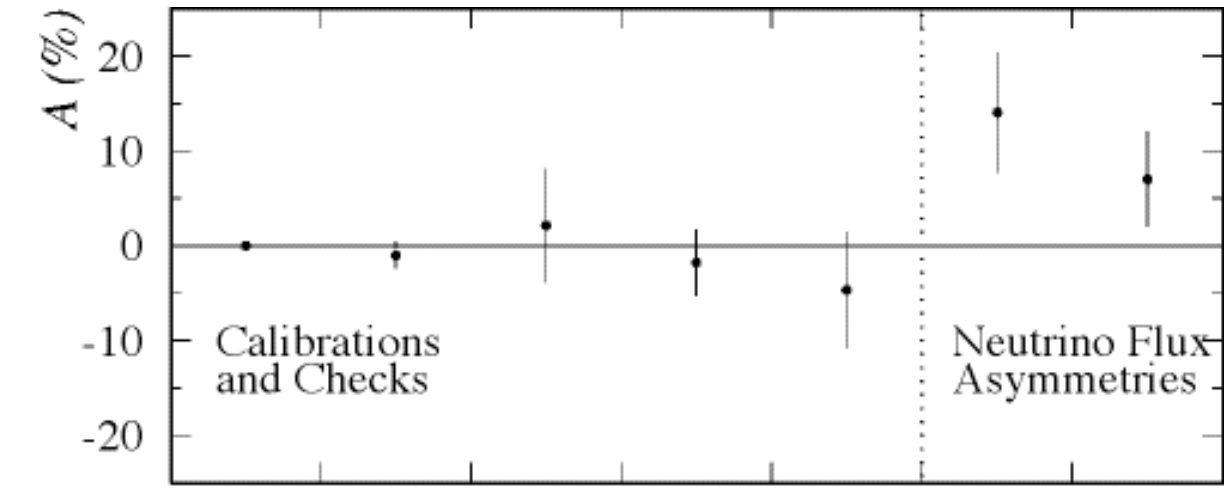
$$A_x = 2\frac{(\phi_{NIGHT} - \phi_{DAY})}{(\phi_{NIGHT} + \phi_{DAY})}$$



ϕ in units of x10^6 cm^{-2} s^{-1}

Day/Night Signals							
	Set 1		Set 2		Combined		
ϕ	D	N	D	N	D	N	A (%)
CC	1.53±0.12	1.95±0.10	1.69±0.12	1.77±0.11	1.62±0.08±0.08	1.87±0.07±0.10	+14.0±6.3±1.5
ES	2.91±0.52	1.59±0.38	2.35±0.51	2.88±0.47	2.64±0.37±0.12	2.22±0.30±0.12	-17.4±19.5±2.4
NC	7.09±0.97	3.95±0.75	4.56±0.89	5.33±0.84	5.69±0.66±0.44	4.63±0.57±0.44	-20.4±16.9±2.5

D-N systematic checks



noise rate

rate

energy response: follower

energy scale: Hot spot

Detector configuration

Checks did not turn up any significant diurnal asymmetry

Systematic Uncertainties (D-N)

Shape constrained

Day/Night Systematics			
Systematic	ΔA_{CC} %	ΔA_{ES} %	ΔA_{NC} %
Long-term Energy Scale	0.40	0.50	0.20
Diurnal Energy Scale	1.20	0.70	1.60
Directional Energy Scale var.	0.20	1.40	0.30
Diurnal Energy Resolution var.	0.10	0.10	0.30
Directional Energy Resolution var.	0.00	0.10	0.00
Diurnal vertex shift var.	0.50	0.60	0.70
Directional vertex shift var.	0.00	1.10	0.10
Diurnal vertex resolution var.	0.20	0.70	0.50
Directional angular recon. var.	0.00	0.10	0.10
PMT □□□backgrounds	0.00	0.20	0.50
AV+H2O □□□backgrounds	0.00	0.60	0.20
D2O b-g, neutrons backgrounds	0.10	0.40	1.20
External neutrons backgrounds	0.00	0.20	0.40
Cut inefficiencies	0.50	0.50	0.50
Total	1.50	2.40	2.40

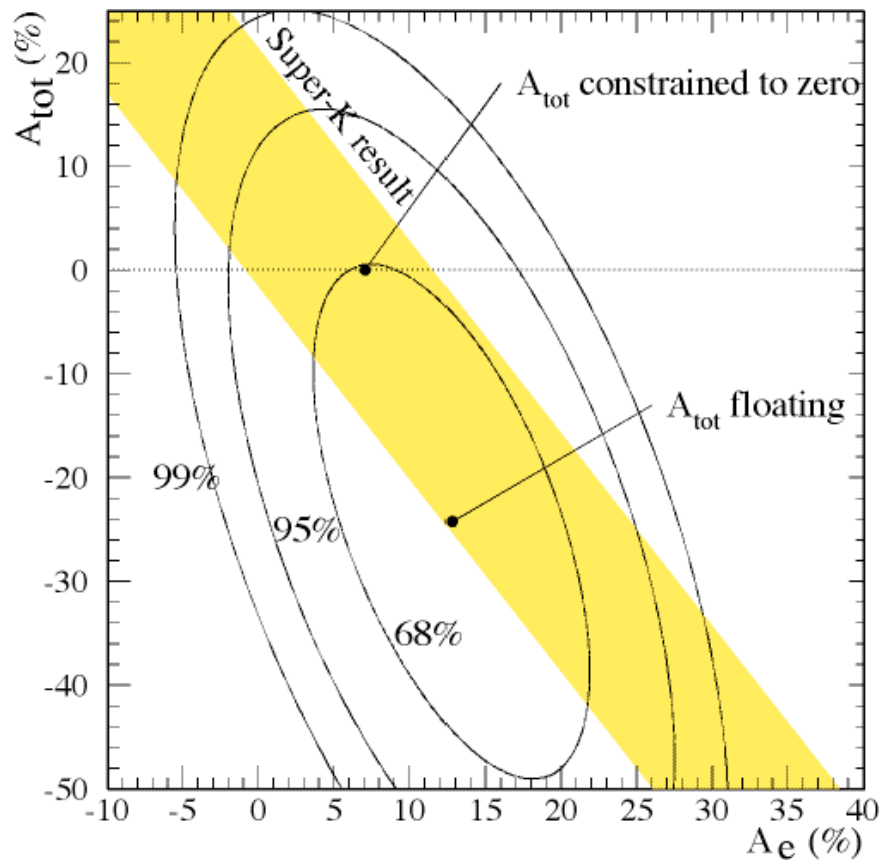
The D-N analysis is currently statistics limited

A_e vs A_{total}

- Signal Extraction in ϕ_{CC}, ϕ_{NC}, ϕ_{ES}:

$$A_{CC} = 14.0 \pm 6.3^{+1.5}_{-1.4}\%$$
$$A_{NC} = 20.4 \pm 16.9^{+2.4}_{-2.5}\%$$

Using: $\phi_{ES} = (1-\alpha)\phi_e + \alpha\phi_{Total}$
$[\phi_{Total} = \phi_e + \phi_\mu + \phi_\tau,\ \alpha = 1/6.48]$



- Signal Extraction in ϕ_e, ϕ_{Total}:

$[\phi_{Total} = \phi_e + \phi_\mu + \phi_\tau]$

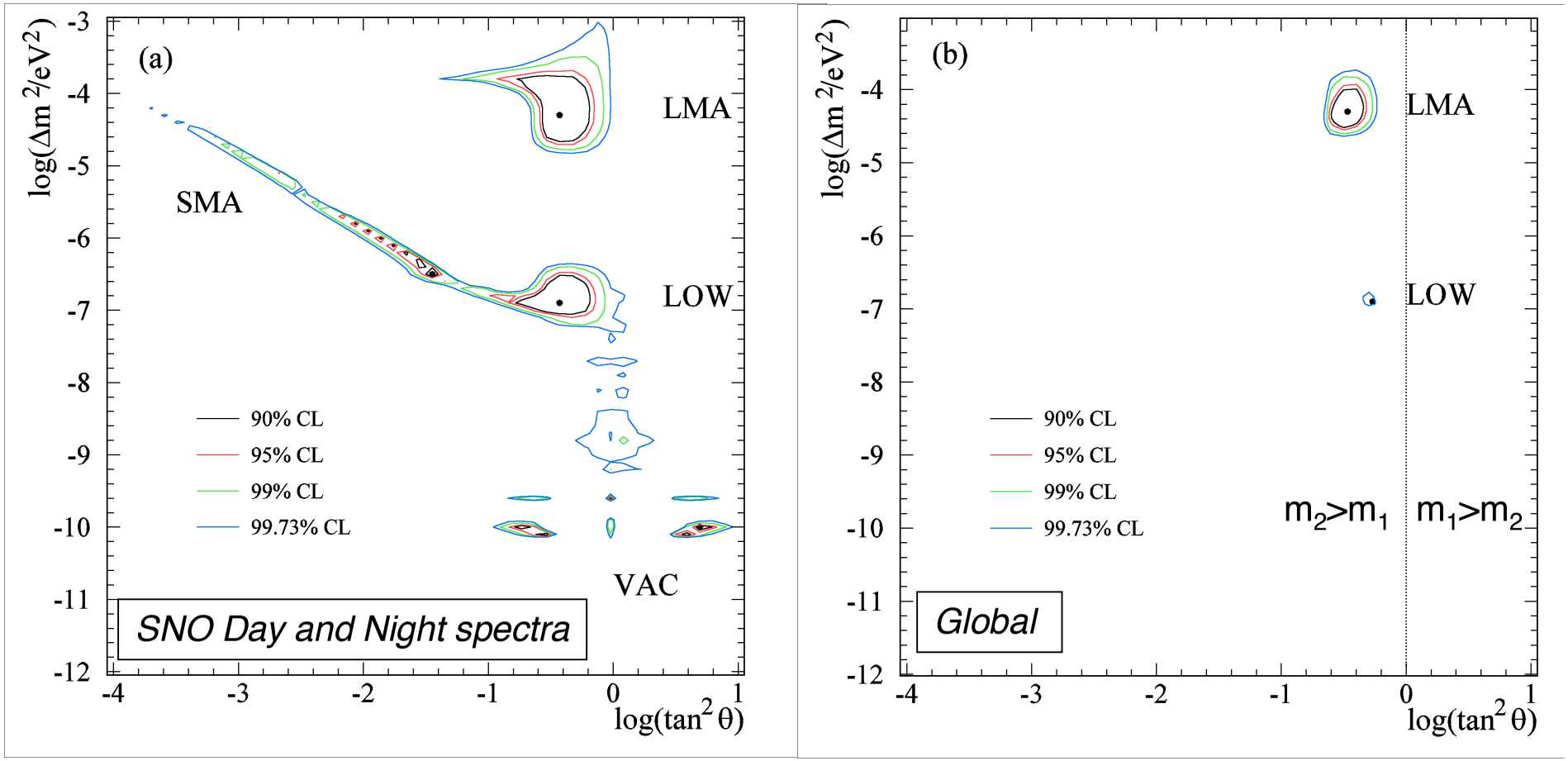
$$A_e = 12.8 \pm 6.2^{+1.5}_{-1.4}\%$$
$$A_{Total} = 24.2 \pm 16.1^{+2.4}_{-2.5}\%$$

- Signal Extraction in ϕ_e, $\phi_{Total} + A_{total} = 0$:

$$A_e = 7.0 \pm 4.9^{+1.3}_{-1.2}\%$$
$$A_e^{SK} = 5.3 \pm 13.7^{+2.0}_{-1.7}\%$$ [using SK A_{ES} and SNO ϕ_{Total}]

Global Solar ν Analysis

Inputs:
- ^{37}Cl, latest Gallex/GNO, new SAGE, SK 1258-day day & night spectra
- SNO day spectrum (total: CC+NC+ES+background)
- SNO night spectrum (total: CC+NC+ES+background)
- ^{8}B floats free in fit, hep ν at 1 SSM



Global □ Analysis Fit Results

Region	χ^2_{min}/dof	ϕ_{8B}	A_e(%)	Δm^2	$\tan^2\theta$	CL(%)
LMA	57.0/72	5.86	6.4	5.0×10^{-5}	0.34	□
LOW	67.7/72	4.95	5.9	1.3×10^{-7}	0.55	99.5%

- SNO CC/NC measurement directly constrains the survival probability at high energy
  - □ *forces* LOW *solution to confront the Ga experimental results*:

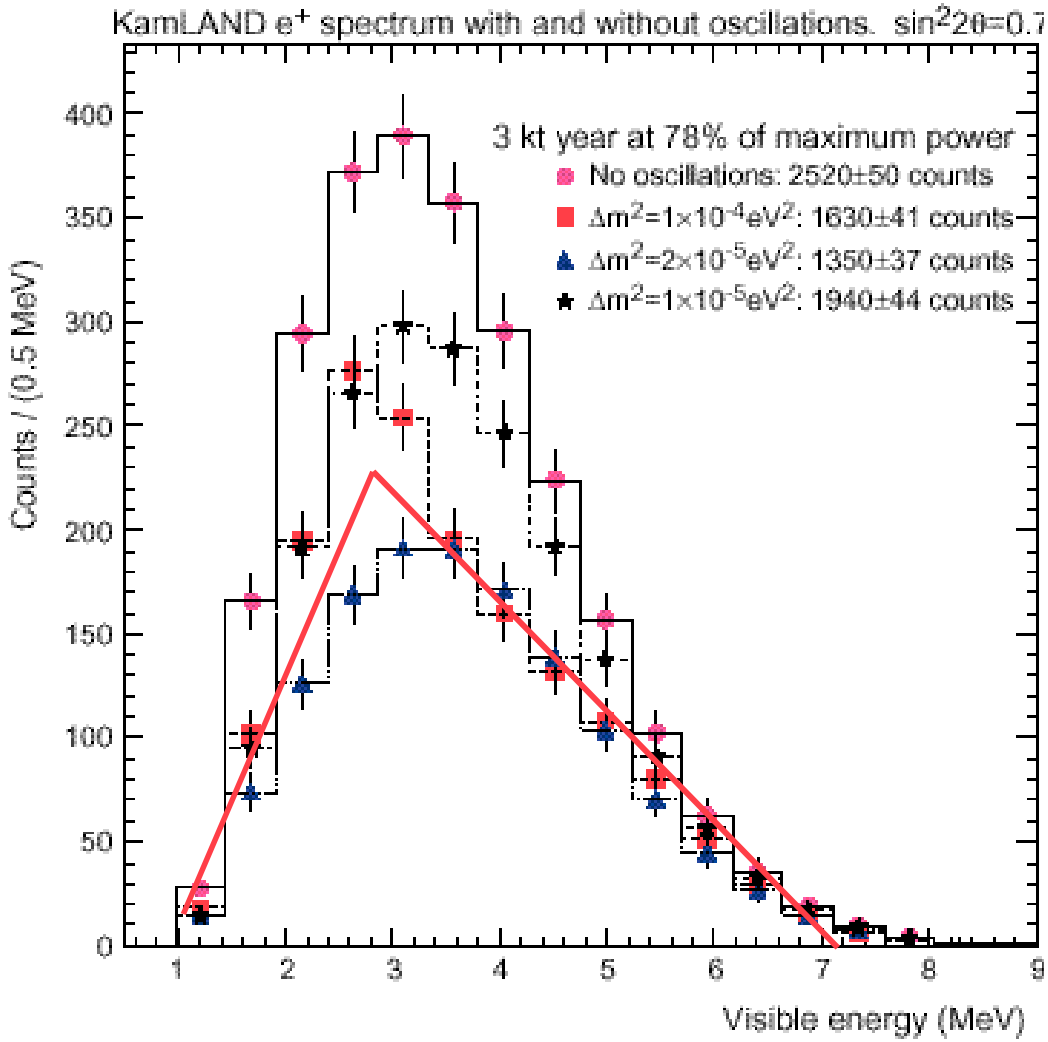
	LMA	LOW
SNO NC	5.86×10^6 cm^{-2} s^{-1}	4.95×10^6 cm^{-2} s^{-1}
SNO CC day	1.66×10^6 cm^{-2} s^{-1}	1.83×10^6 cm^{-2} s^{-1}
SNO A_e	6.4%	5.9%
SK ES	2.30×10^6 cm^{-2} s^{-1}	2.30×10^6 cm^{-2} s^{-1}
SK A_{ES}	3.5%	4.4%
Cl rate	3.0 SNU	3.0 SNU
Ga rate	72.8 SNU	61.2 SNU

[Experimental results: SK=2.32×10^6 cm^{-2} s^{-1}, Ga=72.0±4.5 SNU, Cl=2.56±0.23 SNU]

Prediction for KamLAND

Global fit:

LMA□ □m^2=5x10^{-5} eV^2



Present Status & Future of SNO

The Salt Phase

- 2 tonnes of NaCl added to D_2O
- Higher n-capture
- Higher event light output
- Light isotropy differs from e^-
- Running since June 2001

Neutral Current Detectors

^{3}He proportional counters

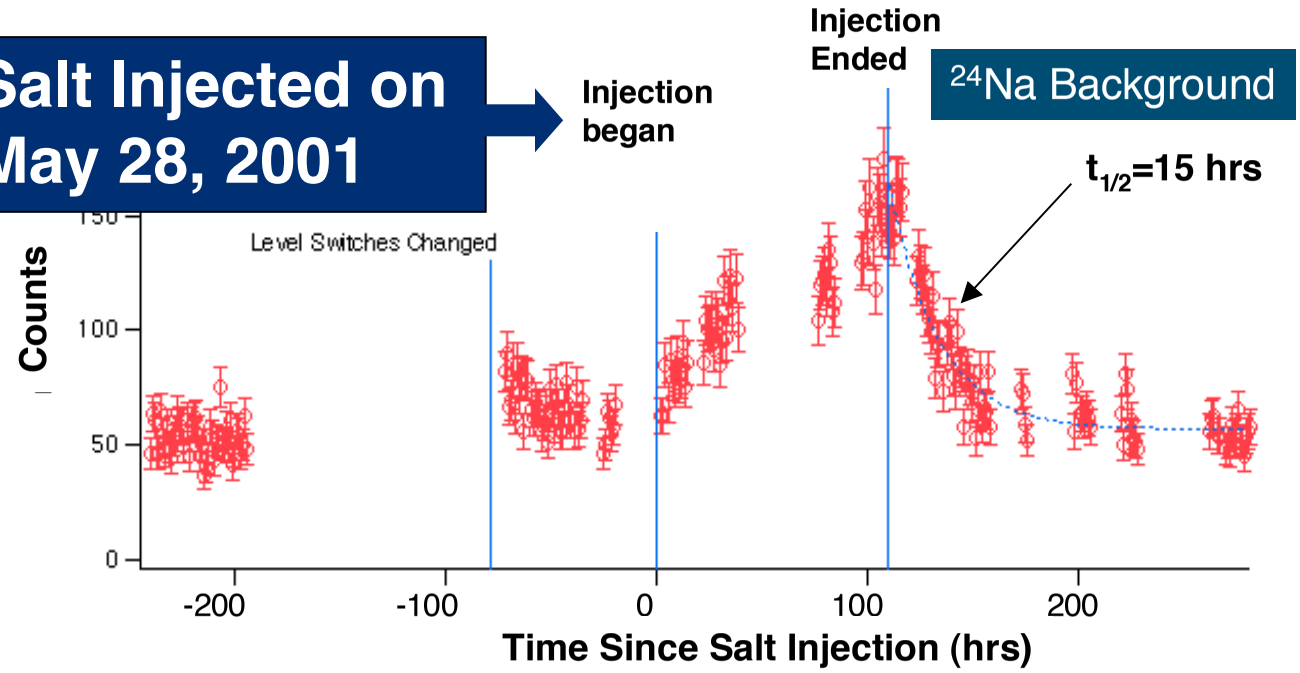
$n + {}^3He \rightarrow p + t$

To be deployed in early 2003

Salt Phase

Detector is in GREAT shape

Salt Injected on May 28, 2001



The NaCl brine in the underground buffer tank was activated by neutrons from the rock wall. We observed the decay of ^{24}Na after the brine is injected in the SNO detector.

Summary

Newest SNO results **:**

- $\nu_e \rightarrow \nu_\mu$ or ν_τ appearance at 5.3 σ
- Total ^8B ν flux measured for E_ν>2.2 MeV
- SSM prediction for total active ^8B ν flux verified
- Day-Night results consistent with MSW hypothesis

Global fit including the newest SNO results **:**

- LMA highly favored ($\Delta m^2 \sim 5.0 \times 10^{-5}$ eV^2)
- No "dark side" ($m_1 > m_2$, $\tan^2(\theta) < 1$)
- Predictions for Borexino & KamLAND

The NC and Day-Night papers (accepted for publication in PRL), along with a HOWTO guide on using the SNO results are available at the official SNO website:

http://sno.phy.queensu.ca