Results from SNO

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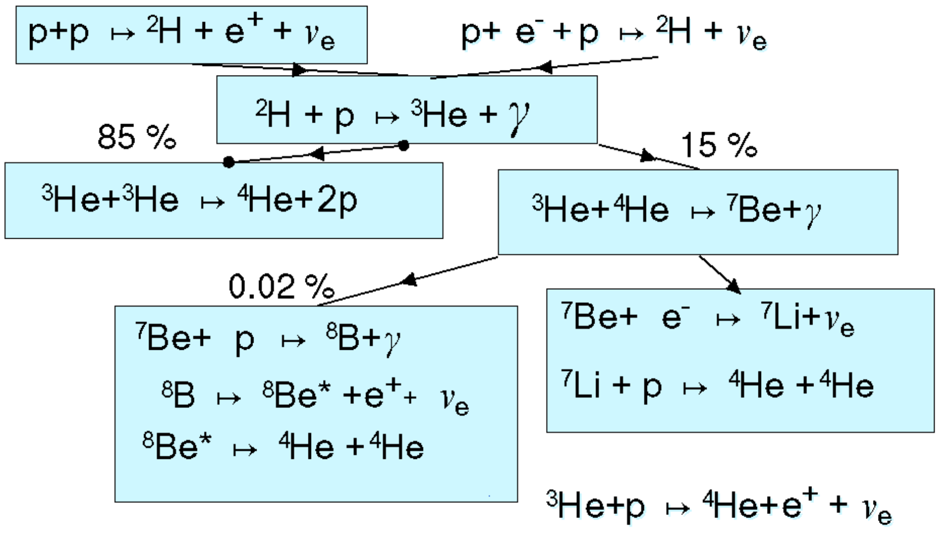
for the SNO Collaboration(*)

29th SLAC Summer Institute Topical Conference (8/23/2001)

Q: $m_\nu > 0$? [since 1932]

Q: solar neutrino → evidence for neutrino flavor mixing ? [Pontecorvo 1968]

The solar neutrino problem



$p+p \mapsto {}^2H + e^+ + \nu_e$

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

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

85 %

15 %

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

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

0.02 %

$^7Be + p \mapsto {}^8B + \gamma$

$^8B \mapsto {}^8Be^* + e^+ + \nu_e$

$^8Be^* \mapsto {}^4He + {}^4He$

$^7Be + e^- \mapsto {}^7Li + \nu_e$

$^7Li + p \mapsto {}^4He + {}^4He$

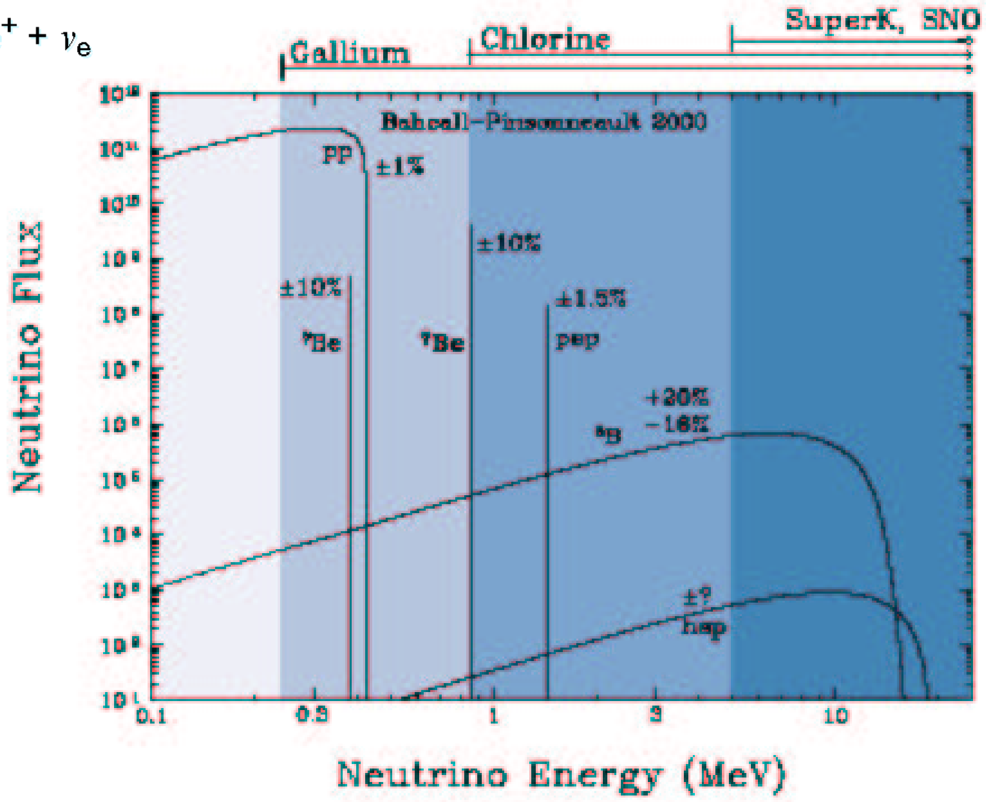
$^3He + p \mapsto {}^4He + e^+ + \nu_e$

Pioneer: Homestake

1965 (Davis et al.)

$$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$$

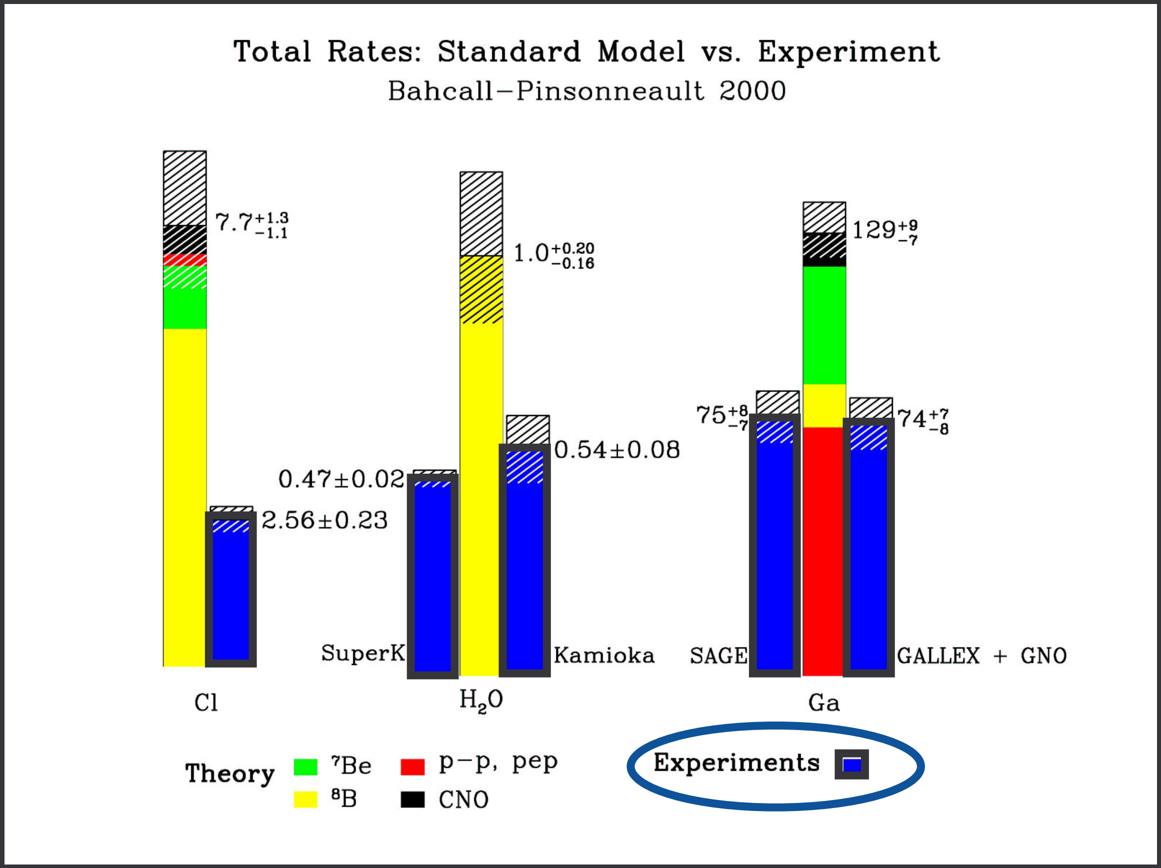
Deduced flux significantly less than SSM predictions



An experimental problem ?

More measurements in 3 decades…

all reported a lower than expected (SSM) solar neutrinos flux



Standard Solar Model?

Physics? (neutrino mass & flavor mixing)

Neutrino Oscillation

A neutrino of a given flavor (e.g. e, μ, τ) need not necessary be a mass eigenstate.

$$|\nu_L> = \sum U_{LM} \, | \, \nu_M>$$

L={Active, Sterile} M={m1, m2, …}

Standard Electroweak Interaction :

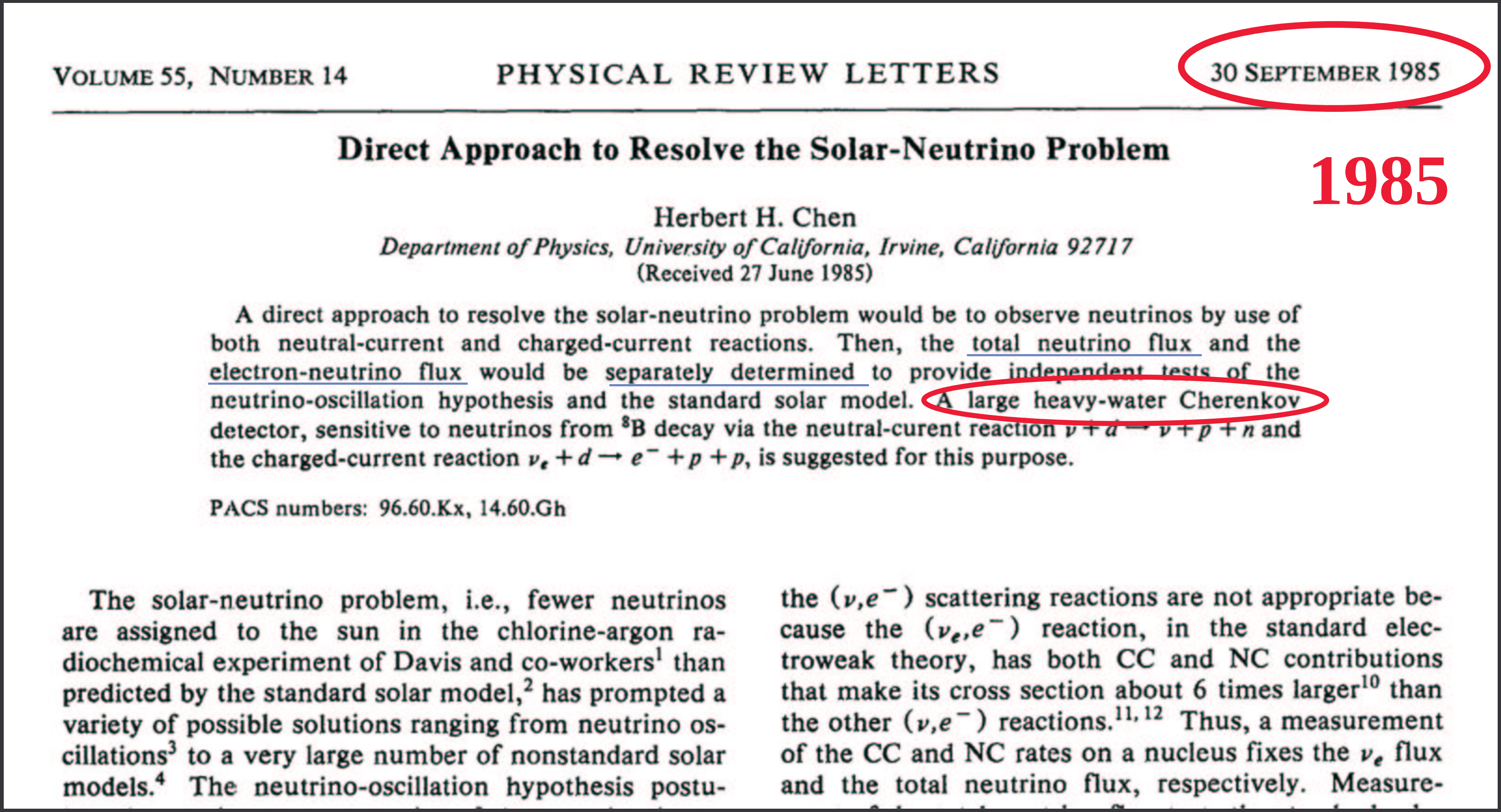
Active neutrino

(Left-handed $\nu_e \nu_\mu \nu_\tau$; Right-handed $\bar{\nu}_e \bar{\nu}_\mu \bar{\nu}_\tau$)

Sterile neutrino

(Any neutrinos not coupling to Z^o)

SNO's design goal:
To provide a definitive answer …



VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

1985

Direct Approach to Resolve the Solar-Neutrino Problem

Herbert H. Chen
Department of Physics, University of California, Irvine, California 92717

(Received 27 June 1985)

A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-curent reaction $\nu + d \rightarrow \nu + p + n$ and the charged-current reaction $\nu_e + d \rightarrow e^- + p + p$, is suggested for this purpose.

PACS numbers: 96.60.Kx, 14.60.Gh

The solar-neutrino problem, i.e., fewer neutrinos are assigned to the sun in the chlorine-argon radiochemical experiment of Davis and co-workers[1] than predicted by the standard solar model,[2] has prompted a variety of possible solutions ranging from neutrino oscillations[3] to a very large number of nonstandard solar models.[4] The neutrino-oscillation hypothesis postu-

the (ν,e^-) scattering reactions are not appropriate because the (ν_e,e^-) reaction, in the standard electroweak theory, has both CC and NC contributions that make its cross section about 6 times larger[10] than the other (ν,e^-) reactions.[11, 12] Thus, a measurement of the CC and NC rates on a nucleus fixes the ν_e flux and the total neutrino flux, respectively. Measure-

Neutrino interactions in D2O

Charged-Current (CC) sensitive to ν_e only

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

direct Cerenkov light

$E_{\mathbf{thresh}} = 1.4$ MeV

Neutral-Current (NC) sensitive to and same for all ν_x (total flux)

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

n-capture in nuclei → γ
→ Compton e- → Cerenkov light

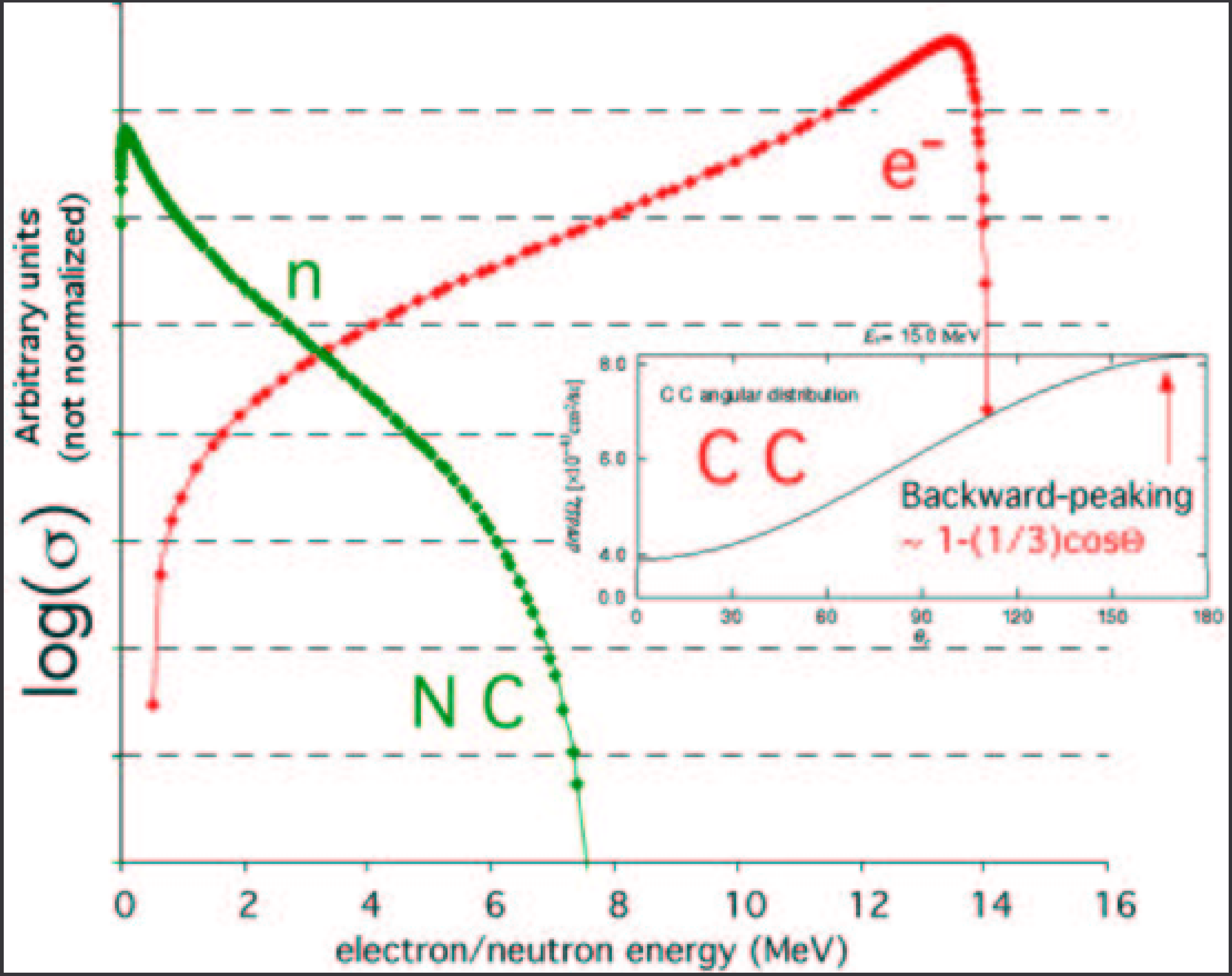
$E_{\mathbf{thresh}} = 2.2$ MeV

Elastic Scattering (ES) sensitive to all ν_x but 6x larger for ν_e

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

direct Cerenkov light

Energy distribution of reaction products from 15 MeV ν_e+d (theory)

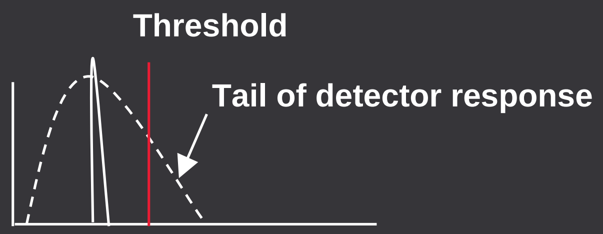


Backgrounds

Charged-Current (CC) $\nu_e + d \rightarrow e^- + p + p$

Any other Cerenkov light sources

(e.g. low energy β–γ radioactivity)



Neutral-Current (NC) $\nu_x + d \rightarrow \nu_x + n + p$ $E_{\mathbf{thresh}} = 2.2$ MeV

photo-disintegration of d : $\gamma + d \rightarrow n + p$ for $\gamma > 2.2$ MeV

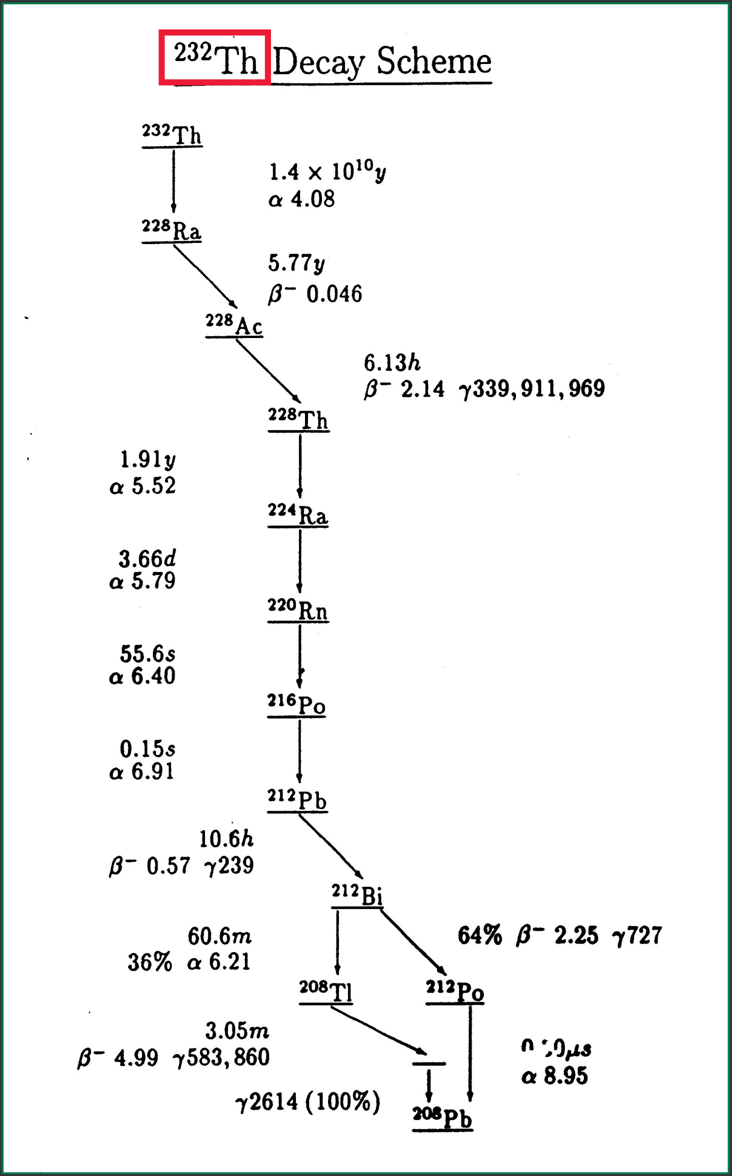
n from muon-induced spallation

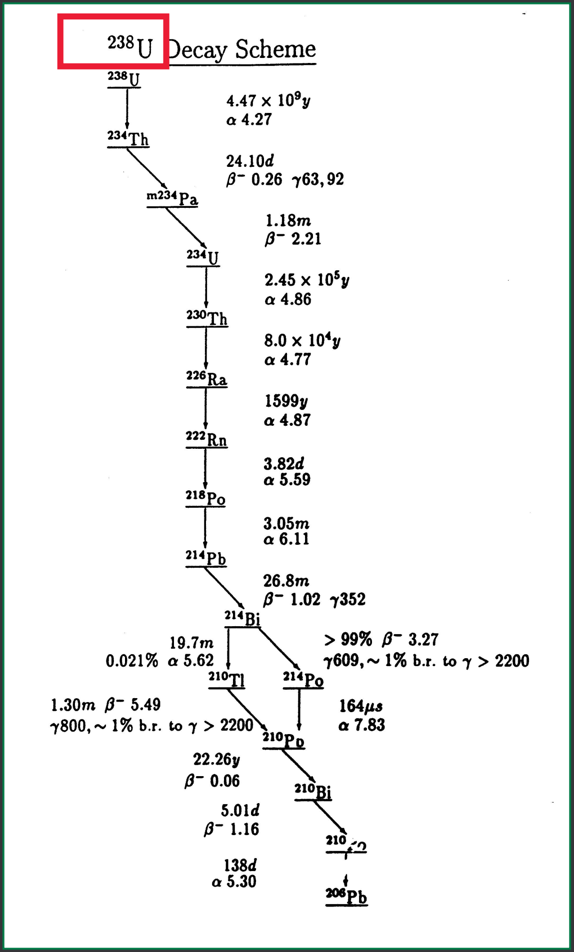
n from radioactivity /nuclear reactions

Elastic Scattering (ES) $\nu_x + e^- \rightarrow \nu_x + e^-$

Same as CC, but $\cos\Theta_{sun}$ helps

Backgrounds from Natural Radioacitvity

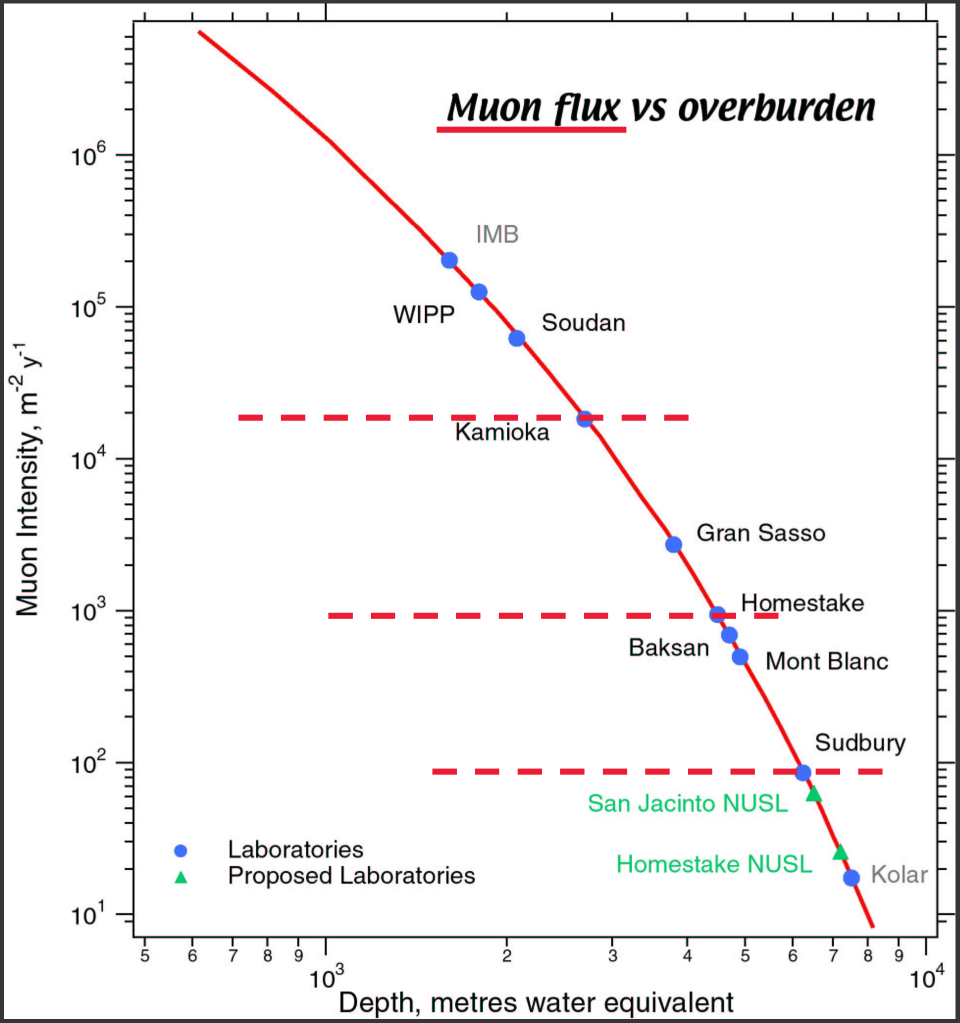




γ's over 2.2 MeV

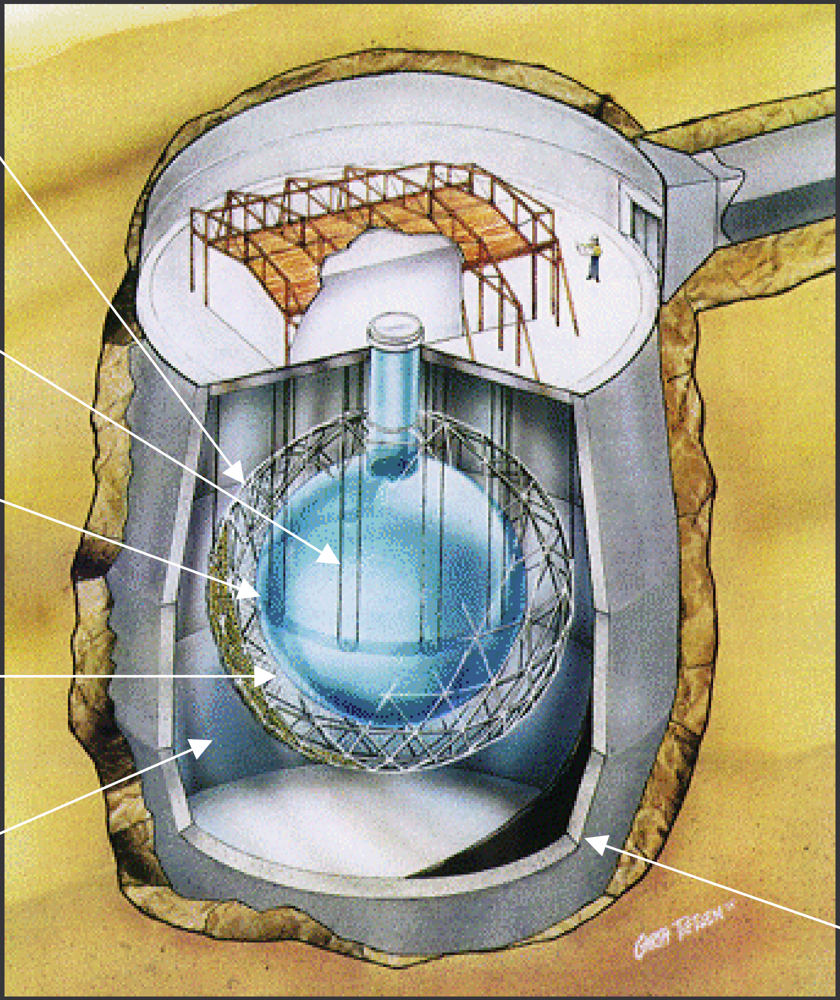
$d + \gamma \rightarrow n + p$

Creighton Mine
Sudbury, Ontario, Canada



The Sudbury Neutrino Observatory

3010 m water equivalent overburden



17.8 m Diameter Support Structure for 9456 PMTs, 56% coverage

1006 Metric Tons D_2O

12.01 m Diameter Acrylic Vessel

1700 Metric Tons Inner Shielding Ultra-pure H_2O

5300 Tons Outer Shield H_2O

Urylon Liner and Radon Seal

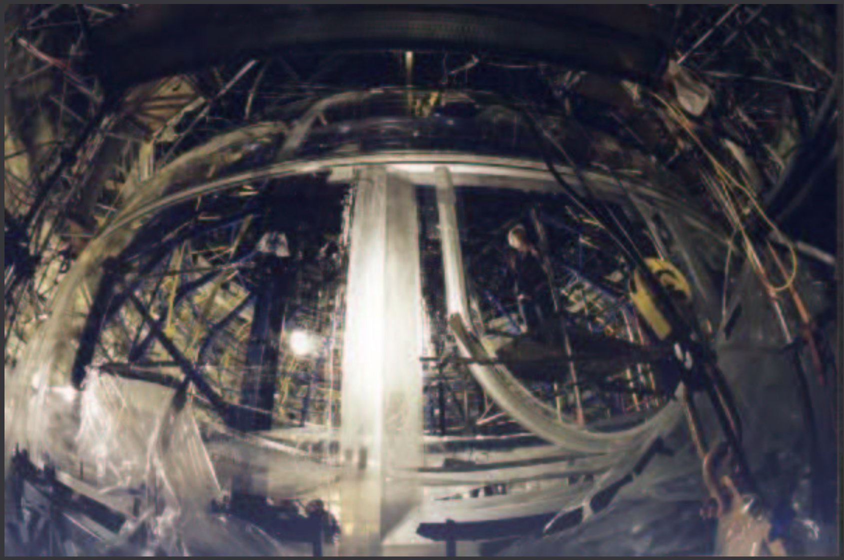
Ultra-low Activity Components

+

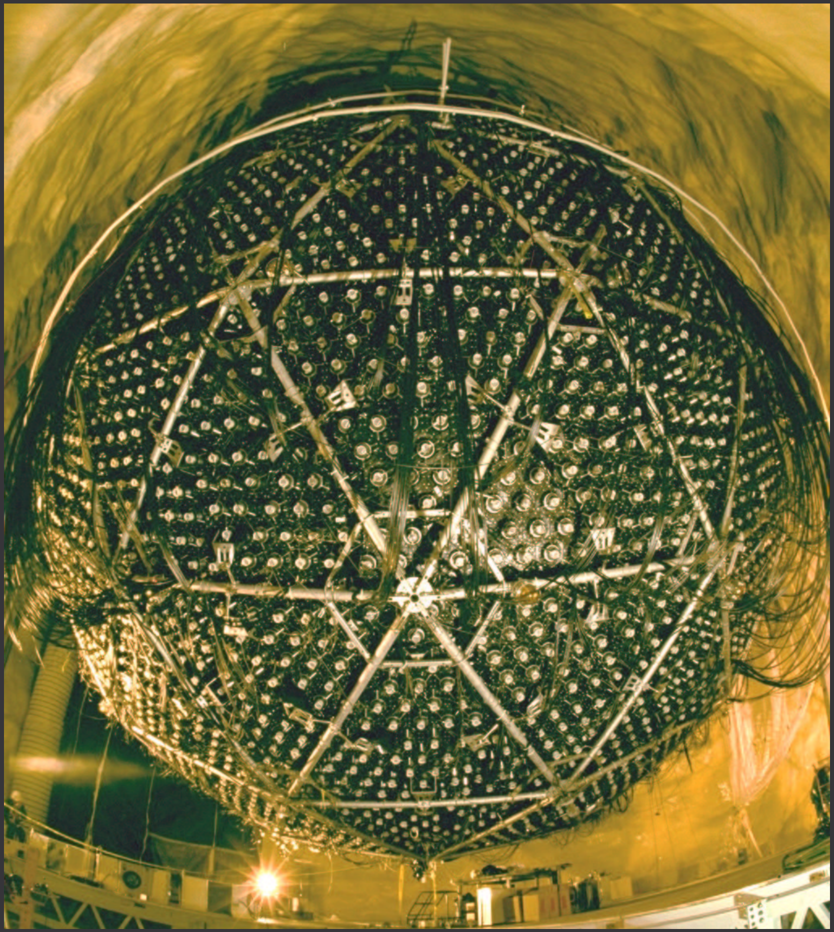
Straight Clean Room Construction Procedures

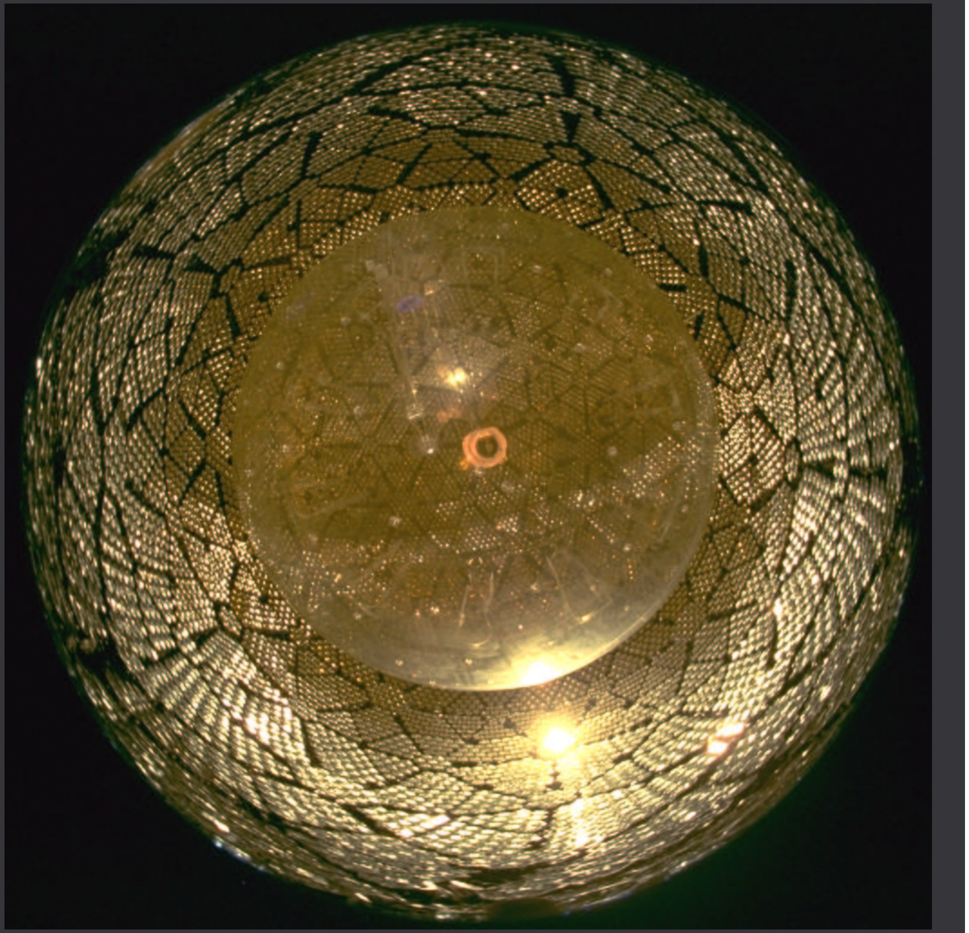
NIM A449, 127 (2000)

Acrylic Vessel for the D_2O target and water systems during construction

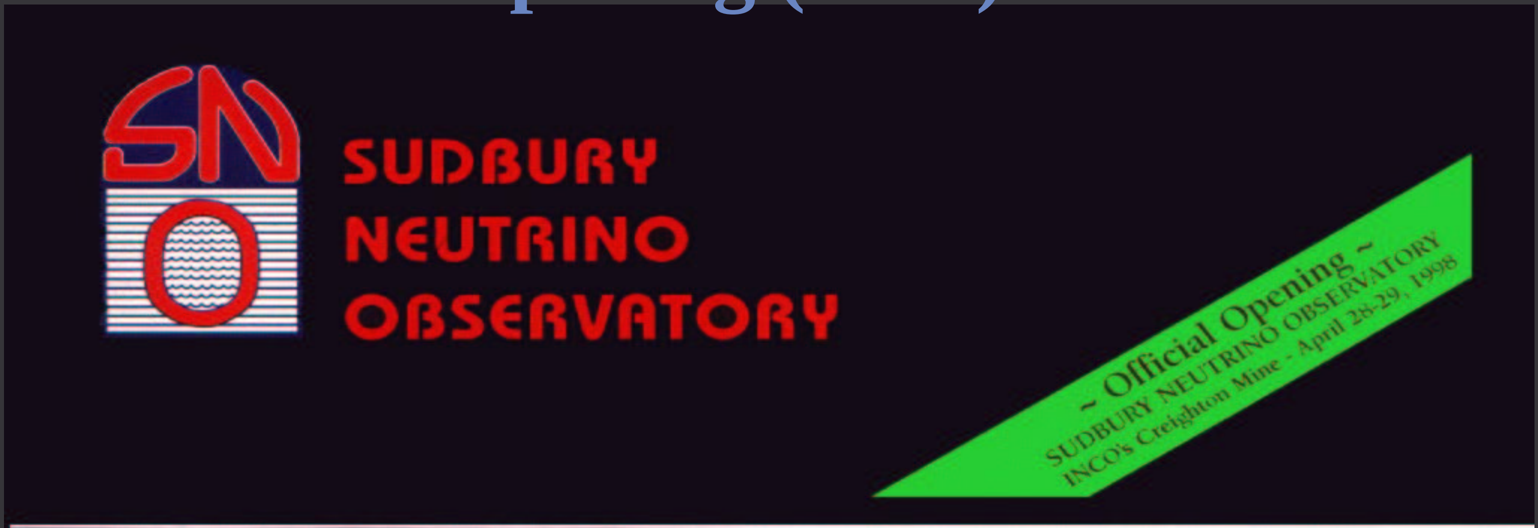


Two views of the detector





Official SNO Opening (1998)



SUDBURY
NEUTRINO
OBSERVATORY

~ Official Opening ~
SUDBURY NEUTRINO OBSERVATORY
INCO's Creighton Mine - April 28-29, 1998

Guest of Honor for Opening Ceremony: Prof. Steven Hawkings

SNO Solar Neutrino Physics Program

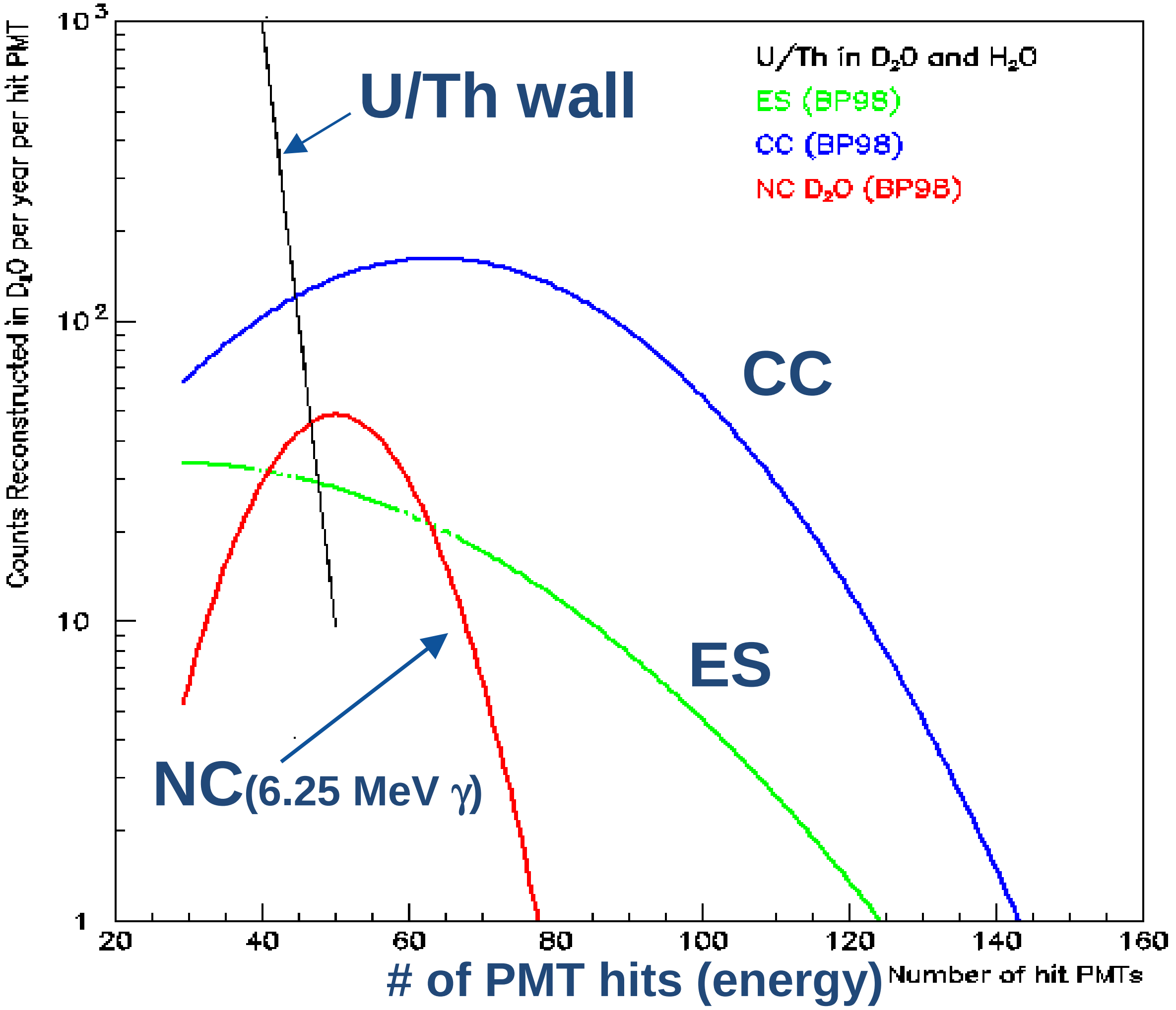
Phase I : D2O CC spectrum/Flux, NC, ES

Phase II : D2O+Salt Enhanced NC, also CC, ES

Phase III : D2O + Neutral Current Detector (NCD) array
independent NC, CC, ES

Also: supernova ready

Monte Carlo Cerenkov Signal for SNO Phase I



Detector

  - Characterization/calibration

Background

Data Analysis

Results

Calibration and Detector Response

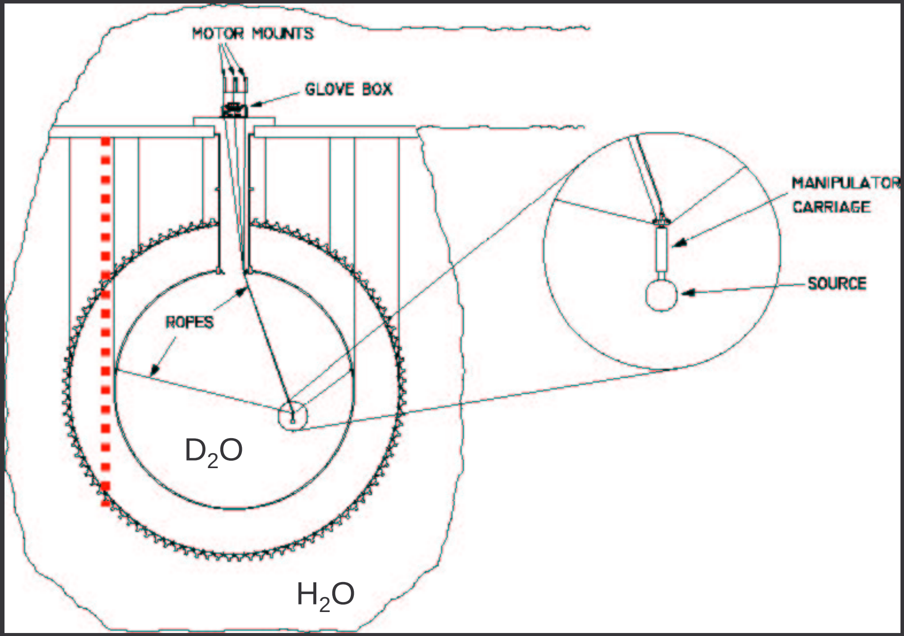
Calibration Issues

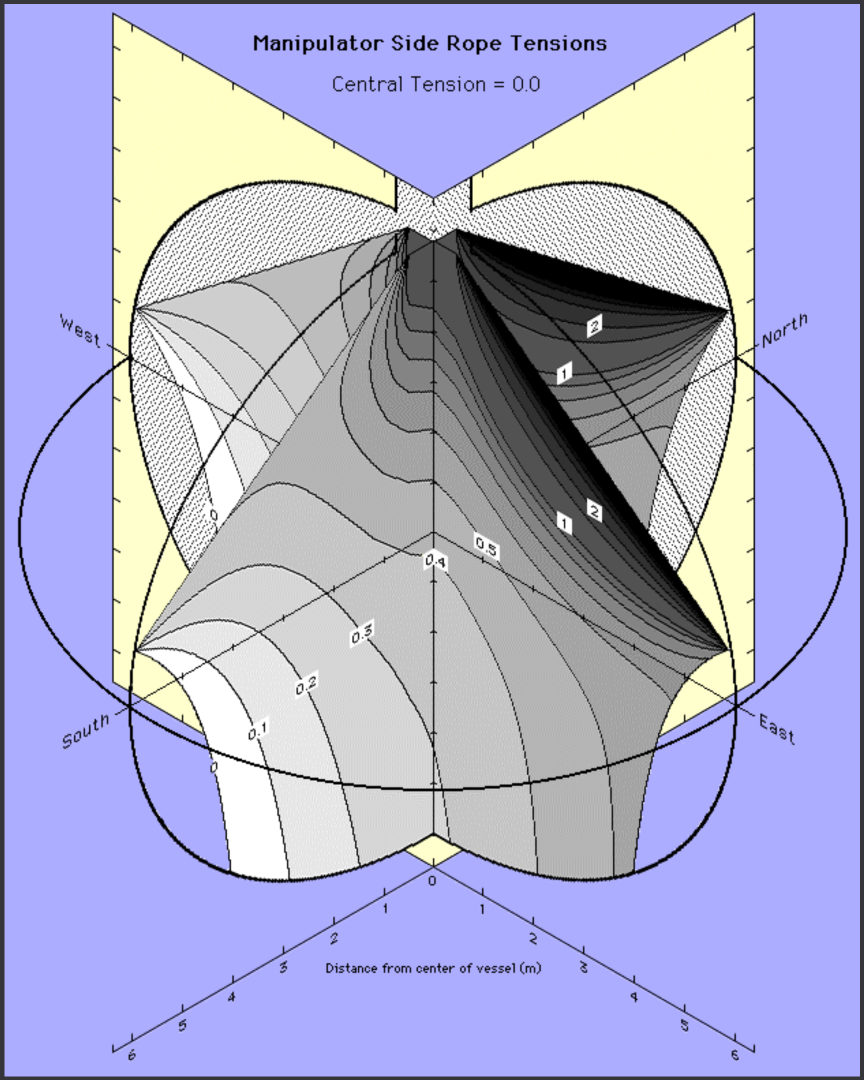
- Optical response (photon transport and detection)
- Energy scale
- Geometry (reconstruction)
- Background level
- Detector temporal stability

Calibration Techniques

Electronics	electronic pulsers, pulsed light sources	
Optical Response	pulsed laser at λ=337, 365, 386, 420, 500, and 620 nm, ~2 ns resolution	
Energy response	^{16}N	6.13 MeV γ, tagged
	p,t	19.8 MeV γ
	neutrons	6.25 MeV γ
	^{8}Li β spectrum	13 MeV endpoint
		(^{8}B 15 MeV endpoint)

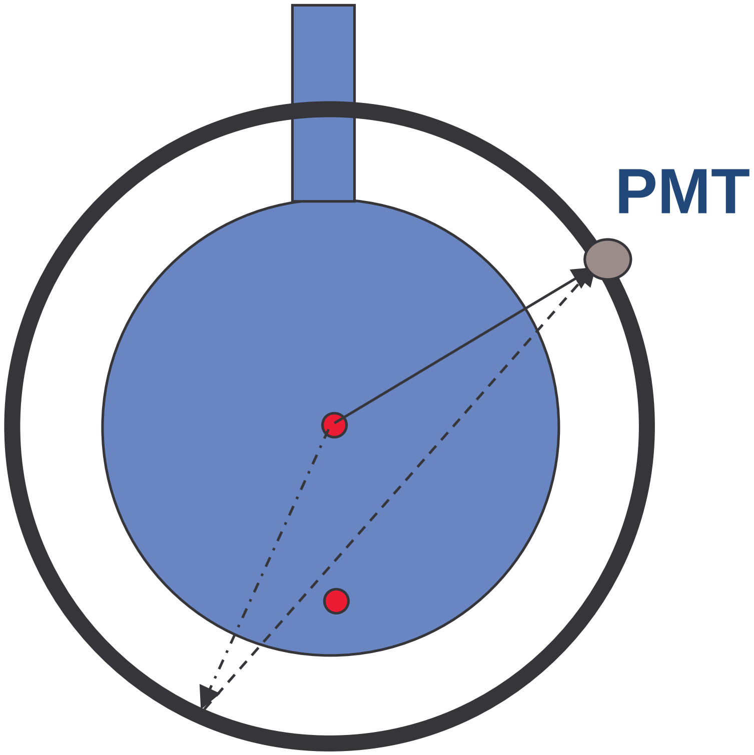
Calibration Systems

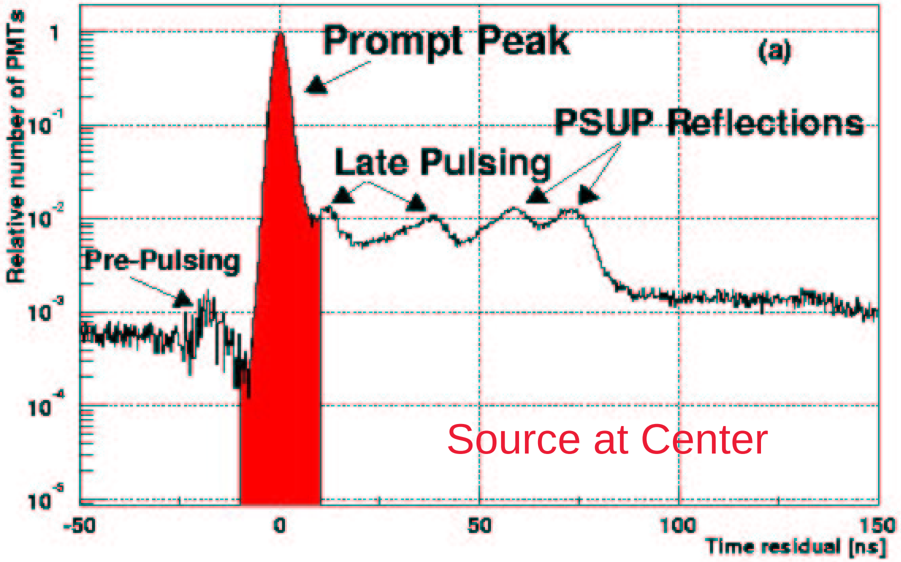


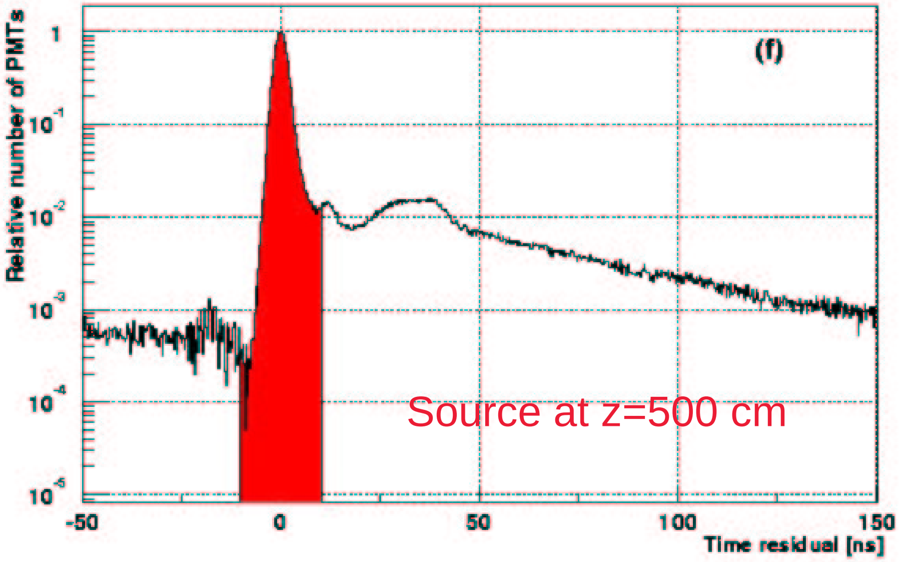


Optical Response (prompt vs late light)

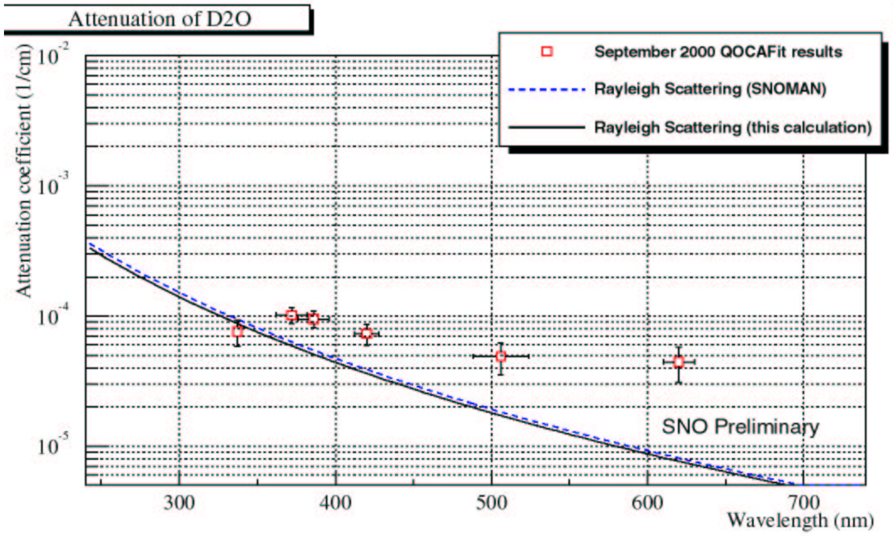
Timing Residuals
Difference in time between hit and direct flight time from vertex

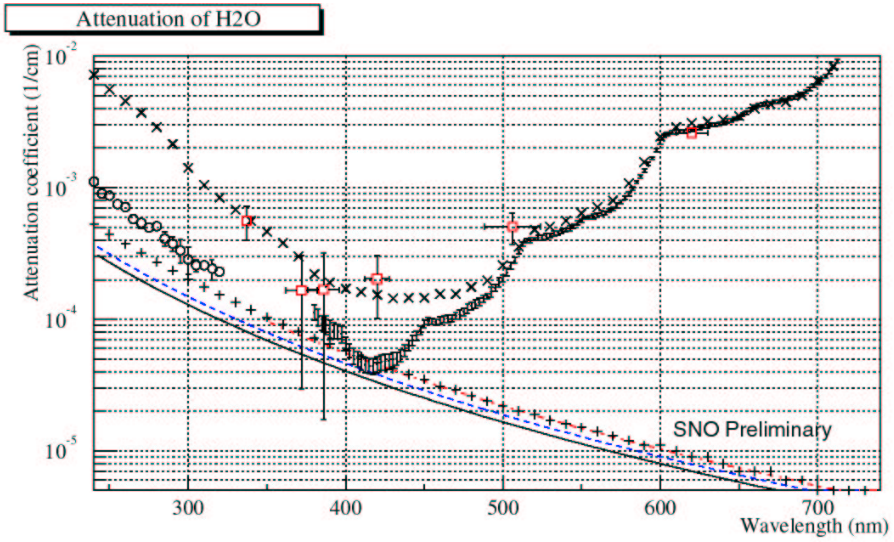


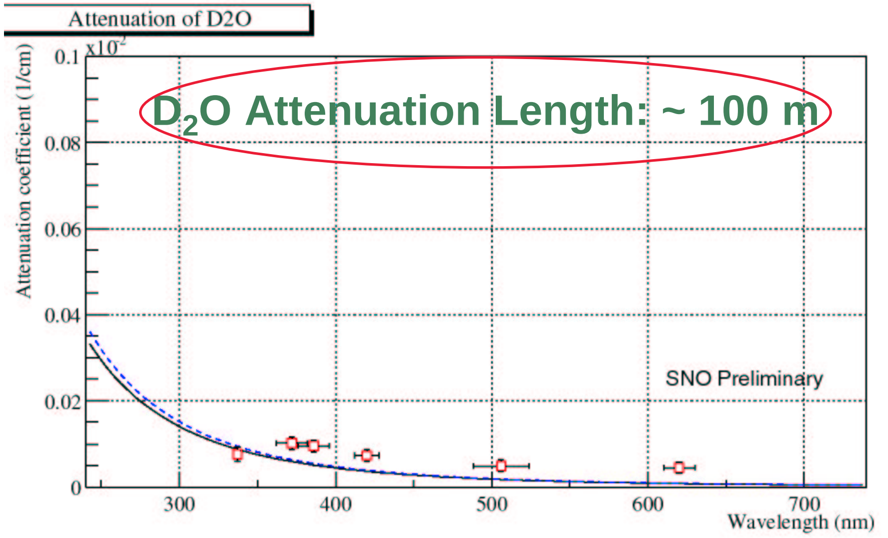




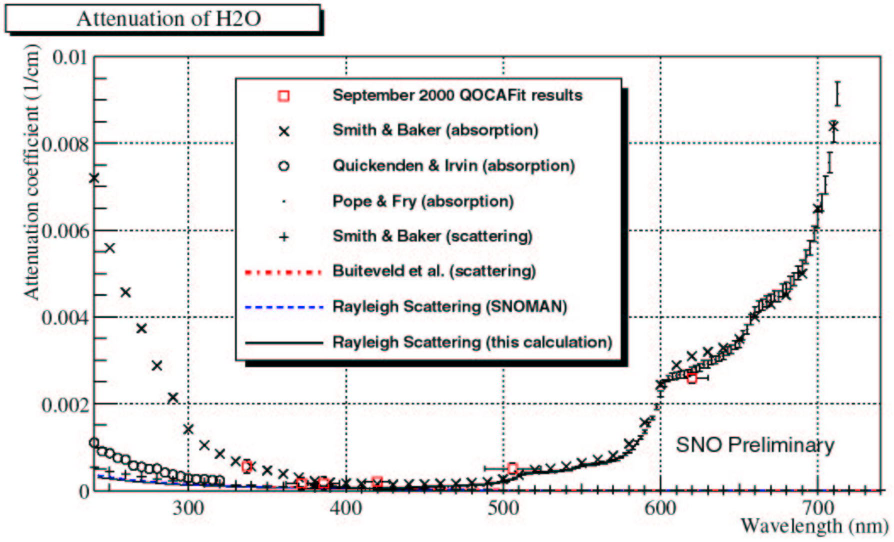
Optical Response: D_2O and H_2O Attenuation



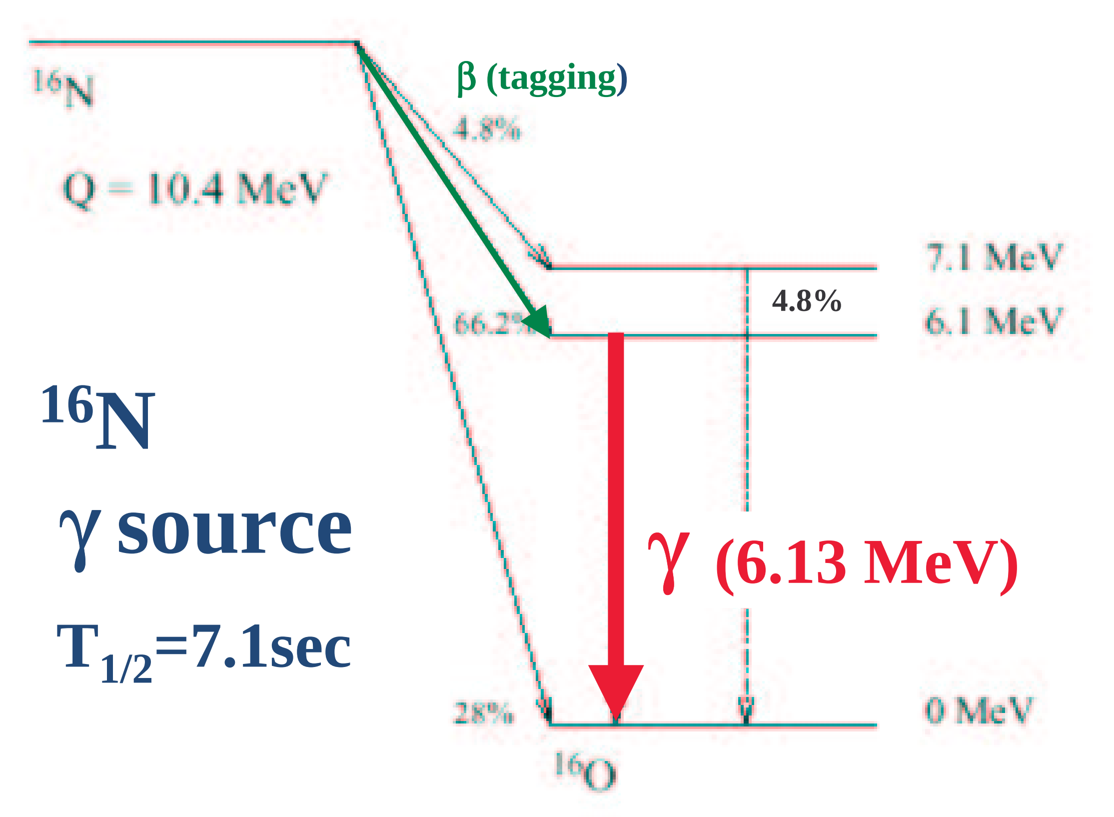




D_2O Attenuation Length: ~ 100 m



SNO absolute energy calibration

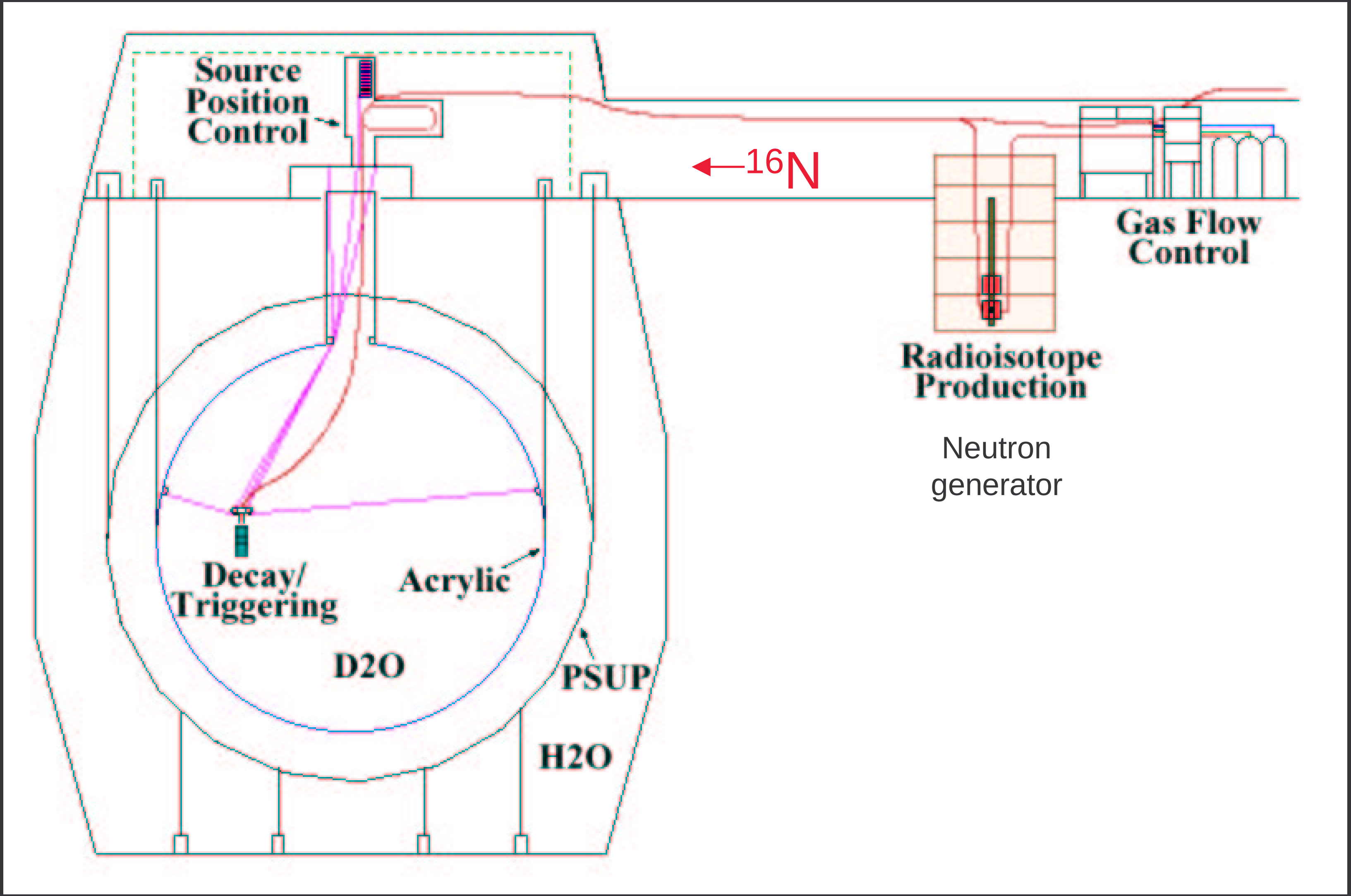


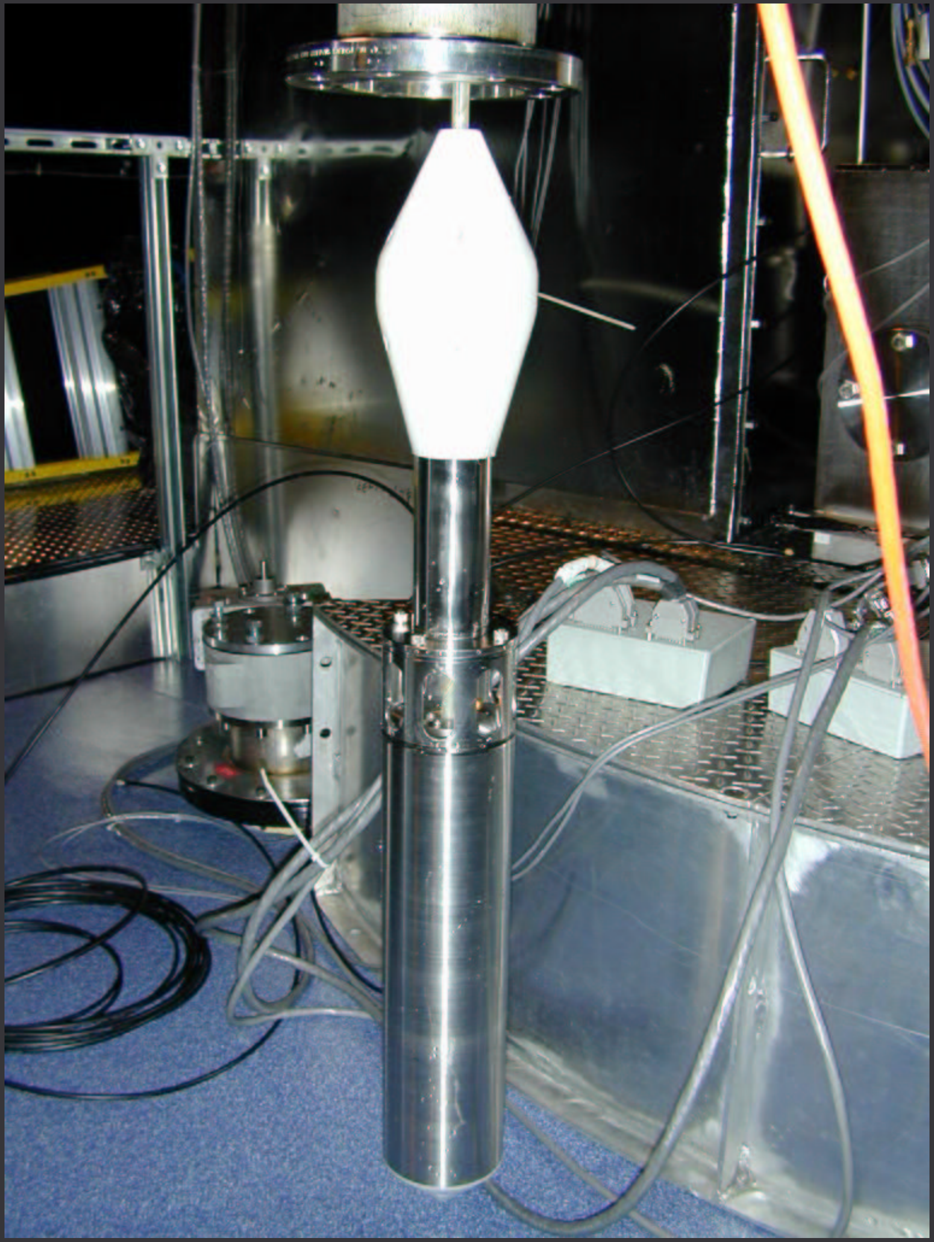
^{16}N

γ source

$T_{1/2}$=7.1sec

Delivery system for short-lived isotopes





SNO Energy Response - Absolute Energy Scale

- Established with triggered ^{16}N γ source (E_γ= 6.13 MeV)
- Tested against other β and γ sources (^{8}Li,^{252}Cf, and pT)

^{16}N

6.13 MeV γ
(predominant)
(n,p) on ^{16}O

^{8}Li

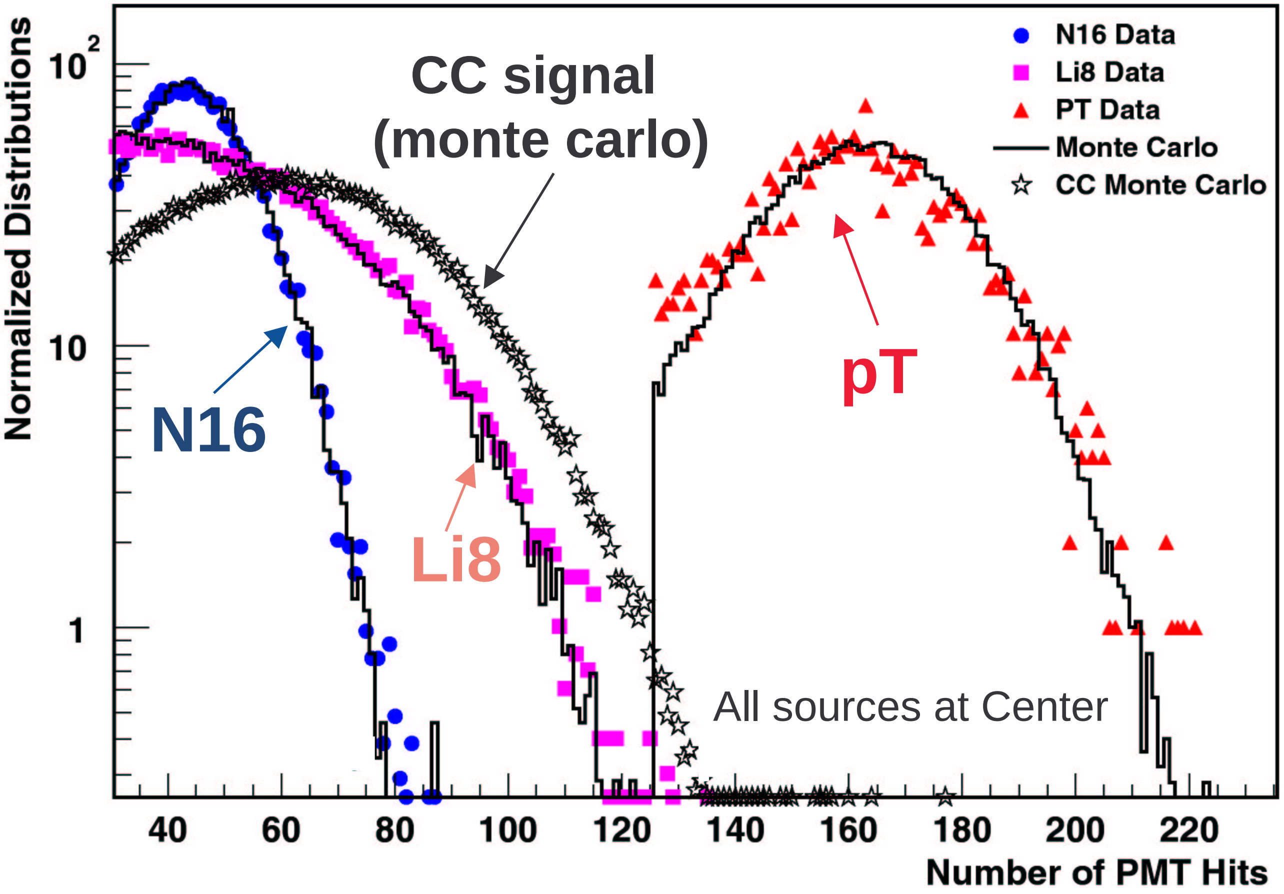
13 MeV endpoint
(n,α) on ^{11}B

(p,t)

Eγ=19.8 MeV
from ^{3}H(p,γ)^{4}He

^{252}Cf

Eγ= 6.25 MeV
from n capture
(next slide)

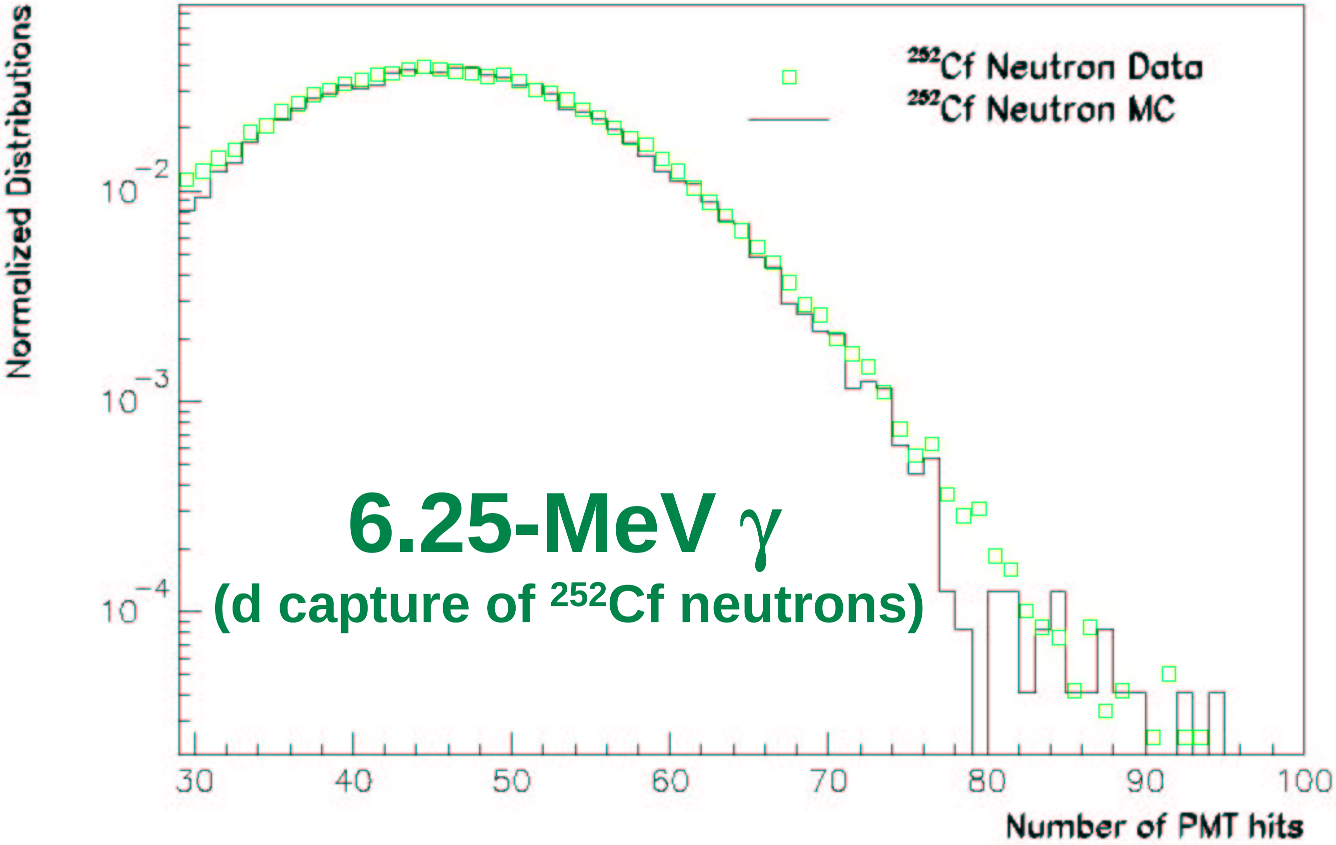


SNO Energy Response - Spatial Dependence

- various ^{16}N positions inside D_2O
- Monte-Carlo prediction tested against extended distribution of 6.25-MeV γ from ^{252}Cf neutrons

→ more difficult to analyze passive neutron source

→ tagged neutron source under development



6.25-MeV γ

(d capture of ^{252}Cf neutrons)

Event Reconstruction

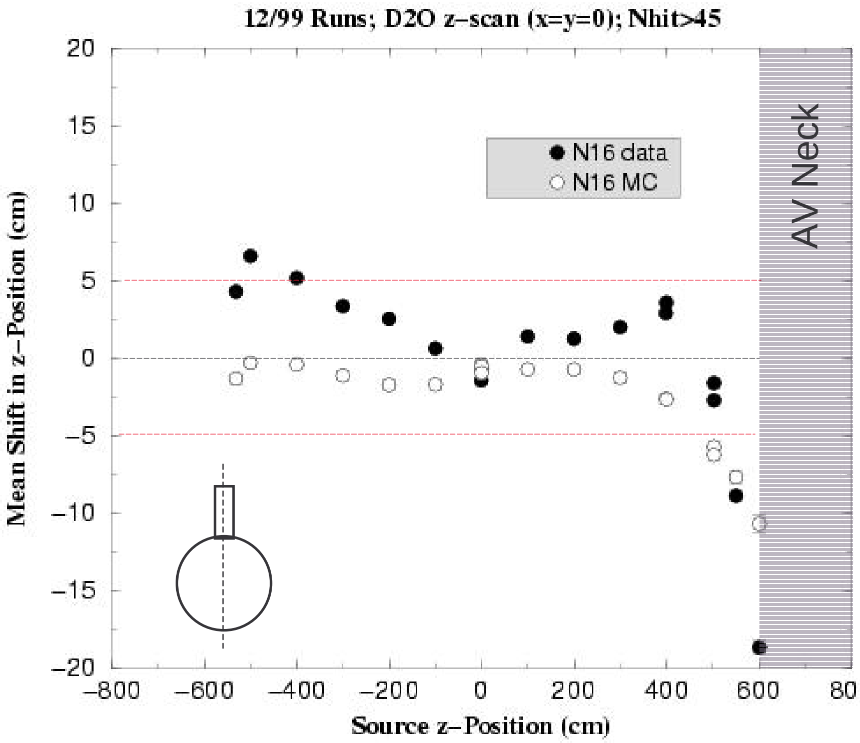
1. position resolution

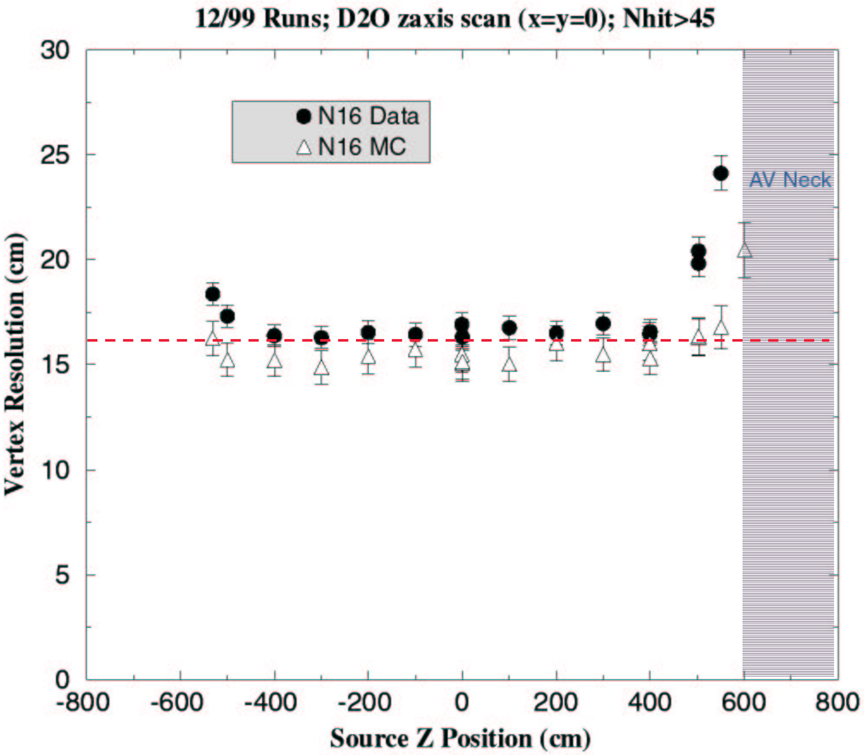
Calibration Sources **in D_2O** ^{16}N γ's and ^{8}Li β's

in H_2O ^{16}N γ's

Vertex resolution: ~ 16 cm

Vextex shift: ~ 5 cm





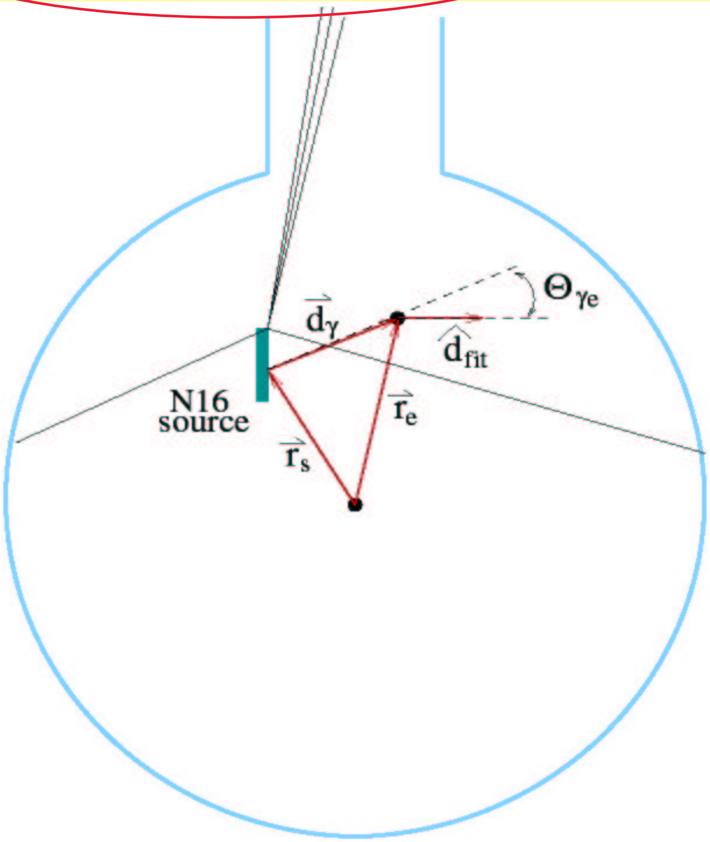
Event Reconstruction

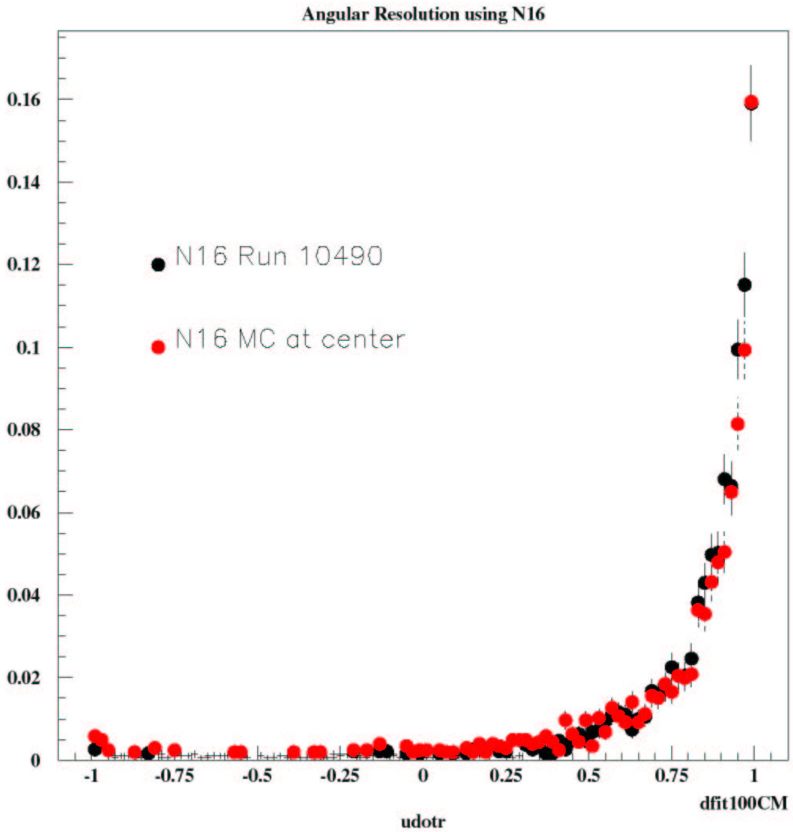
2. Angular Resolution (based on 16N γ)

Error in reconstructed event direction: $\theta_e = \vec{u}_{fit} \bullet \vec{u}_e$

Resolution function: **true angular resolution**
+ multiple scattering of e^-

Angular resolution: 26.7 º → **small effect on flux determination**





D2O & H2O Background Determination

(1) Radiochemical Assay

(2) Data stream based (low nhit events)
+ background calibration sources

Meet or lower than design target level !

D_2O Backgrounds

Target Level

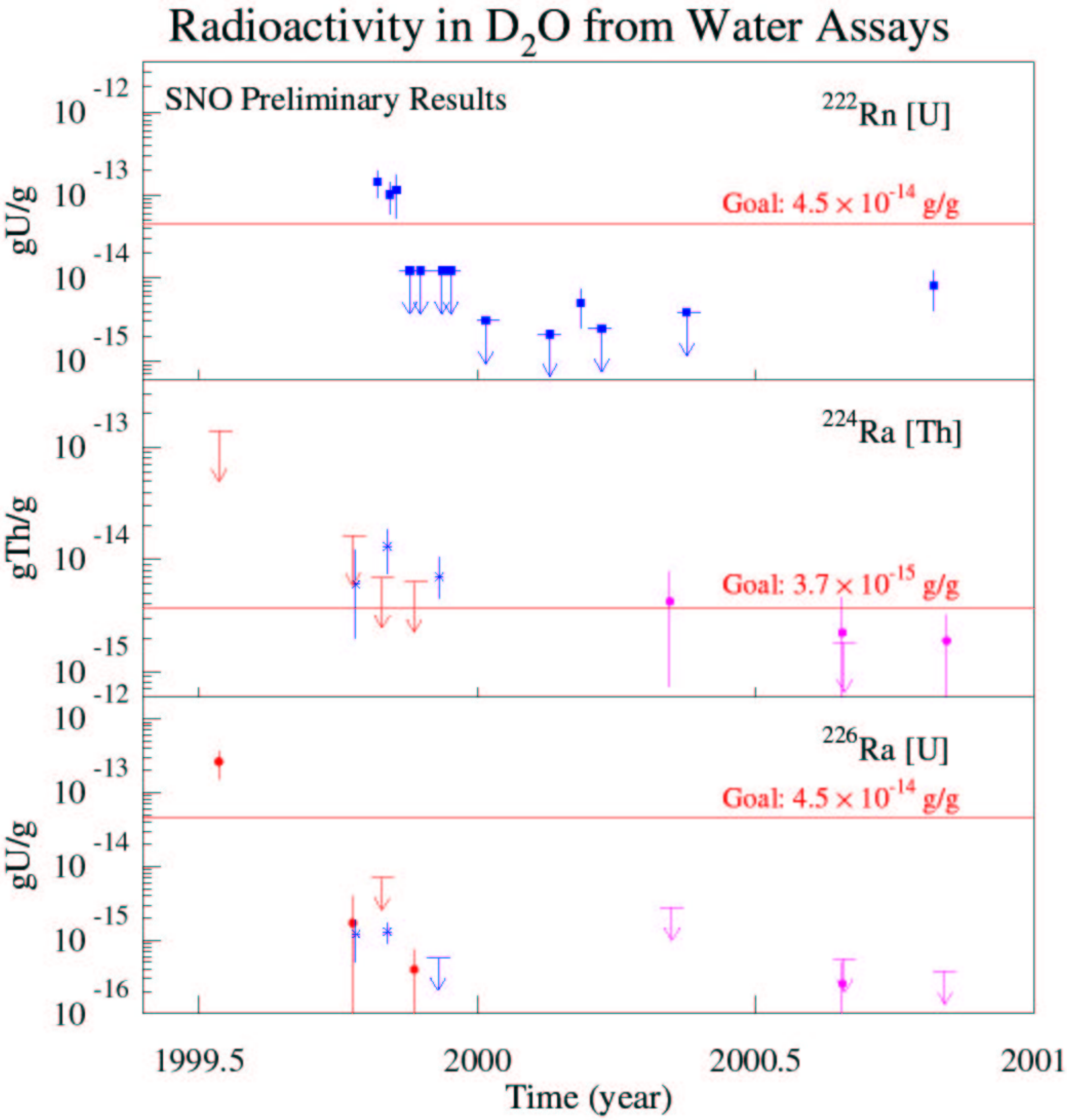
- Equivalent of 7% SSM neutrons

Measurement Techniques

- Radiochemical assays
- In-situ Cerenkov measures

Status

⇒ at or below target level



H_2O Backgrounds

Target

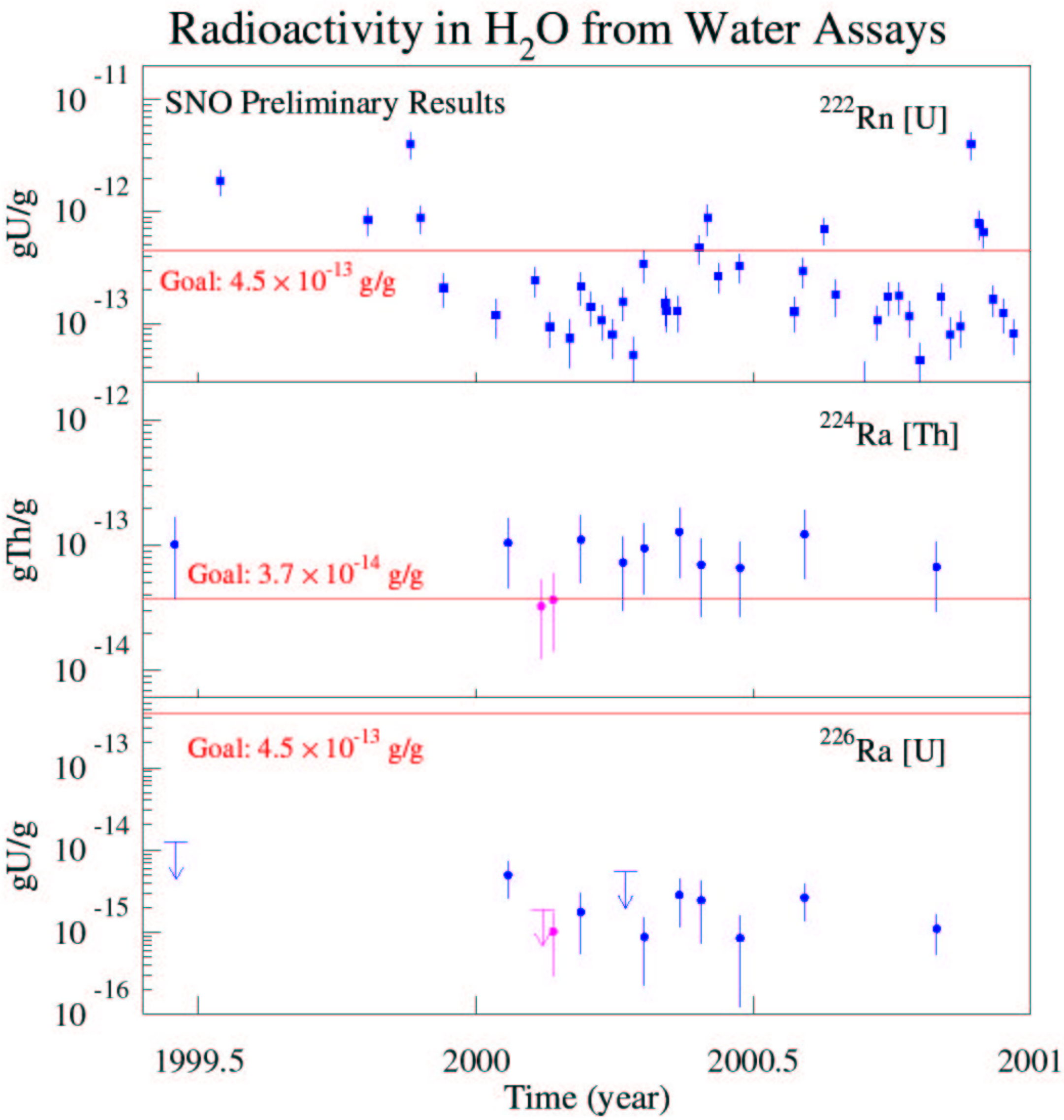
- Equivalent of 7% SSM neutrons

Measurement Technique

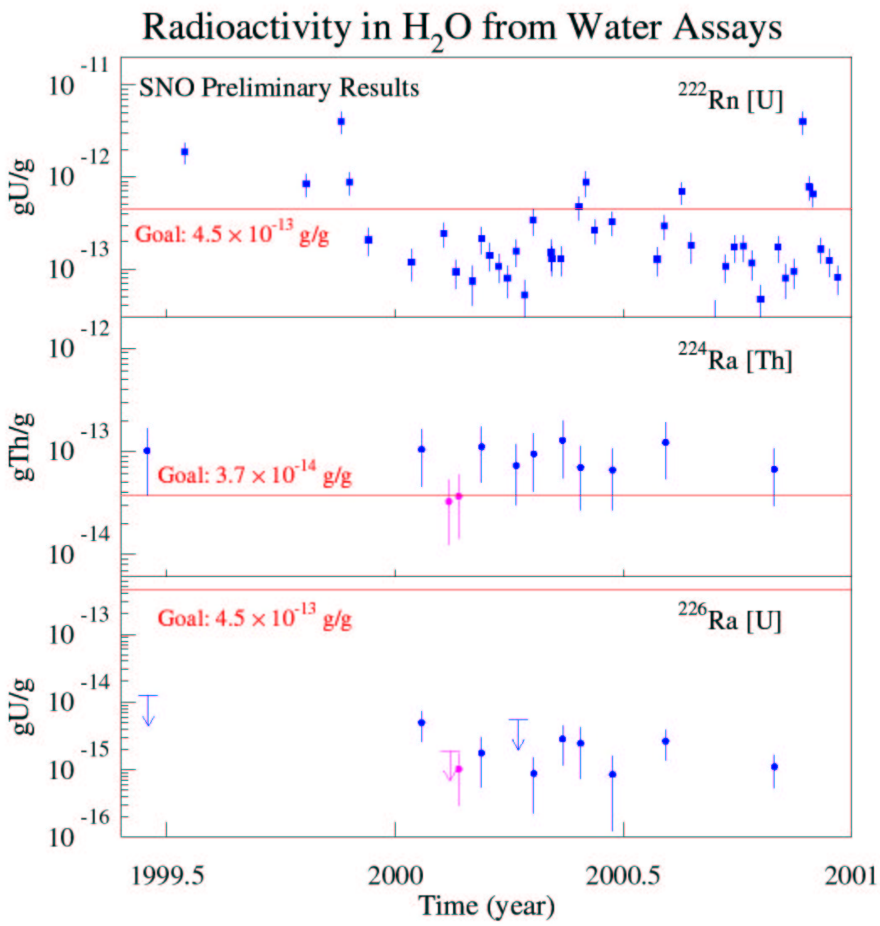
- Radiochemical assay
- Encapsulated sources
- High radon runs

Status

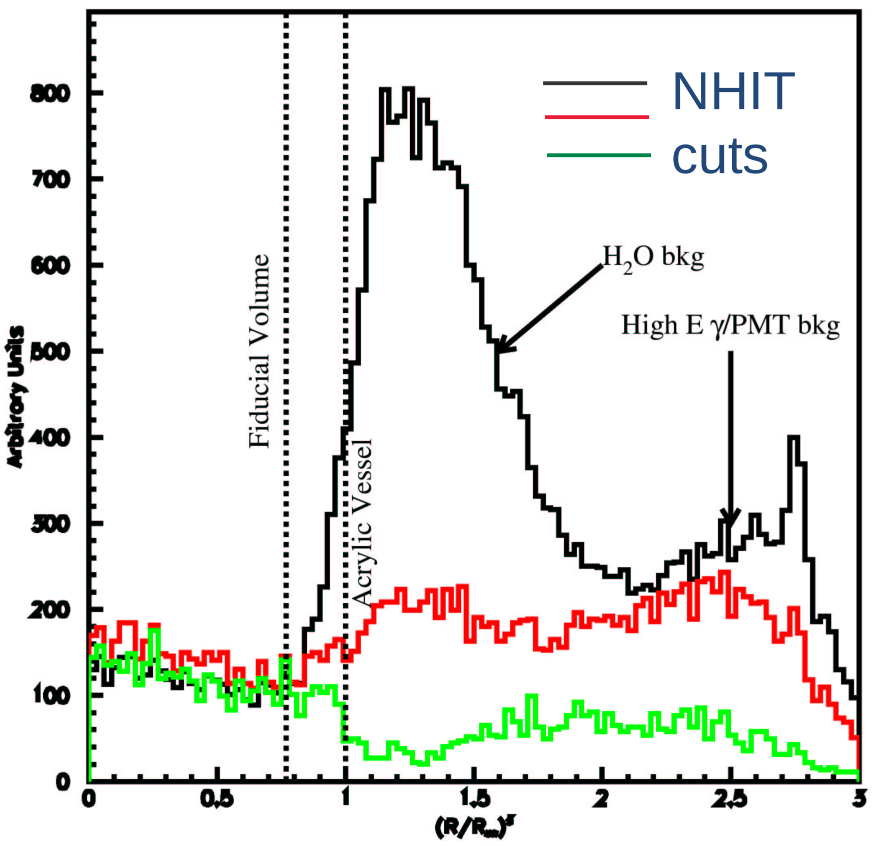
⇒ near or below target levels



H_2O and PMT Backgrounds



AV



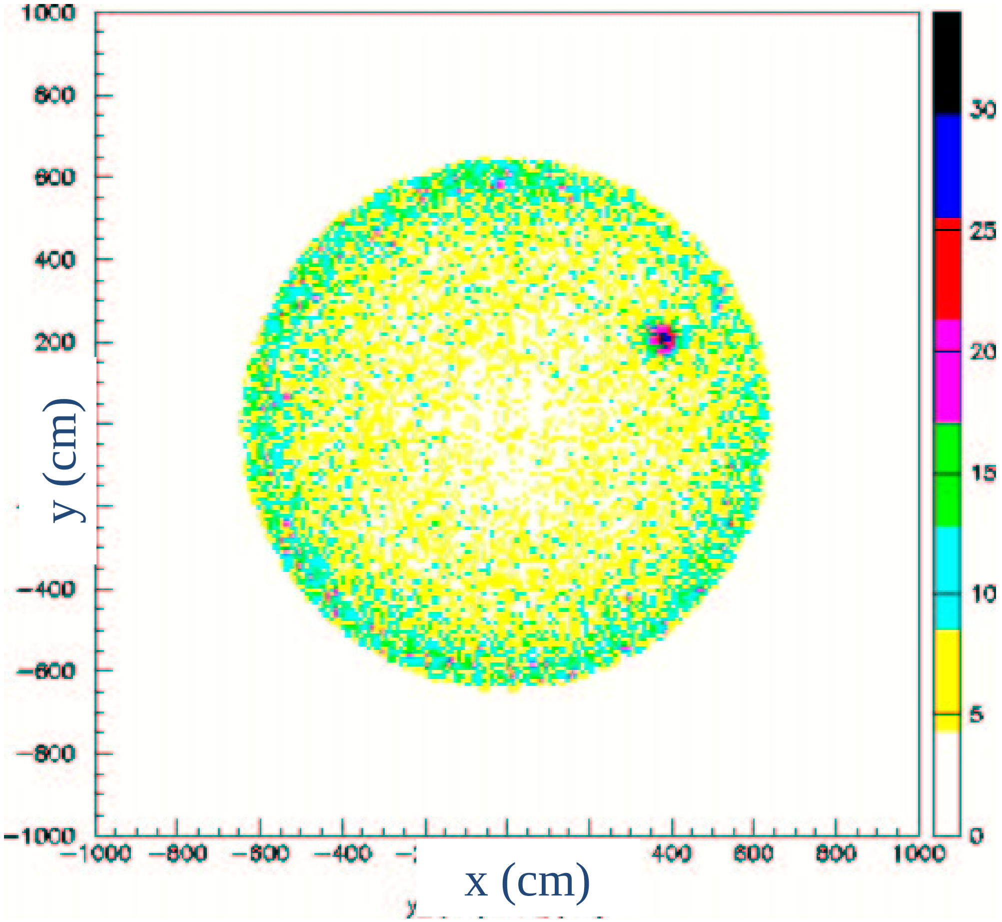
Radioassay and *in situ* Cerenkov Measurements

Acrylic Vessel Backgrounds

Activities assayed are
<10% Targets ~0.2 ppt

Or ~ 6 µg Th or U

Original Target was
60 µg Th or U



F “Berkeley Blob”

$$= 9^{+20}_{-5} \pm 3 \mu g' \, Th'$$

Data Analysis

Data cleaning cuts

High level cuts

Characteristic distributions

- PDF’s (Monte Carlo)

Signal extraction

Systematics

Rate & Flux calculation

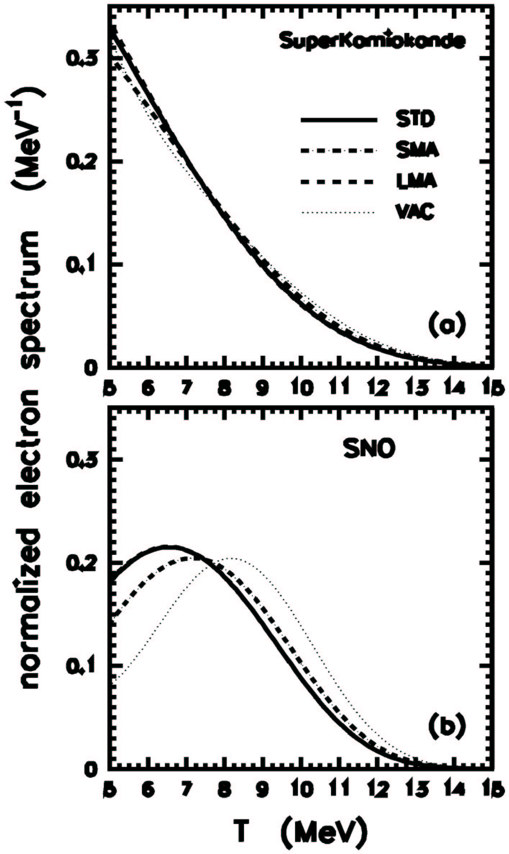
“Smoking-gun” Signals

- NC-CC, CC/NC ratio

  (No conversion→ CC=NC)
- CC, ES spectral distortion
- ES – CC

  (No conversion → ES = CC)
- Day/Night rate difference

  (MSW earth matter effect)
- Seasonal difference



ES

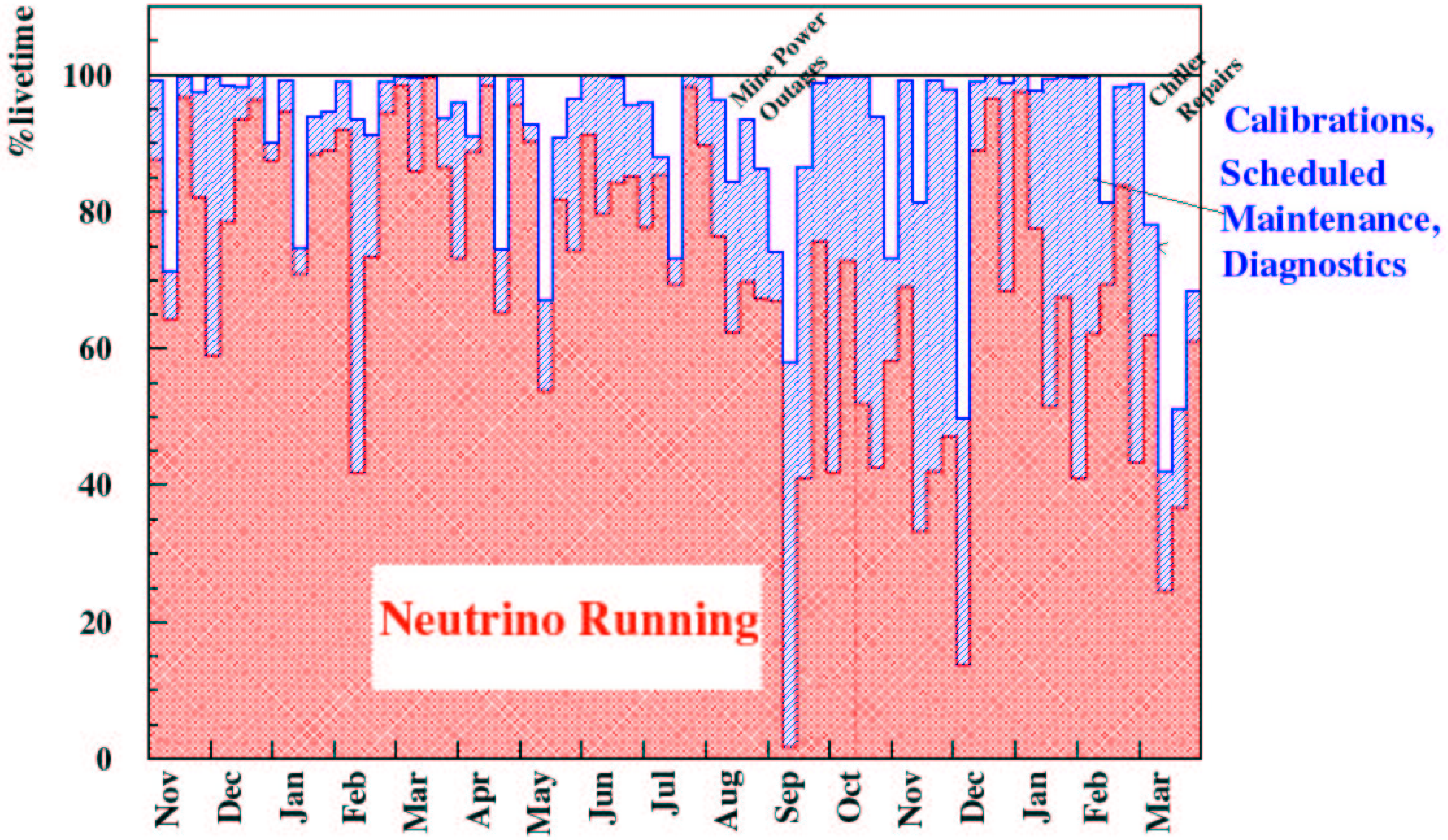
CC

Bahcall *et al.*

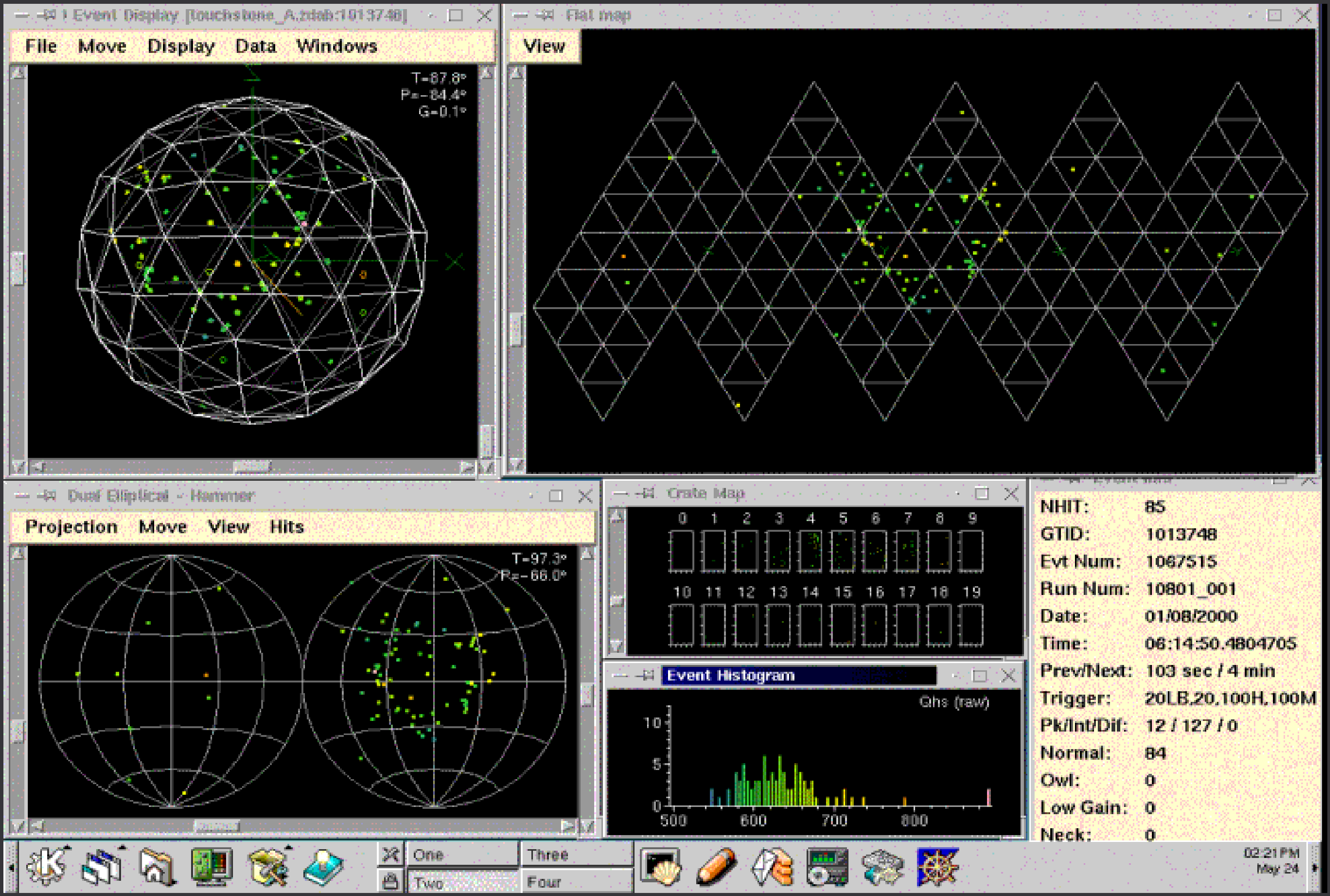
Data Taking and Live Time

Nov 2, 1999 → Jan 15, 2001

240.9 live days neutrino runtime



Neutrino Event



NHIT: 85
GTID: 1013748
Evt Num: 1067515
Run Num: 10801_001
Date: 01/08/2000
Time: 08:14:50.4804705
Prev/Next: 103 sec / 4 min
Trigger: 20LB,20,100H,100M
Pk/Int/Dif: 12 / 127 / 0
Normal: 84
Owl: 0
Low Gain: 0
Neck: 0

Detector Performance

Trigger Rates and Thresholds in 2001

Trigger Type	Hardware Threshold	Rate (Hz)
Pulsed Trigger	Zero Bias	5
100 ns Coincidence	16 PMTs	8
20ns Coincidence	16 PMTS	0.02
Energy sum	~150 p.e.	4
Prescaled (1:1000)	11 PMTs	0.1

Channel threshold:	~ 0.25 photo-electrons
Multiplicity trigger:	18 Nhit within 93 ns
Trigger efficiency:	100% efficiency by 25 Nhit (~3 MeV)

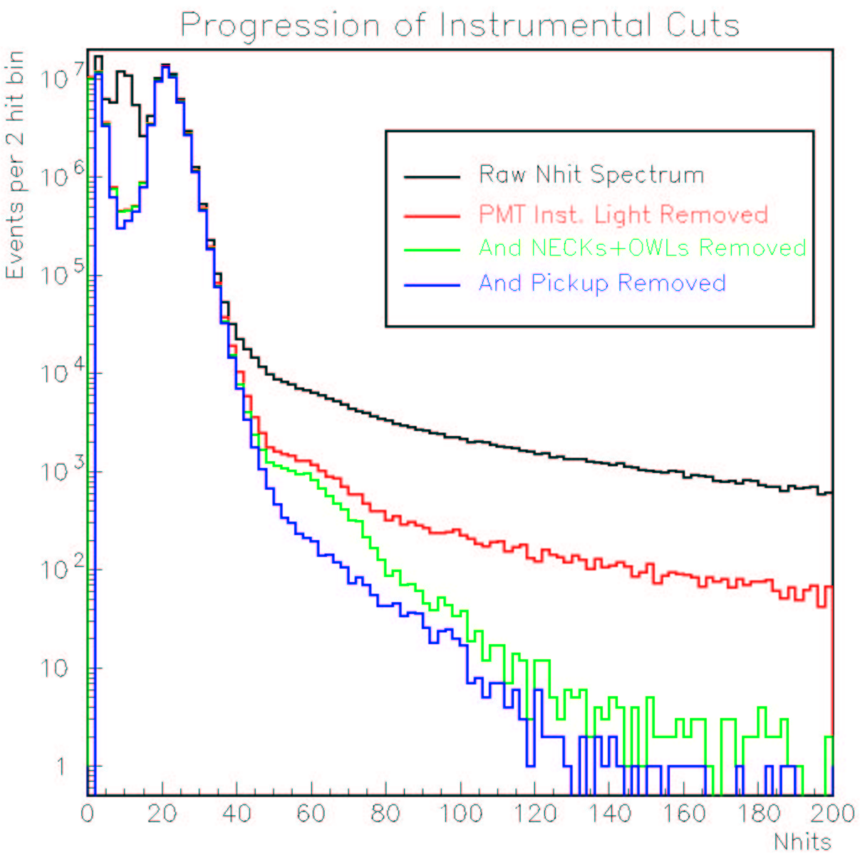
Instantaneous Trigger Rate	~ 15-18 Hz
Data Trigger Rate	~ 6-8 Hz
Hardware Threshold	~ 2 MeV

Data Flow & Instrumental Background Cuts

Data Flow

Analysis Step	**Events**
Total Event Triggers	355,320,964
Neutrino Data Triggers	143,756,178
Nhit≥30	6,372,899
Instrumental Background	1,842,491
Muon Followers	1,809,979
High Level Cuts	956,535
Fiducial Volume Cut	18,783
Threshold Cut,T_{eff}≥6.75 MeV	1169

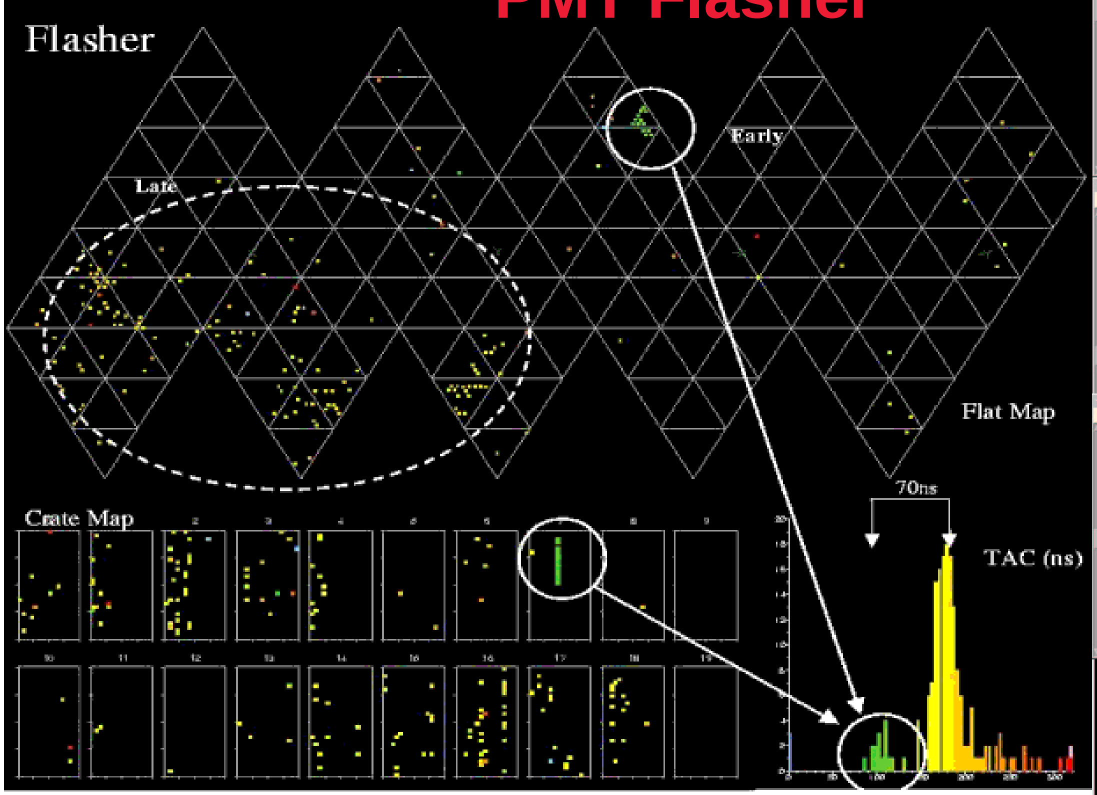
Total Events
In Final Data Set **1169**



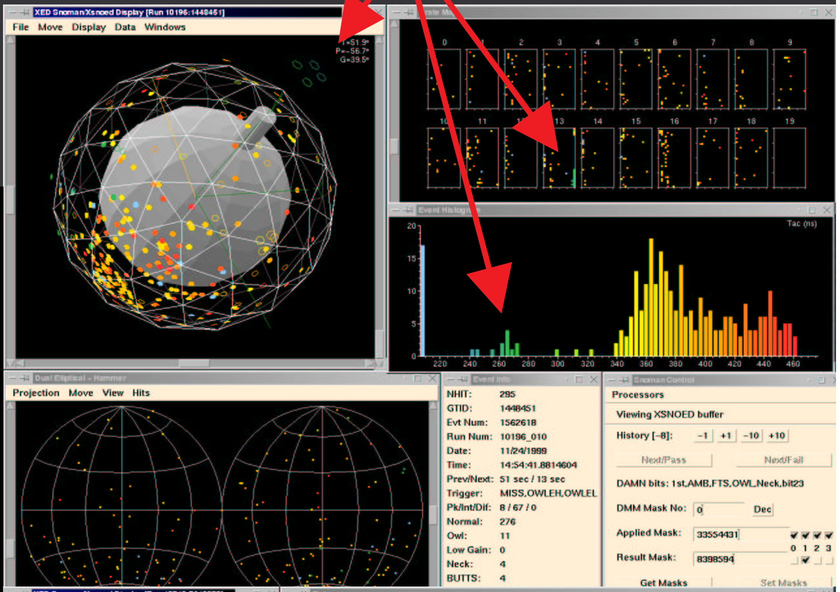
High Level Cuts: Reconstruction figures of merit
In-time light
Event isotropy (θ_{ij})

Instrumental Backgrounds

PMT Flasher



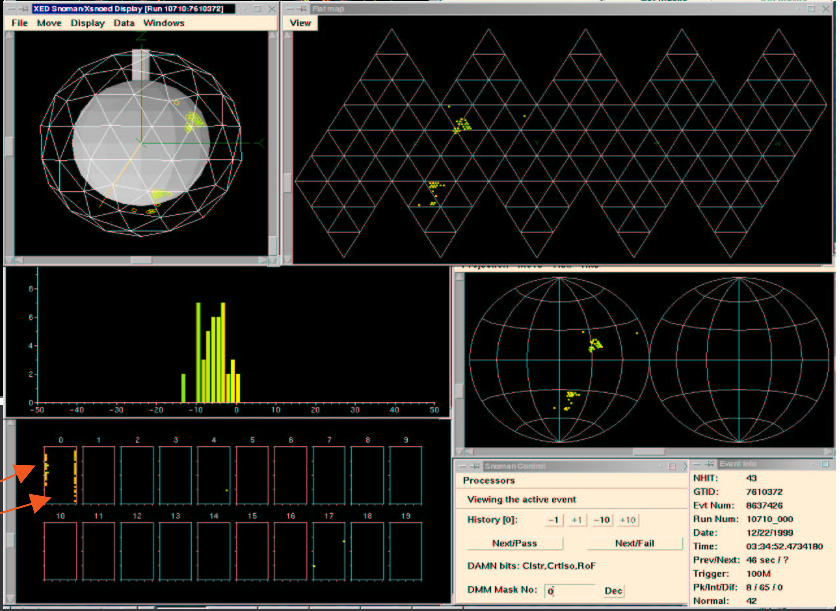
Neck Tubes Fired



NHIT: 295
GTID: 1448451
Evt Num: 1562618
Run Num: 10196_010
Date: 11/24/1999
Time: 14:54:41.8814604
Prev/Next: 51 sec / 13 sec
Trigger: MISS,OWLEH,OWLEL
Pk/Int/Dif: 8 / 67 / 0
Normal: 276
Owl: 11
Low Gain: 0
Neck: 4
BUTTS: 4

Processors
Viewing XSNOED buffer
History [-8]: -1 +1 -10 +10
Next/Pass Next/Fail
DAMN bits: 1st,AMB,FTS,OWL,Neck,bit23
DMM Mask No: 0 Dec
Applied Mask: 33554431 ☑ 0 ☑ 1 ☑ 2 ☑ 3
Result Mask: 8398594 ☐ ☑ ☐ ☐
Get Masks Set Masks

Electronic Pickup

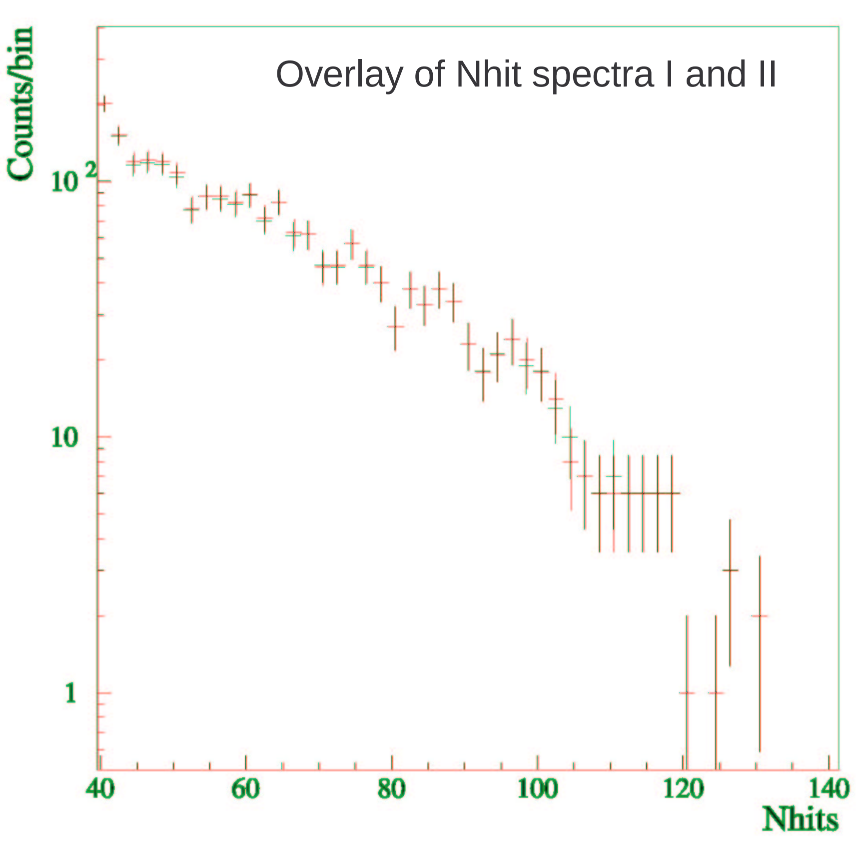


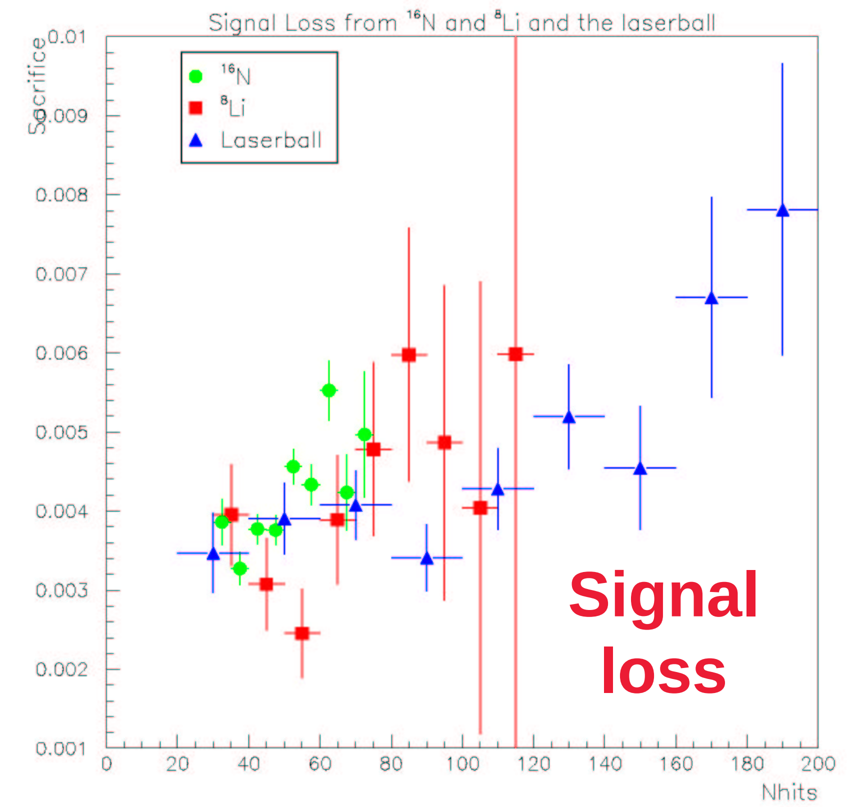
Processors
Viewing the active event
History [0]: -1 +1 -10 +10
Next/Pass Next/Fail
DAMN bits: Clstr,CrtIso,RoF
DMM Mask No: 0 Dec

NHIT: 43
GTID: 7610372
Evt Num: 8637426
Run Num: 10710_000
Date: 12/22/1999
Time: 03:34:52.4734180
Prev/Next: 46 sec / ?
Trigger: 100M
Pk/Int/Dif: 8 / 65 / 0
Normal: 42

Removal of Instrumental Background

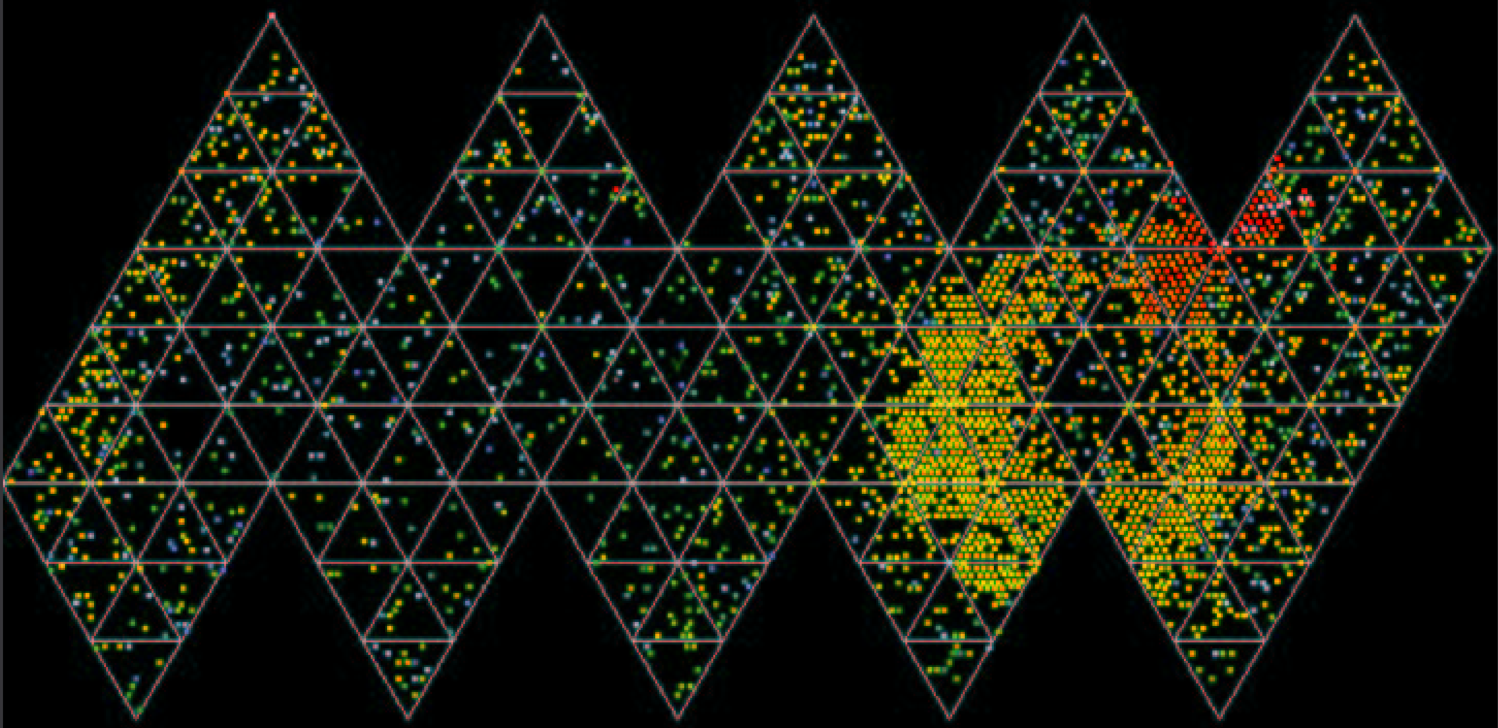
Instrumental removal: **Two independent methods**
Signal loss: **0.4±0.3%**within $R_{fit} \leq 550$ cm from ^{16}N, ^{8}Li, and the laser ball
Contamination: limits from bifurcated analyses and hand-scanning





Signal loss

Muon follower cut (2s)



A muon event in PSUP event display

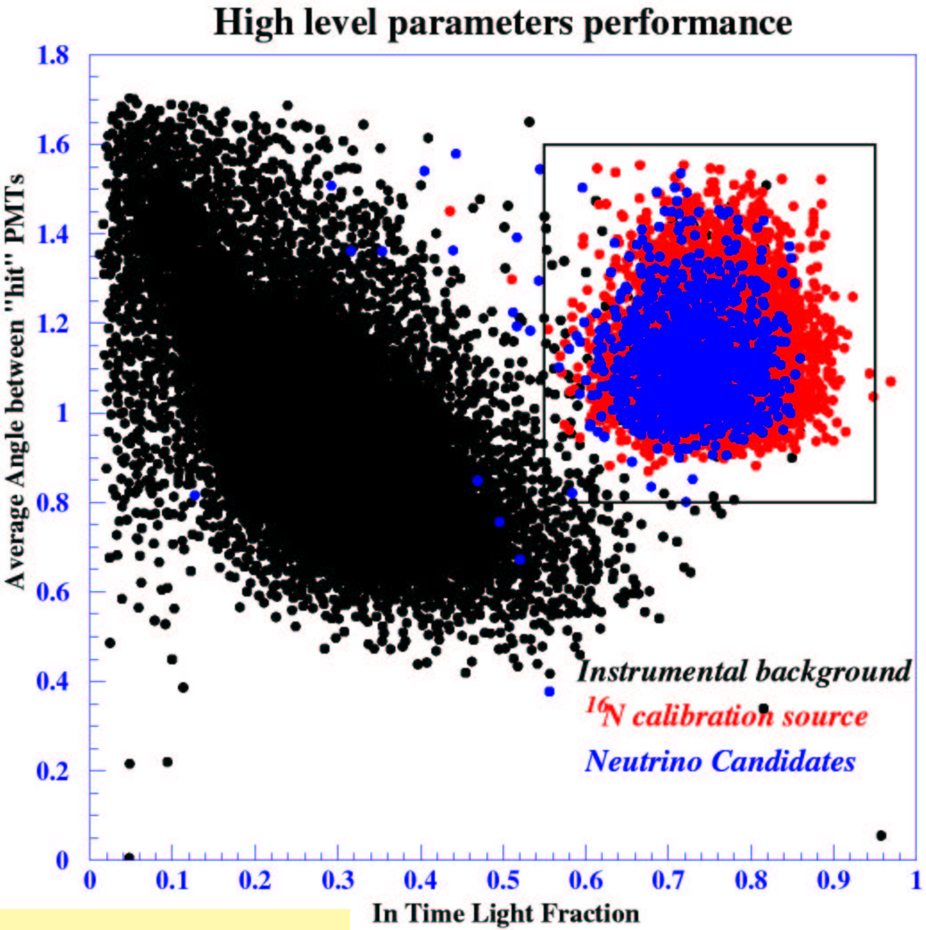
High Level Data Cuts

- **Reconstruction Figures of Merit**

- **In-Time Light Fraction**
→ uses detailed PMT time distributions

- **Event Isotropy**
→ Average angle between hit PMTs

Event Isotropy
- Tests hypothesis of single-particle origin for each event
- Discriminates between simple Cerenkov electron and multiple vertices



From triggered ^{16}N, ^{8}Li, and bifurcated analyses

Volume-weighted signal loss: 1.4 +0.7/-0.6%

Residual instrumental contamination: < 0.2%

Results …

(1) $\cos\Theta_{sun}$

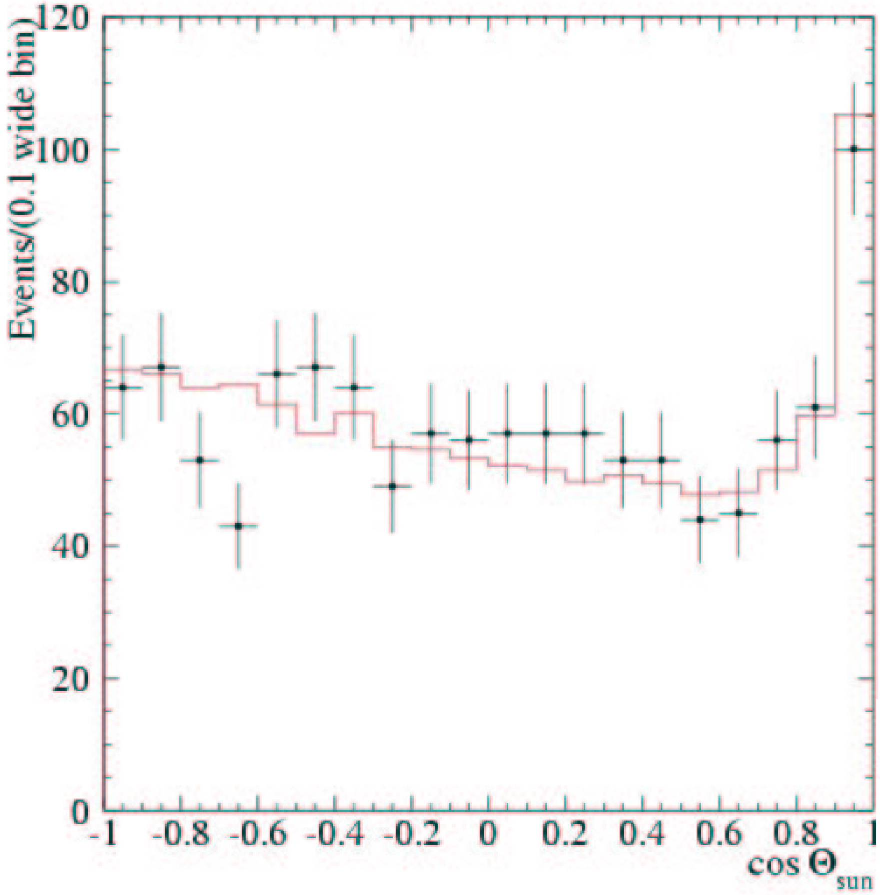
(2) energy

(3) $(R/R_{av})^3$

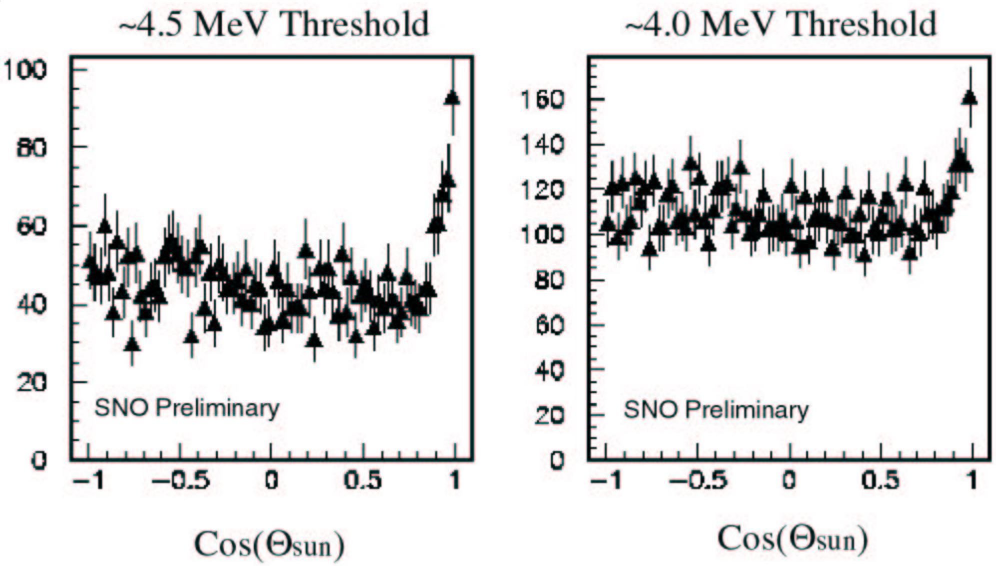
Measurement of the rate of $\nu_e + d \rightarrow p + p + e^-$ interactions produced by ^8B solar neutrinos at the Sudbury Neutrino Observatory

Phys. Rev. Lett. 87 (071307-1)   Nucl-ex/0106015

Results

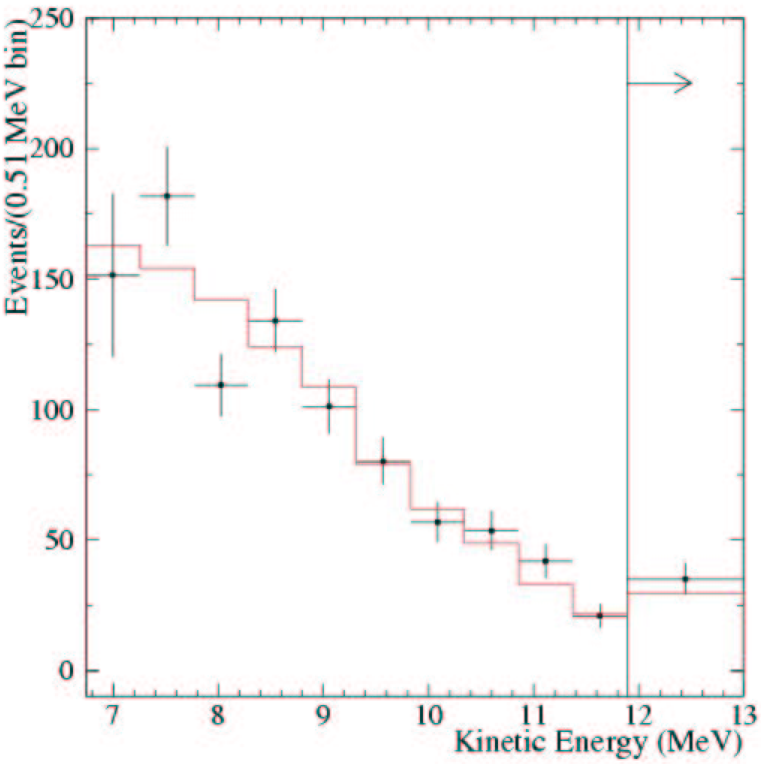


Direction of Events with respect to the SUN

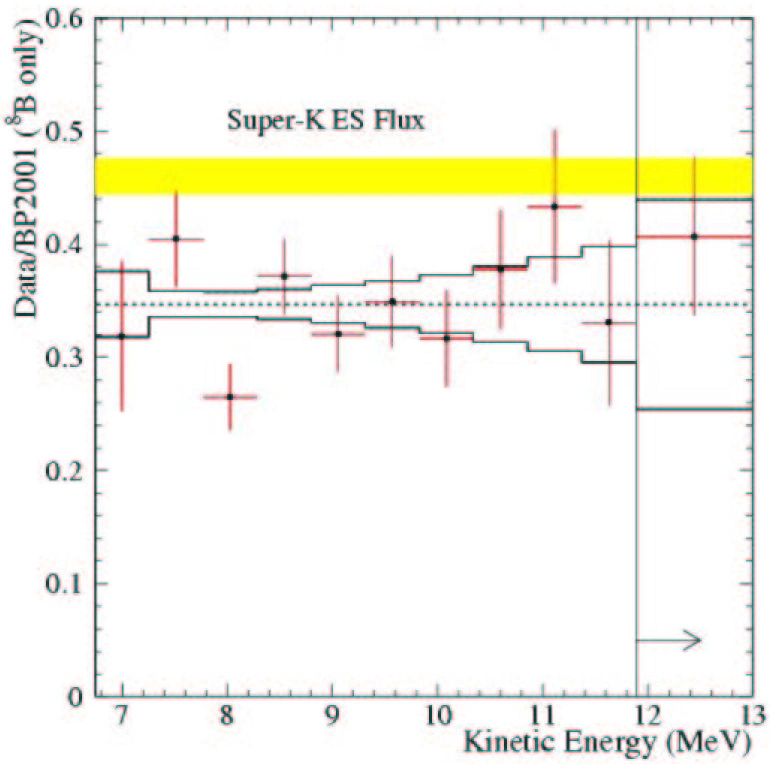


E>=6.75 MeV threshold
R<550cm

Charged Current Energy Spectrum



CC spectrum derived from fit *without* constraint on shape of ^{8}B spectrum

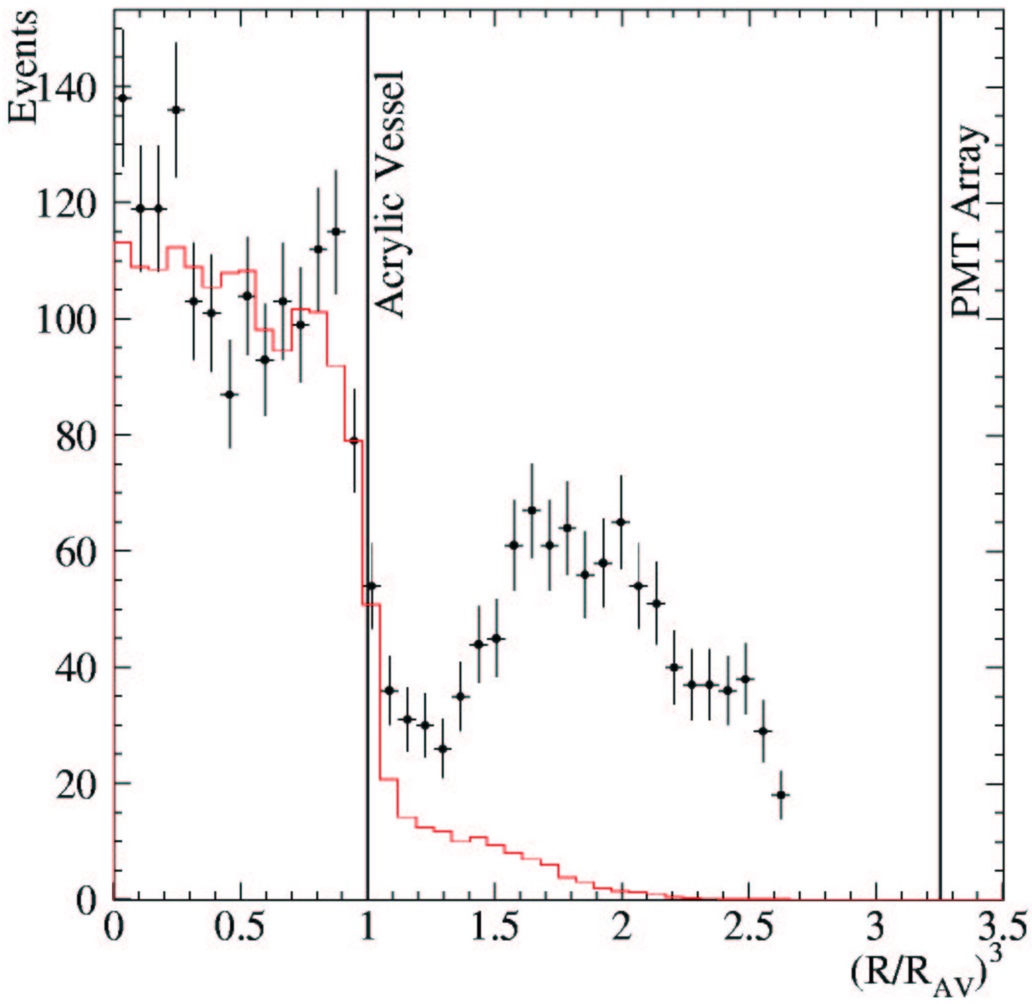


CC spectrum normalized to predicted ^{8}B spectrum.

➥ no evidence for shape distortion.

Volume-weighed radial distribution

Results



Signal Extraction

Extended Maximum-Likelihood Fit to Characteristic Distributions

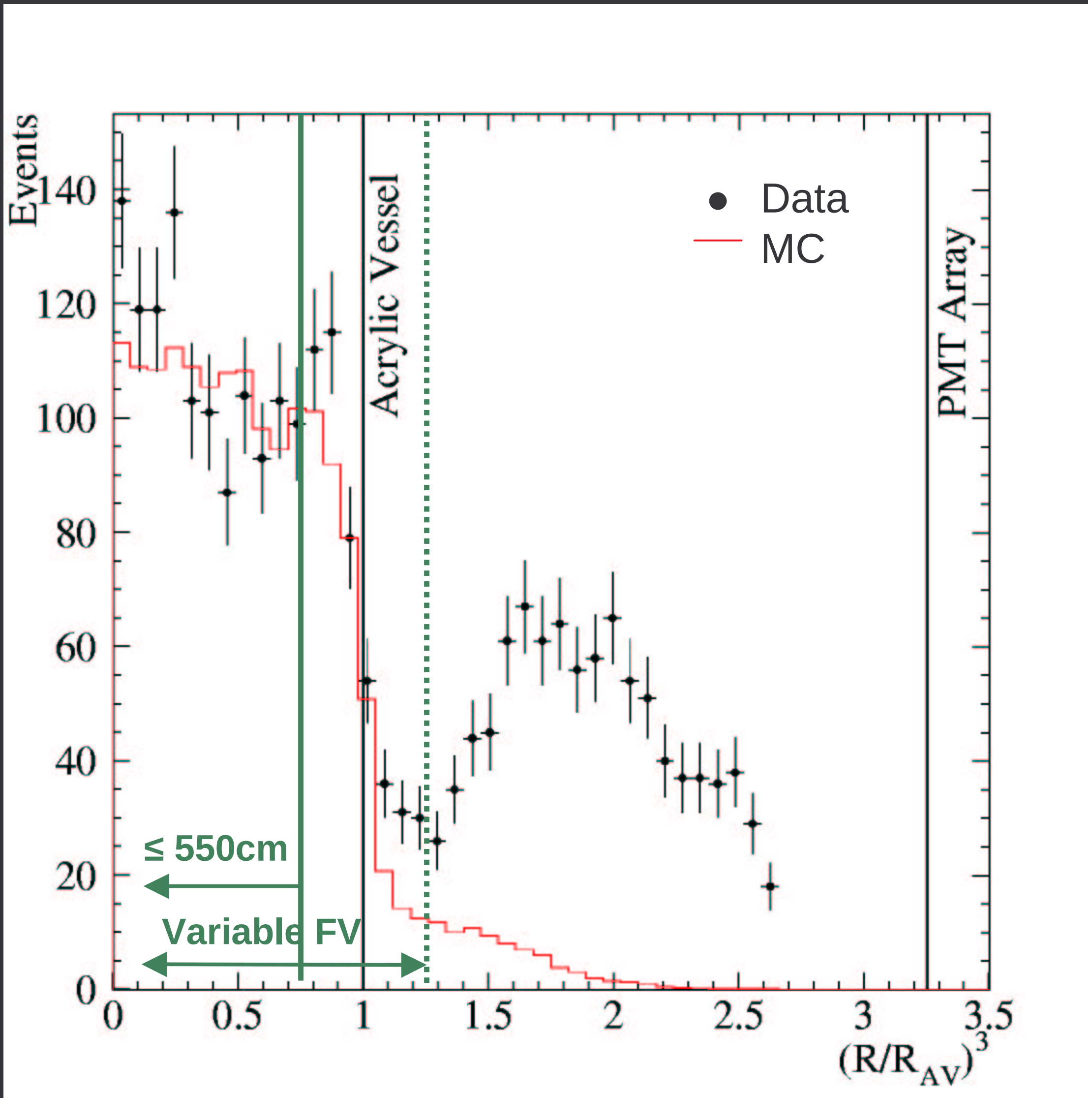
- **R^3**
- **$\cos(\theta_{Sun})$**
- **Neutron Energy Response**

Energy Estimators

- **T_{eff}**
- *or Nhit*

Fiducial Volume

- **$R_{fit} \leq 550$ cm**
- *or variable FV $R \leq 650$ cm*



Signal Extraction

- **Variable Fiducial Volume (6.5 m) and Energy Thresholds**

  Fit CC, ES, Neutrons, Bckgrds PDFs

  Functions (R^3, $\cos\Theta_{sun}$, T)

  Extended Maximum Likelihood

- **“Background Free” Analysis**

  R < 550cm, T > 6.75 MeV

  Lower Systematic Errors

  Fit CC, ES, Neutrons PDFs

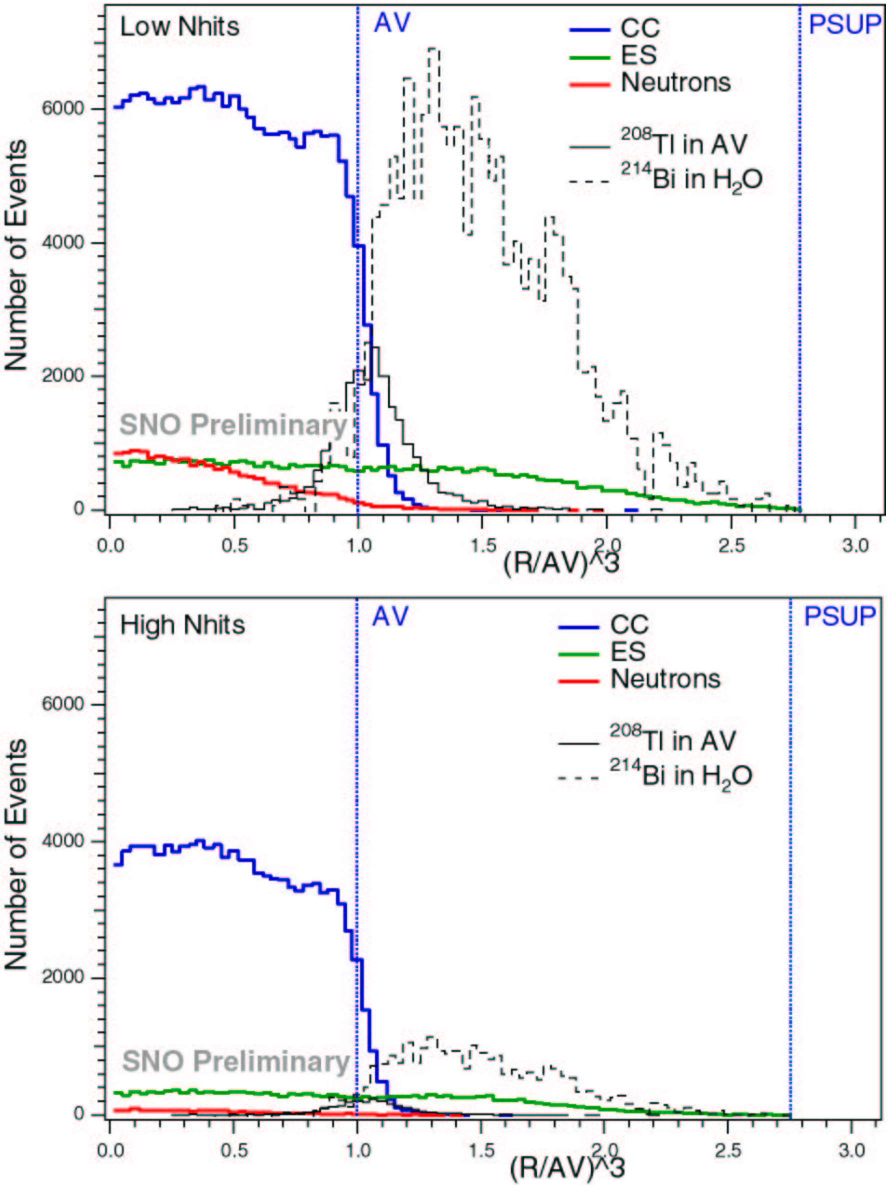
  Functions (R^3, $\cos\Theta_{sun}$, T)

  Extended Maximum Likelihood

Consistent Results

Signal and Background PDFs - Monte Carlo

- Monte-Carlo for period of data taking
- 1st and 2nd Pass Filters



Experimental Systematic Errors on Fluxes

Error Source	**CC Error** (%)	**ES Error** (%)
Energy Scale	+6.1/-5.2	+5.4/-3.5
Energy Resolution	±0.5	±0.3
Energy Scale Non-Linearity	±0.5	±0.4
Vertex Shift	±3.1	±3.3
Vertex Resolution	±0.7	±0.4
Angular Resolution	±0.5	±2.2
Live Time	±0.1	±0.1
Trigger Efficiency	0.0	0.0
Cut Acceptance	+0.7/-0.6	+0.7/-0.6
Residual Backgrounds ($R_{fit} \leq 550$ cm)		
Instrumental Background	±0.1	-0.6/+0.0
High Energy γ's	-0.8/+0.0	-1.9/+0.0
Low Energy Background	-0.2/+0.0	-0.2/+0.0
Experimental Uncertainty	**+7.0/-6.2**	**+6.8/-5.7**
Cross Section	**3.0**	**0.5**

First Solar Neutrino Results from SNO (see PRL paper)

Solar Angle Distribution

$T_{eff} \geq 6.75$ MeV and $R_{fit} \leq 550$ cm

Energy Spectrum

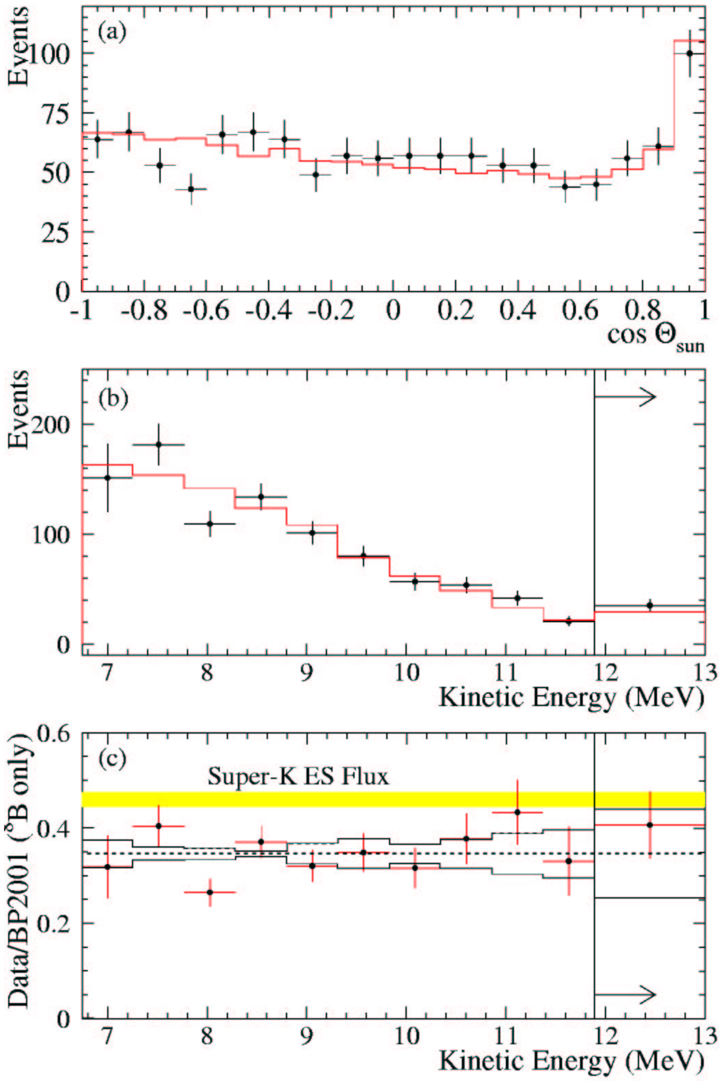
$T_{eff} \geq 6.75$ MeV and $R_{fit} \leq 550$ cm

derived from fit without constraint on ^8B shape

CC Spectrum Normalized to Predicted ^8B Spectrum

$T_{eff} \geq 6.75$ MeV and $R_{fit} \leq 550$ cm

With correlated systematic errors



Result for Solar Neutrino Fluxes

241 day Data from SNO

$\Phi^{CC}_{SNO}(^8B)$ = **1.75** ± 0.07 (stat.) +0.12/-0.11 (sys.) ± 0.05 (theor.) $\times 10^6$ cm^{-2} s^{-1}
$\Phi^{ES}_{SNO}(^8B)$ = **2.39** ± 0.34 (stat.) +0.16/-0.14 (sys.) $\times 10^6$ cm^{-2} s^{-1}

→ assuming ^{8}B spectral shape, $T_{eff} < 6.75$ MeV
→ radiative corrections are not applied yet, will only decrease CC flux

CC Flux Relative to BPB2001

$R^{CC}(^8B)$ = **0.347** ± 0.029

Total ^{8}B Flux from the Sun

$\phi_{SNO}(^8B)$ = **5.44 ± 0.99** $\times 10^6$ cm^{-2} s^{-1} (with SK)
$\phi_{SSM}(^8B)$ = **5.01 +1.01/-0.82** $\times 10^6$ cm^{-2} s^{-1} (BP2001)

⇒ good agreement with SSM and CC is only a component of total ^{8}B flux

SNO + SuperKamiokande

***Comparison of ES_{SNO} and ES_{SK}**

Φ^{ES}_{SNO} **(^{8}B) = 2.39** ± 0.34 (stat.) +0.16/-0.14 (sys.) x10^{6} cm^{-2} s^{-1}
Φ^{ES}_{SK} **(^{8}B) = 2.32** ± 0.03 (stat.) +0.08/-0.07 (sys.) x10^{6} cm^{-2} s^{-1}

→ **good agreement**

SNO CC_{SNO} versus SuperKamiokande ES_{SK} (equal if all ν_e)

Φ^{CC}_{SNO} **(^{8}B) = 1.75** ± 0.07 (stat.) +0.12/-0.11 (sys.) ± 0.05 (theor.) x10^{6} cm^{-2} s^{-1}
Φ^{ES}_{SK} **(^{8}B) = 2.32** ± 0.03 (stat.) +0.08/-0.07 (sys.) x10^{6} cm^{-2} s^{-1}

$$\rightarrow \Phi^{ES}_{SK}(^{8}B) - \Phi^{CC}_{SNO}(^{8}B) = 0.57 \pm 0.17 \Rightarrow 3.3\ \sigma$$

(Probability of a downward fluctuation at least this great is: 0.13%)

*S. Fukuda, et al., hep-ex/0103032

Determining the non-electron flavor active neutrino content of the ^{8}B flux

Flavor content analysis of ^{8}B solar neutrino flux from: ϕ^{SK}_{ES}, ϕ^{SNO}_{CC}

$\phi_{CC} = \phi_e$

$\phi_{ES} = \phi_e + \varepsilon\, \phi_{\mu,\tau}$

ϕ^{SNO}_{CC} **= 1.75 ± 0.13**

ϕ^{SK}_{ES} **= 2.32 ± 0.09**

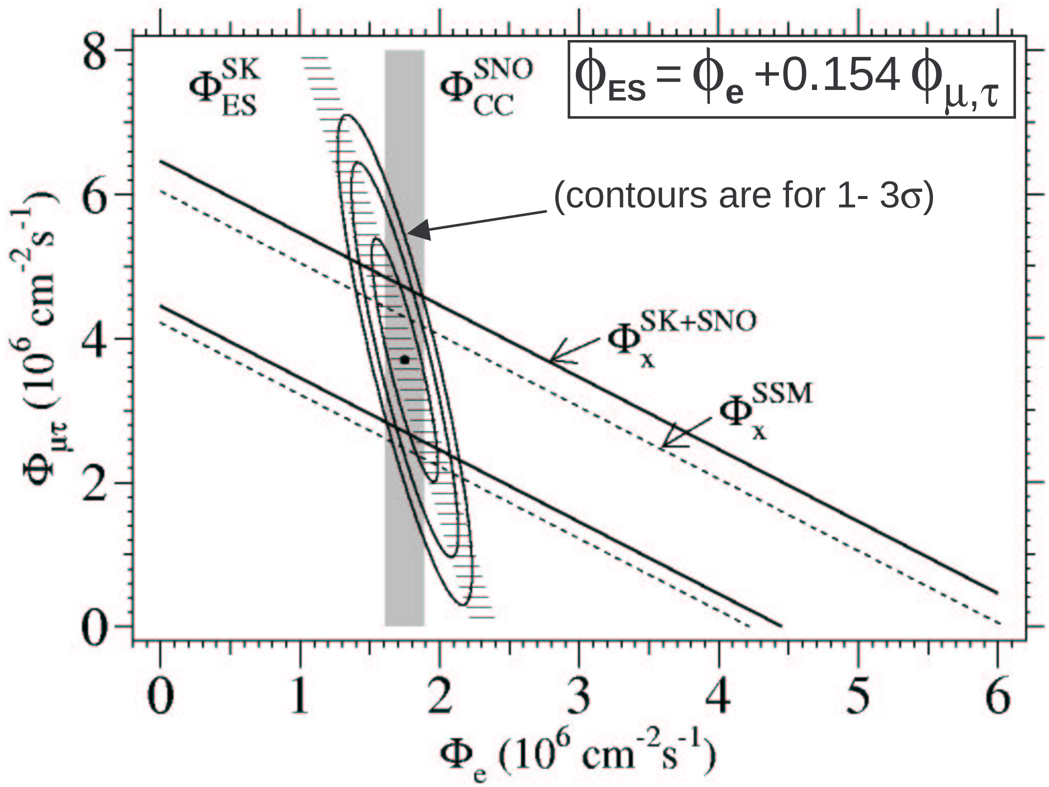
Total active neutrino flux:

$\phi_x = \phi_e + \phi_{\mu,\tau}$

$= \phi_{CC} + (\phi_{ES} - \phi_{CC})/\varepsilon$

ϕ_e = 1.75 ± 0.13

$\boxed{\phi_{\mu,\tau} = 3.69 \pm 1.13}$ appearance!



$\boxed{\phi_{ES} = \phi_e + 0.154\, \phi_{\mu,\tau}}$

(contours are for 1- 3σ)

⇒ Evidence for ‘active’ flavor transformation: $\nu_e \rightarrow \nu_{\mu\tau}$

What About Sterile Neutrinos?

Comparing the Response of SNO and SK

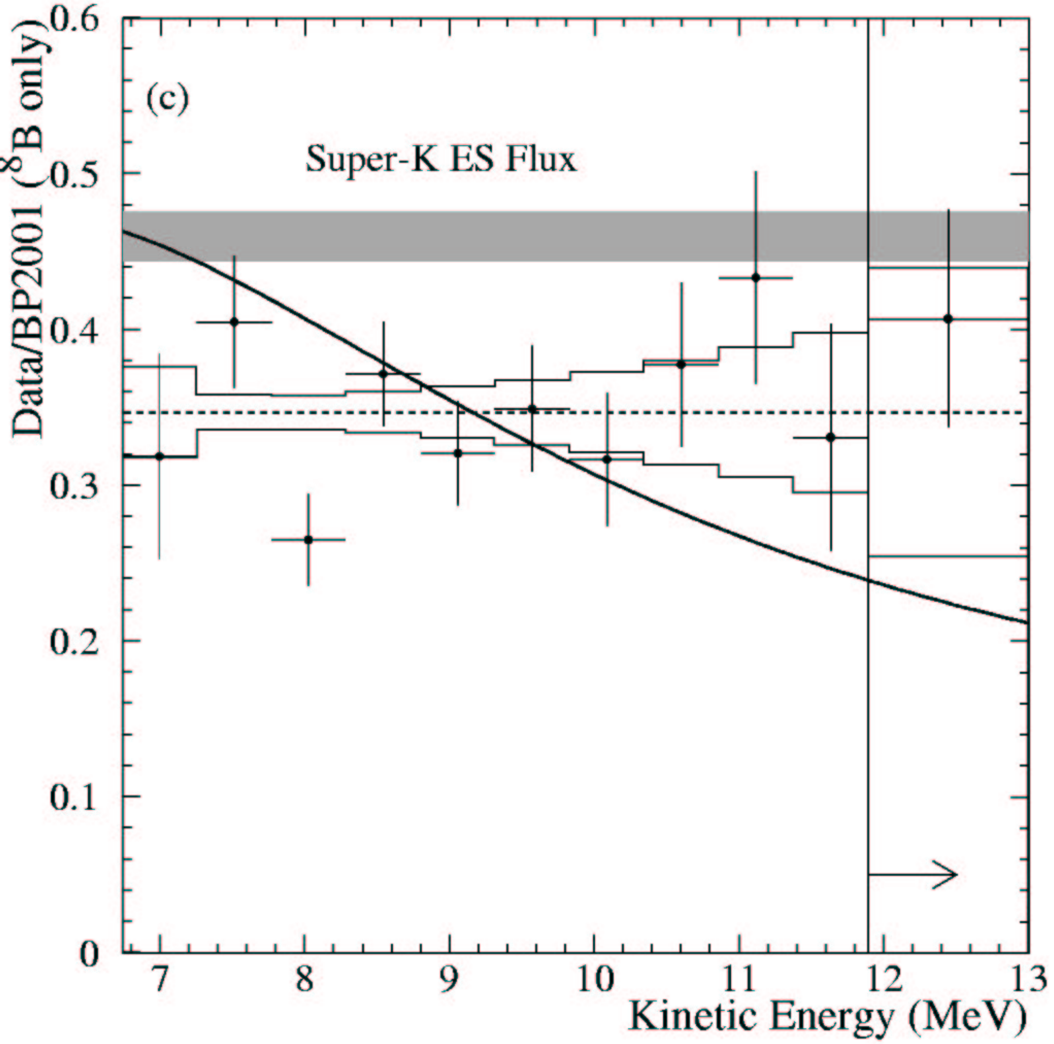
Ref: Fogli, Lisi, et al, hep-ph/0102288,
Villante et al., hep-ph/9807360

→ normalized rates over paired spectral regions are linearly related

SK Flux	**SNO Flux**
> 8.5 MeV	**> 6.75 MeV**

SK^{8B} (ES, >8.5) - SNO^{8B} (CC, >6.75) = 0.54 ± 0.17

⇒oscillations to sterile only excluded at 3.1 σ



Now: Salt Phase II

Next: NCD III

Now in Salt Phase II: NC enhanced mode

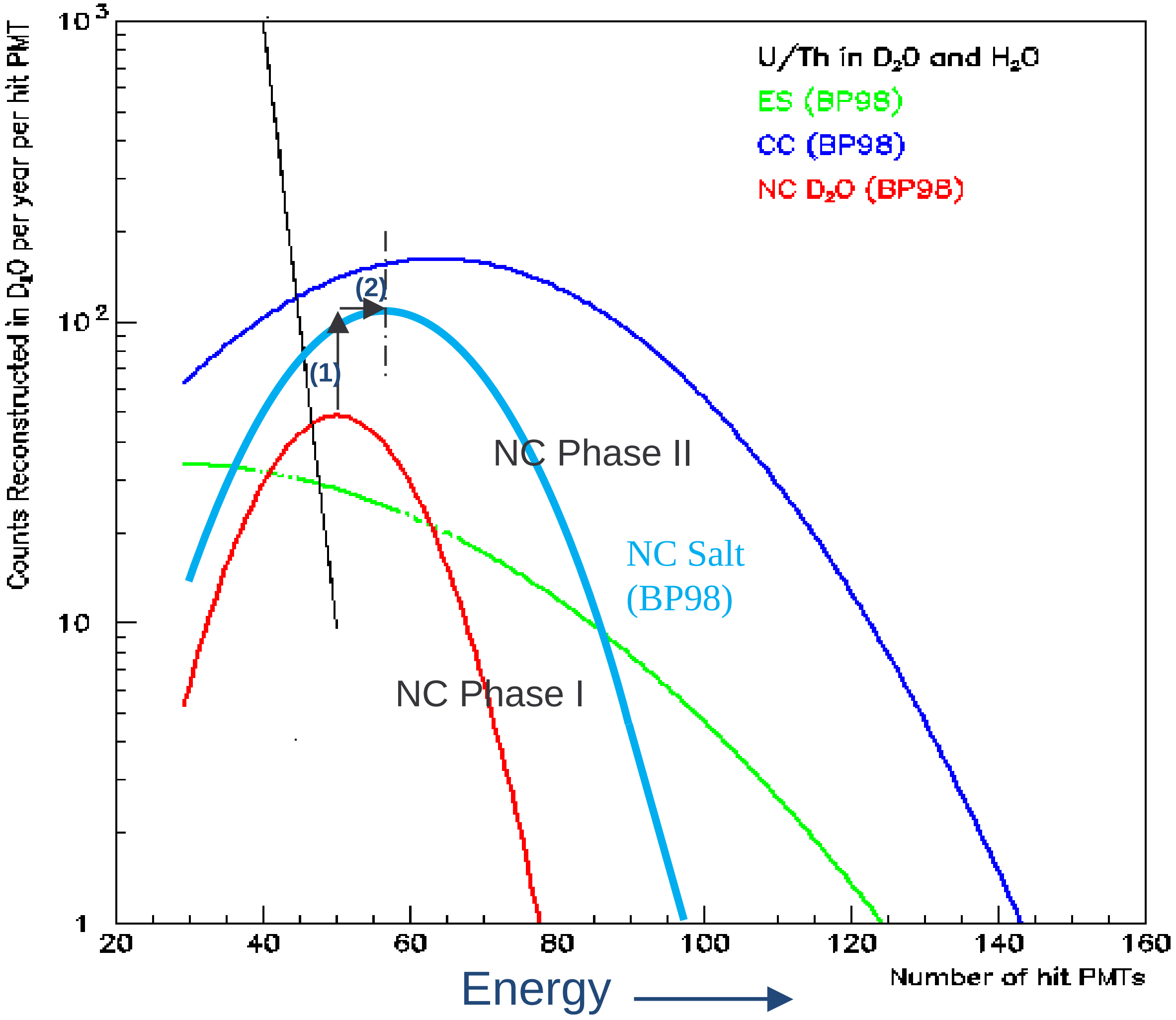
Salt phase:

NC enhanced

- **(1) n capture efficiency (~45% > threshold)**
- **(2) energy Σγ=8.6 MeV**

NC, CC separation

- **(3) different event isotropy (cascade γ's)**



Next : Preparations for Phase III - Neutral Current Detectors

NCD Array

NC Detection:	$n + {}^3He \rightarrow p + t$
Total Length:	775 m
Counters:	292 (300)
Vertical Strings:	96
n capture efficiency:	$\varepsilon_n \sim 45\%$

Neutron Background Estimates from Radioassay

uniform+near vessel:	<4.4% SSM

Status of NCD Project

First deployment of NCD into D_2O	Sep 2000
Counter construction complete	April 2001
Electronics Commissioning	Summer 2001
DAQ partially complete	
Analysis of cooldown data	
Development of pulse shape analysis techniques	

Schedule

Pre-deployment welding:	Winter 2001
Deployment of NCD array:	Summer 2002

Conclusions:

1^{st} SNO CC result together with SK ES provide evidence (3.3σ) of an active non-ν_e component in the ^8B solar flux.

Deduced ^8B total flux agrees with the BP2001 SSM.

“Sterile only” mixing is ruled out at a 3.1σ level.

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