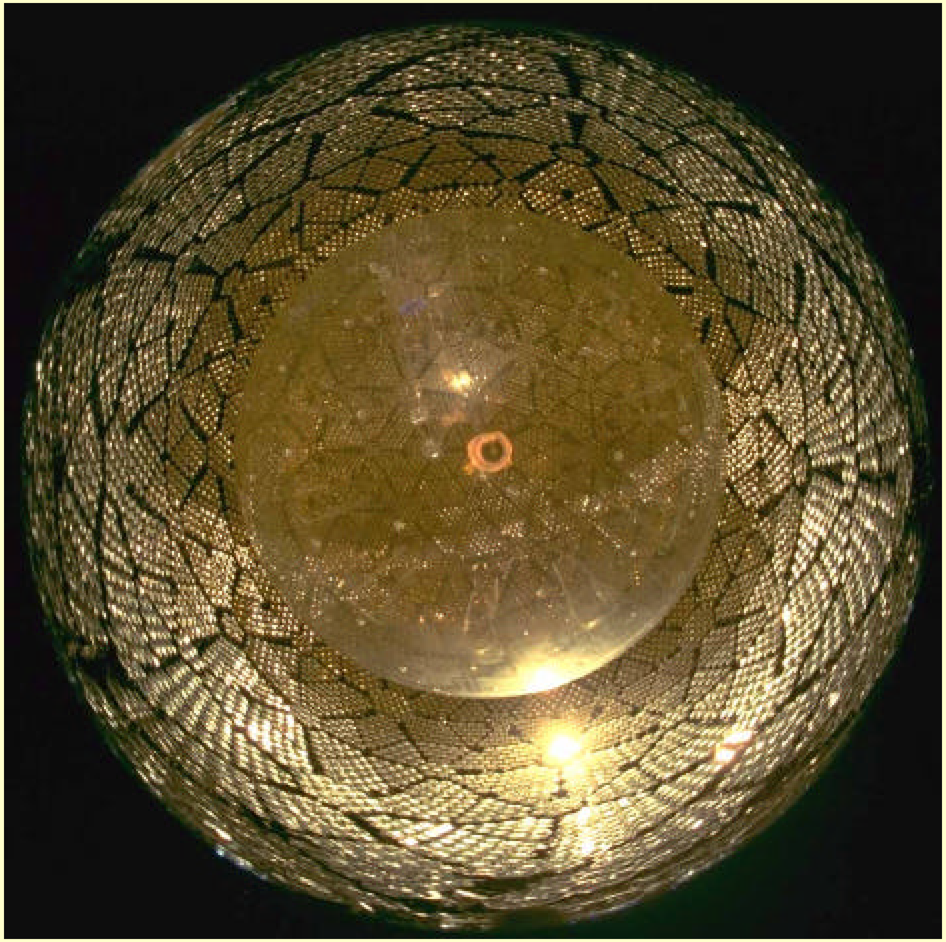
Measurement of CC interactions produced by ^8B solar neutrinos at SNO



Art McDonald

for the **SNO** Scientific Collaboration

Venice, July 24, 2001

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*Deceased

Physics Program

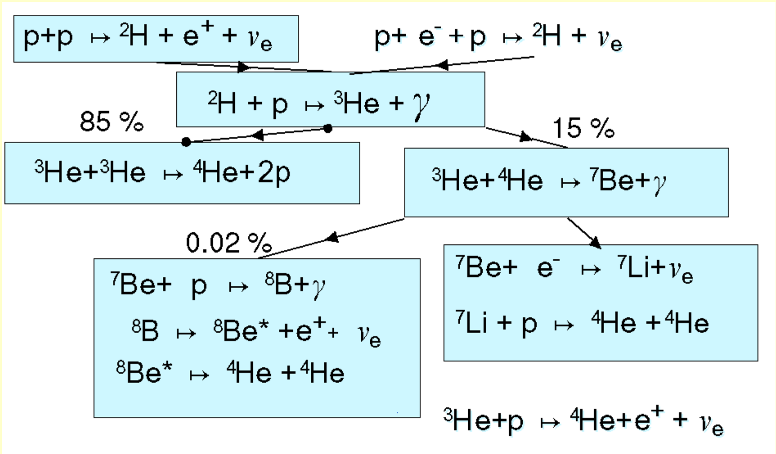
- **Solar Neutrinos**
  - → Electron Neutrino Flux
  - → Total Neutrino Flux
  - → Charged Current Energy Spectrum
  - → Day/Night effects
  - → Seasonal variations

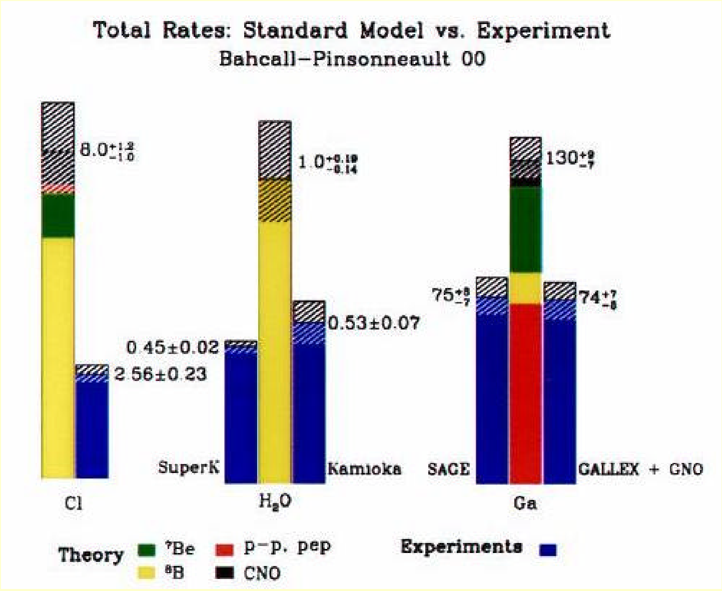
- **Atmospheric Neutrinos & Muons**
  - → Downward going cosmic muon flux
  - → Upward going muons and angular dependence

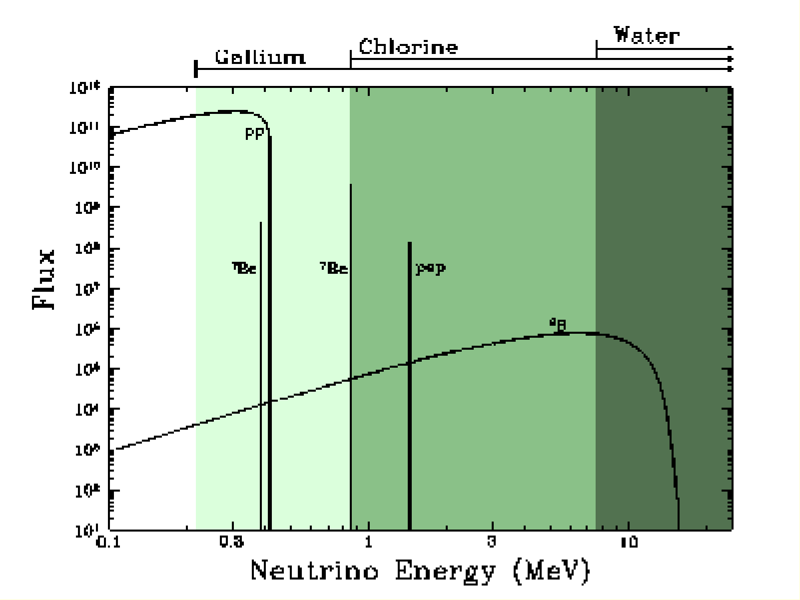
- **Supernova Watch**

- **Antineutrinos, proton decay…**

Solar Neutrino Problem







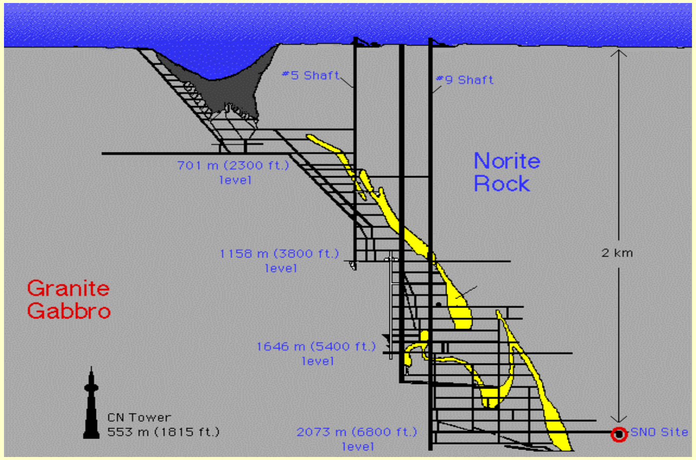
Either

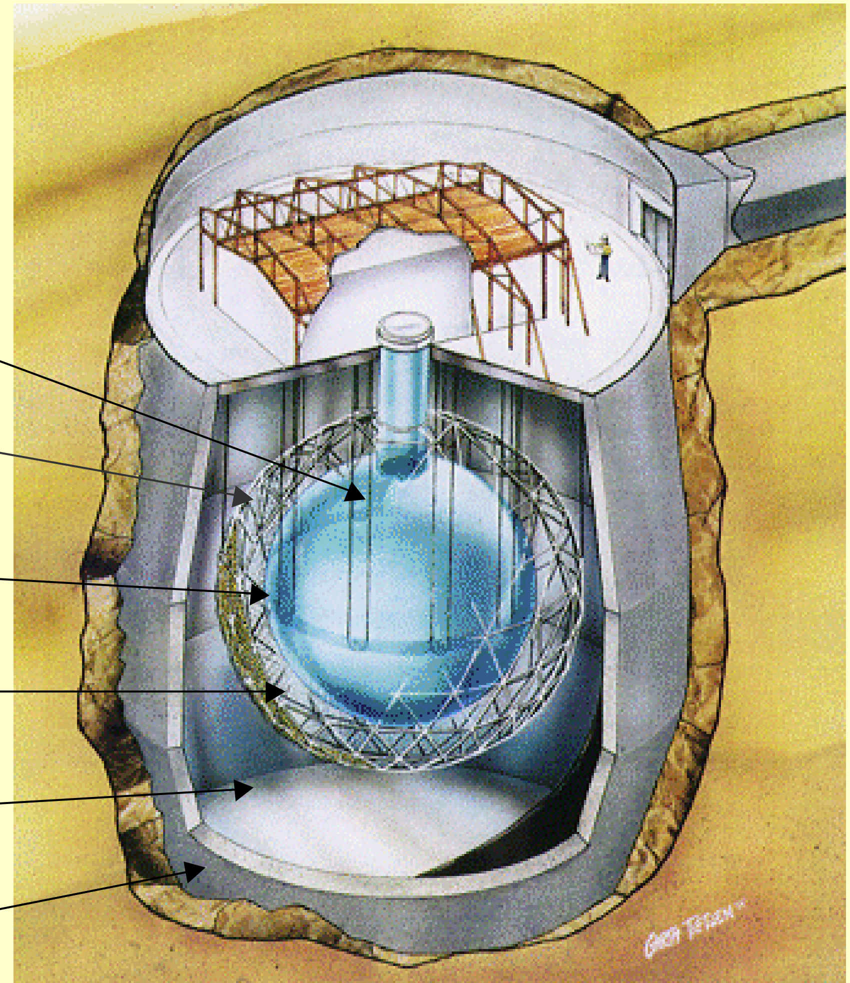
Solar Models are Incomplete or Incorrect

Or

Neutrinos undergo Flavor Changing Oscillations or other new physics.

Sudbury Neutrino Observatory





1000 tonnes D_2O

Support Structure for 9500 PMTs, 60% coverage

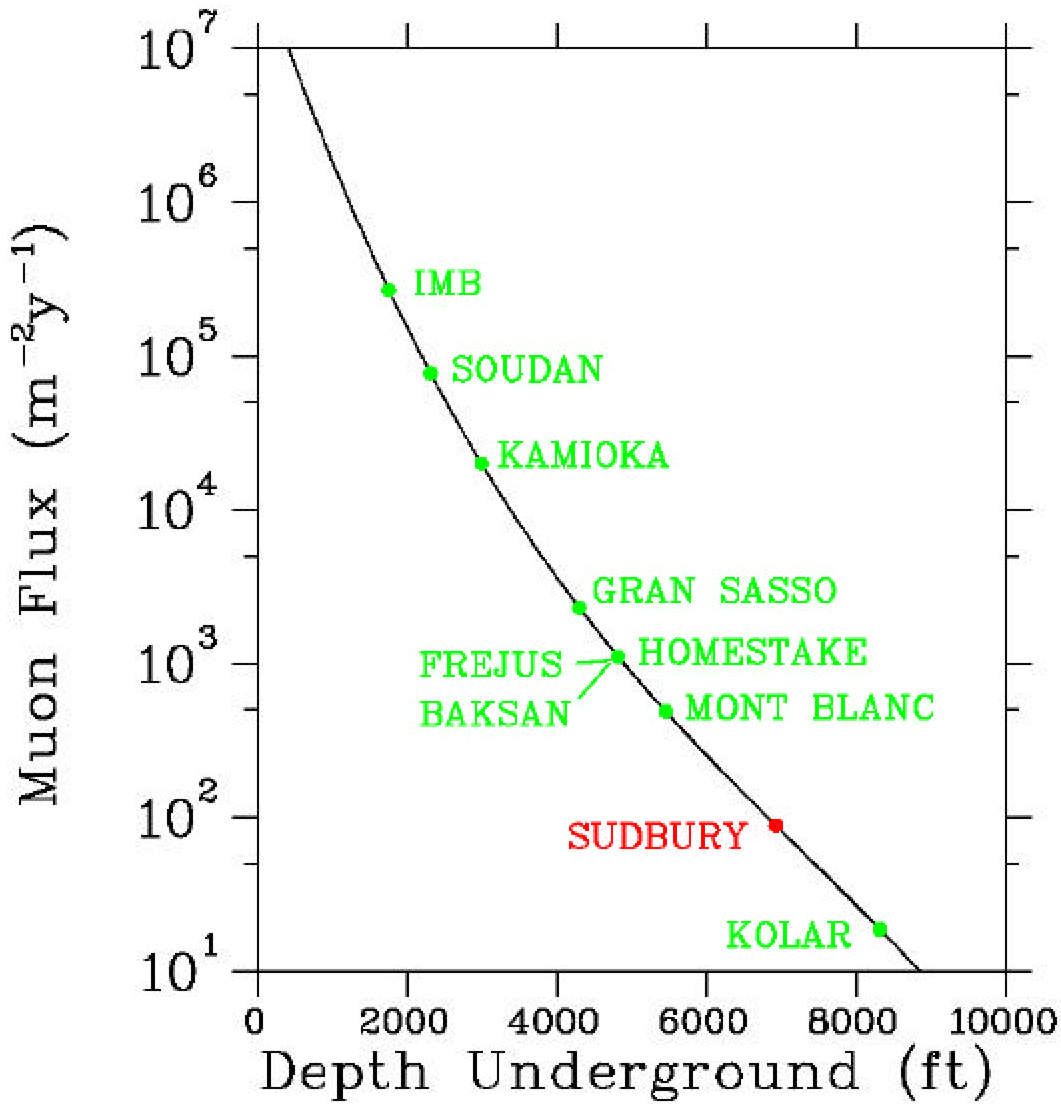
12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding H_2O

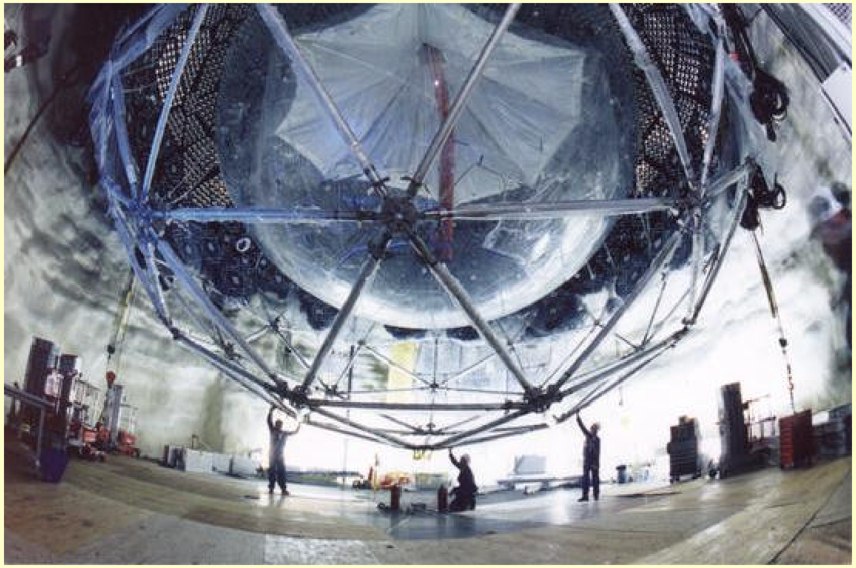
5300 tonnes Outer Shield H_2O

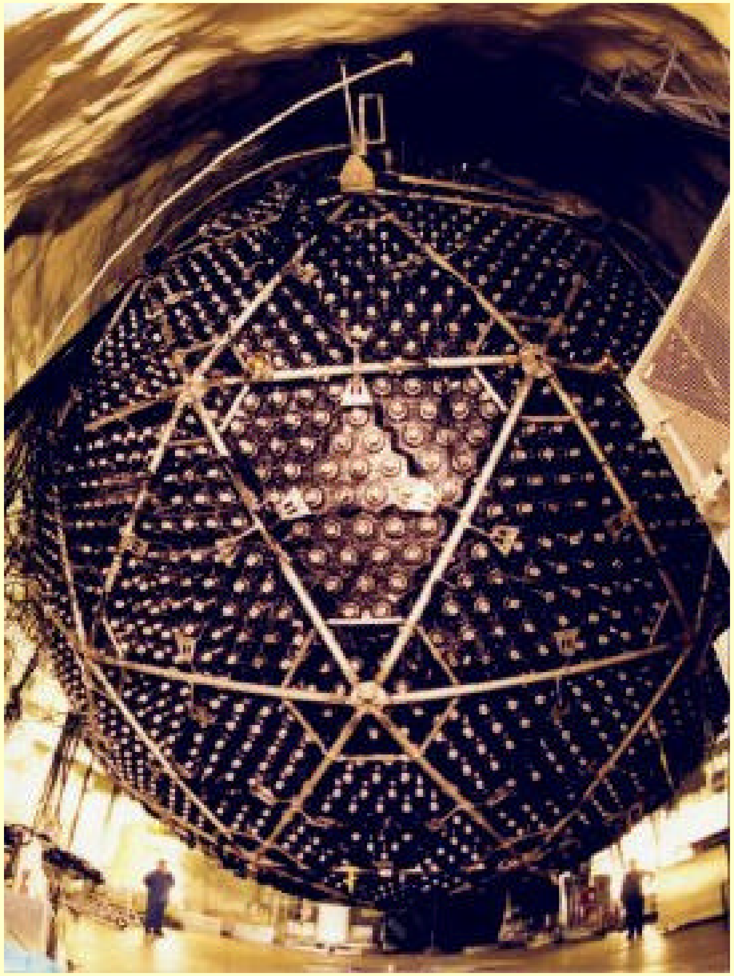
Urylon Liner and Radon Seal

Muon Flux VS Detector Depth



The SNO Detector during Construction





n Reactions in SNO

CC $n_e + d \Rightarrow p + p + e^-$

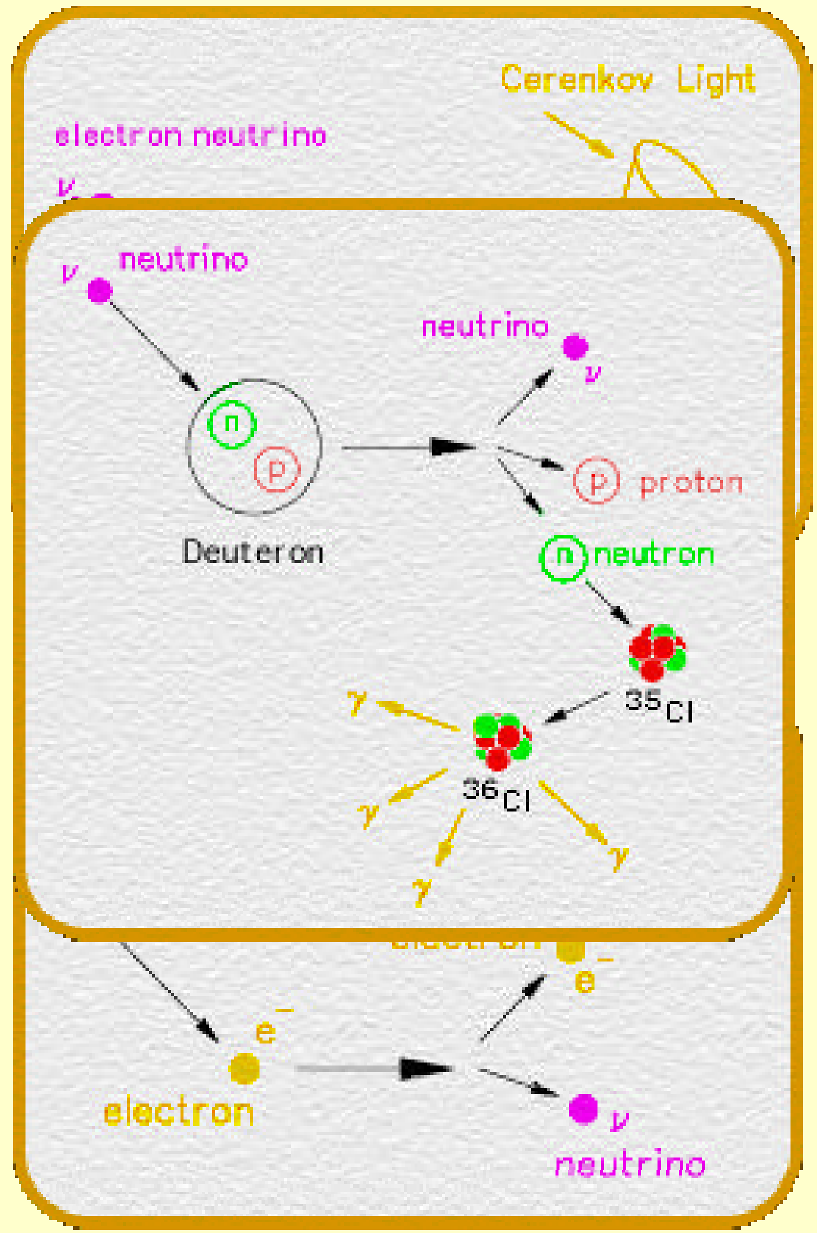
- Good measurement of $\mathbf{n}_e$ energy spectrum
- Weak directional sensitivity µ 1-1/3cos(q)
- $\mathbf{n}_e$ only.

NC $n_x + d \Rightarrow p + n + n_x$

- Measure total ^{8}B **n** flux from the sun.
- Equal cross section for all **n** types

ES $í_x + e^- \Rightarrow í_x + e^-$

- Low Statistics
- Mainly sensitive to $\mathbf{n}_e$, less to $\mathbf{n}_m$ and $\mathbf{n}_t$
- Strong directional sensitivity



What can SNO do?

1) Measure total flux of solar neutrinos vs the pure ν_e flux

Charged-Current to Neutral Current
ratio is a direct signature
for neutrino flavor change

$$\frac{\mathrm{CC}}{\mathrm{NC}} = \frac{n_{\mathrm{e}}}{n_{\mathrm{e}} + n_{m} + n_{t}}$$

CC/ES can also show
flavor change with lower sensitivity

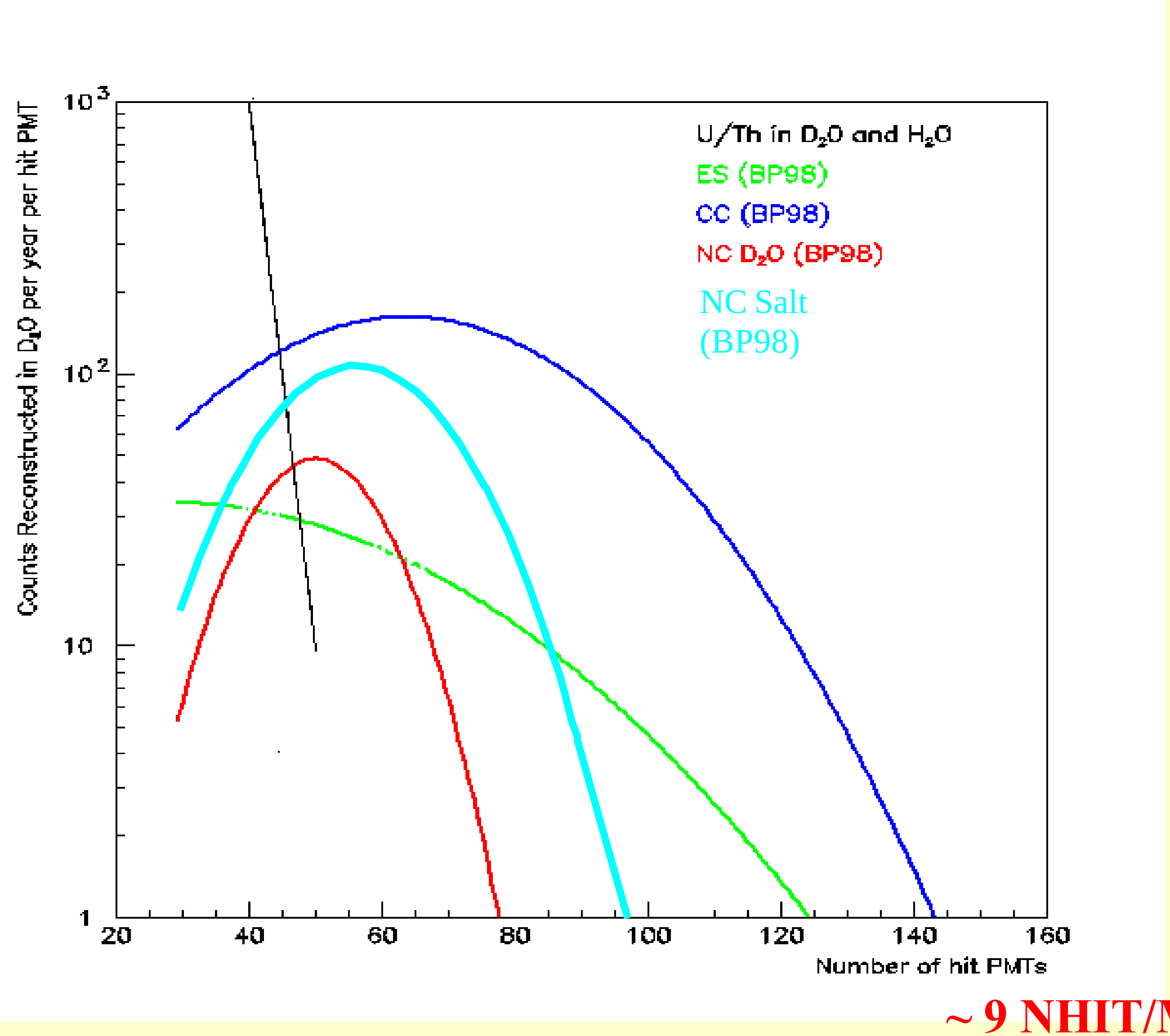
$$\frac{\mathrm{CC}}{\mathrm{ES}} = \frac{n_{\mathrm{e}}}{n_{\mathrm{e}} + 0.14\,(n_{m} + n_{t})}$$

Smoking Guns for Neutrino Oscillations

SNO Run Sequence

The Three Phases	Neutron Detection Method
Pure D_2O • Good CC sensitivity	**Capture on D** *n* + d ® t + g … ® e^- (E_g = 6.3 MeV)
Added Salt in D_2O • Enhanced NC sensitivity	**Capture on Cl** *n* + ^{35}Cl ® ^{36}Cl + Sg … ® e^- (E_{Sg} = 8.6 MeV)
Neutral Current Detectors • ^{3}He proportional counters in the D_2O	**Capture on ^{3}He** *n* + ^{3}He ® p + t **Event by event separation of CC and NC events**

Signals in SNO

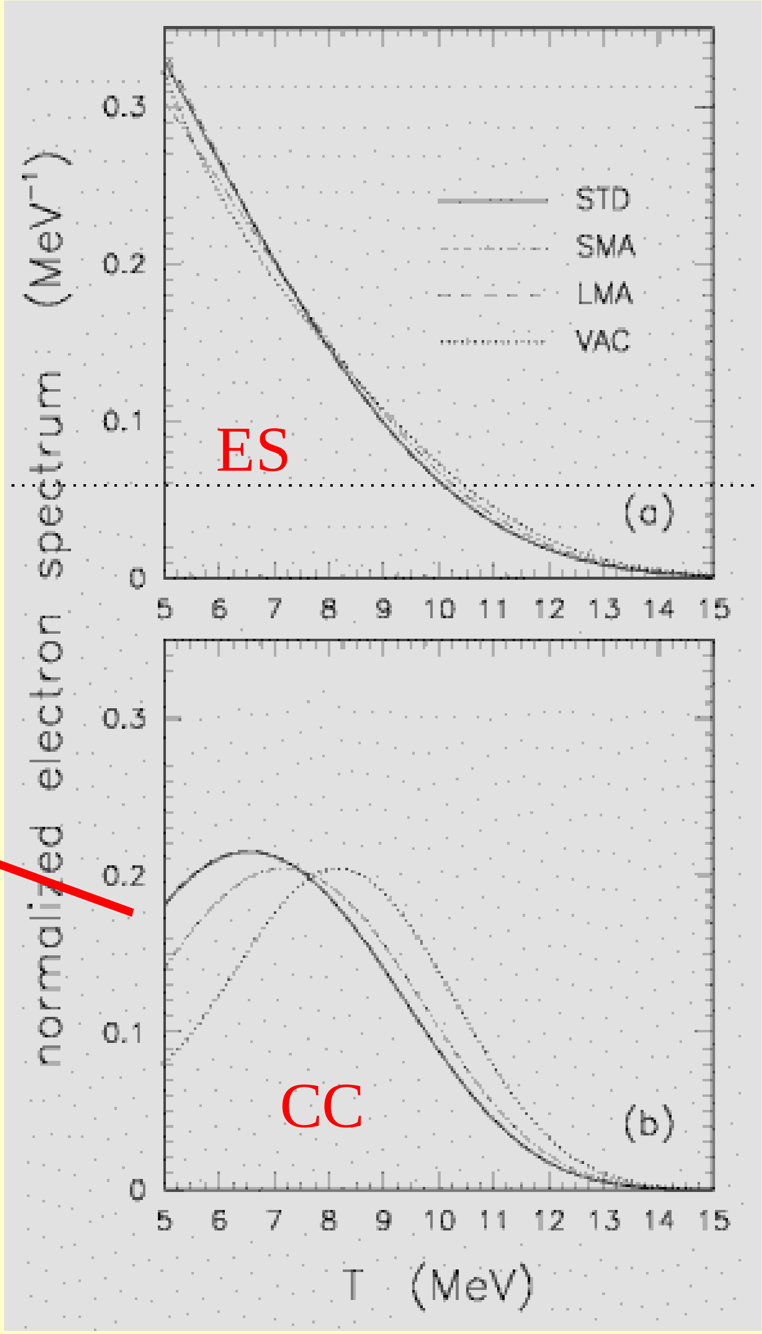


~ 9 NHIT/MEV

What can SNO do?

2) Examine the Charged- Current Energy Spectrum

Charged-current spectrum is sensitive to shape distortions



Calibration Overview

Electronics Calibration

Electronic pulsers

Optical Calibration

Pulsed laser ~2ns (337, 365, 386, 420, 500 and 620 nm)

→Attenuation, Reflection, Scattering, PMT relative QE

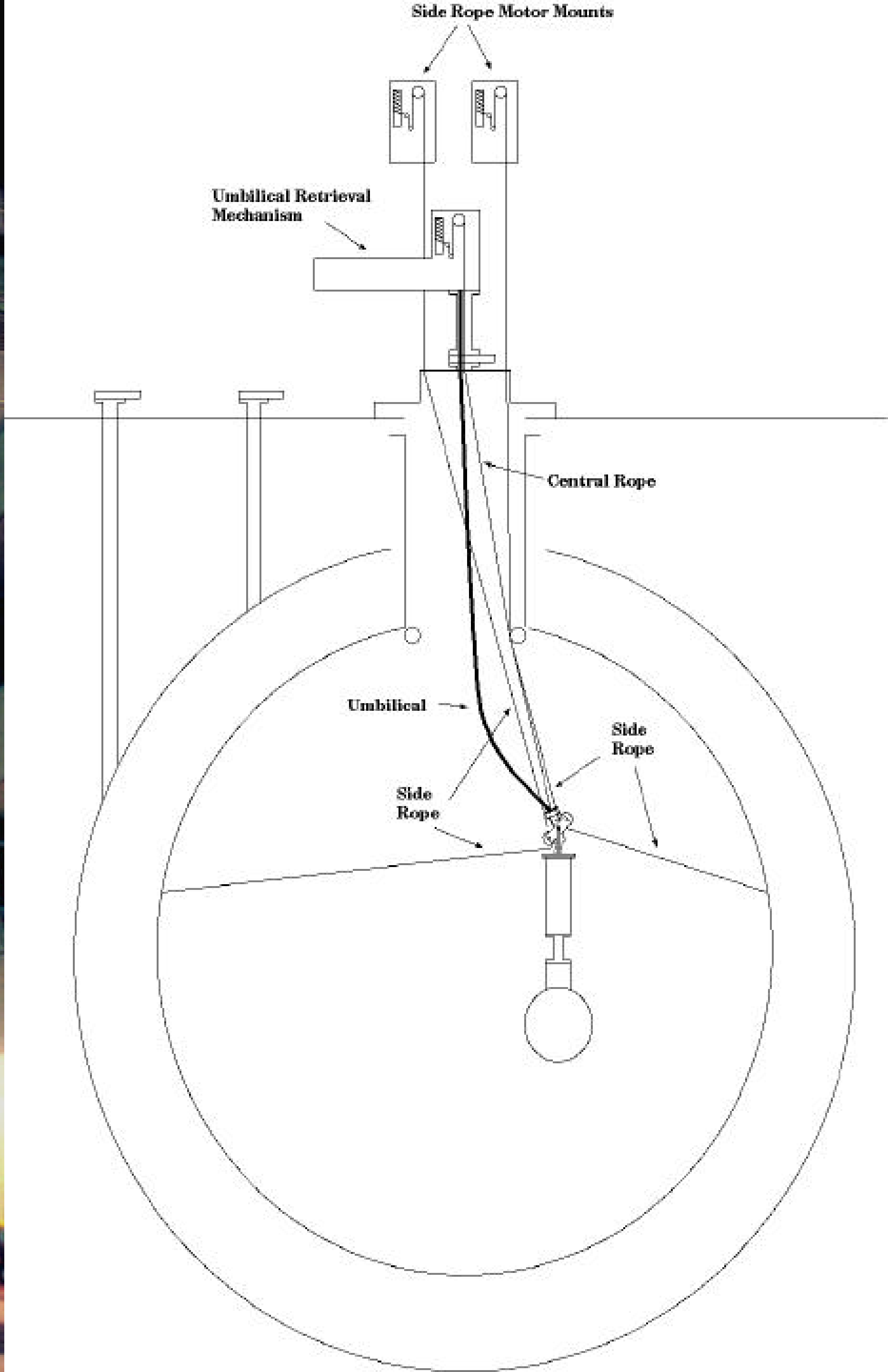
Energy Calibration

- ^{16}N → 6.13 MeV γ's
- p,T → 19.8 MeV γ's
- neutrons → 6.25 MeV γ's
- ^{8}Li → β spectrum. Endpoint ~14 MeV

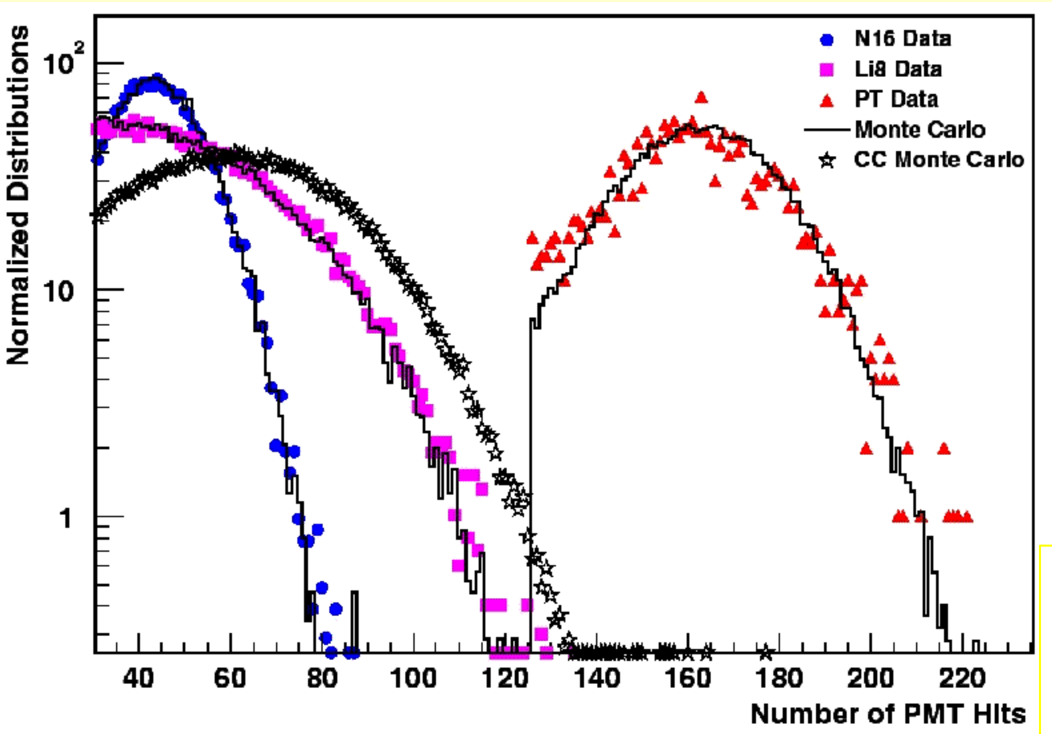
Low Energy Backgrounds

Encapsulated Th and U sources

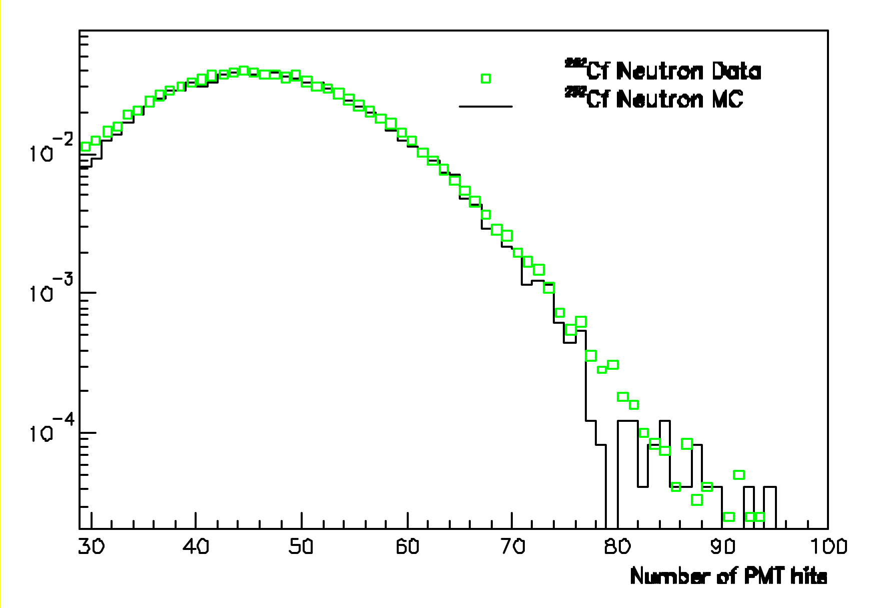

SNO


Side Rope Motor Mounts
Umbilical Retrieval Mechanism
Central Rope
Umbilical
Side Rope
Side Rope

SNO Energy Calibrations



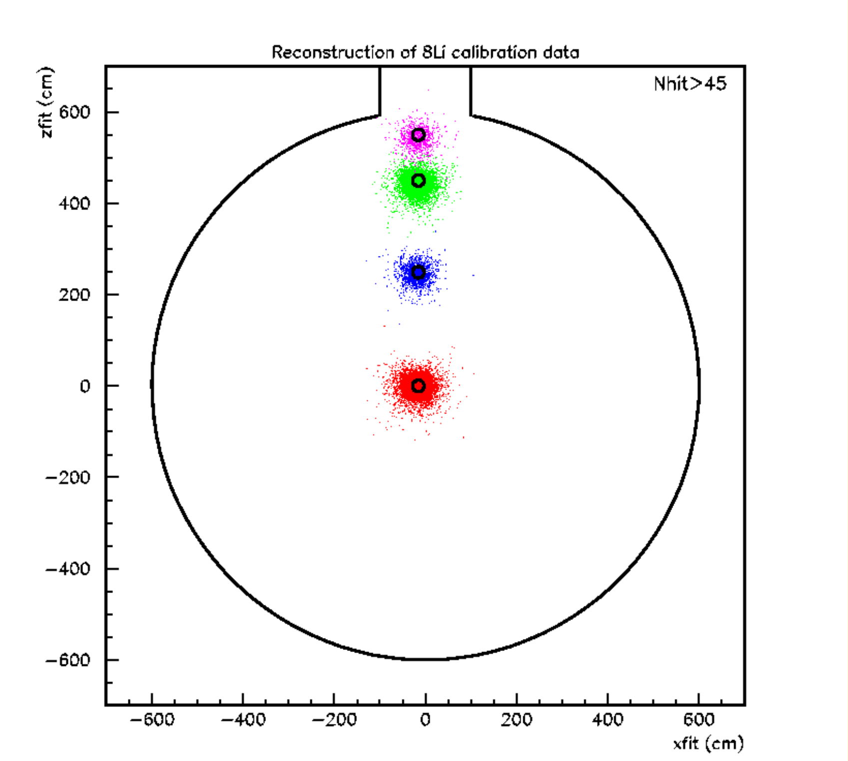
^{252}Cf neutrons

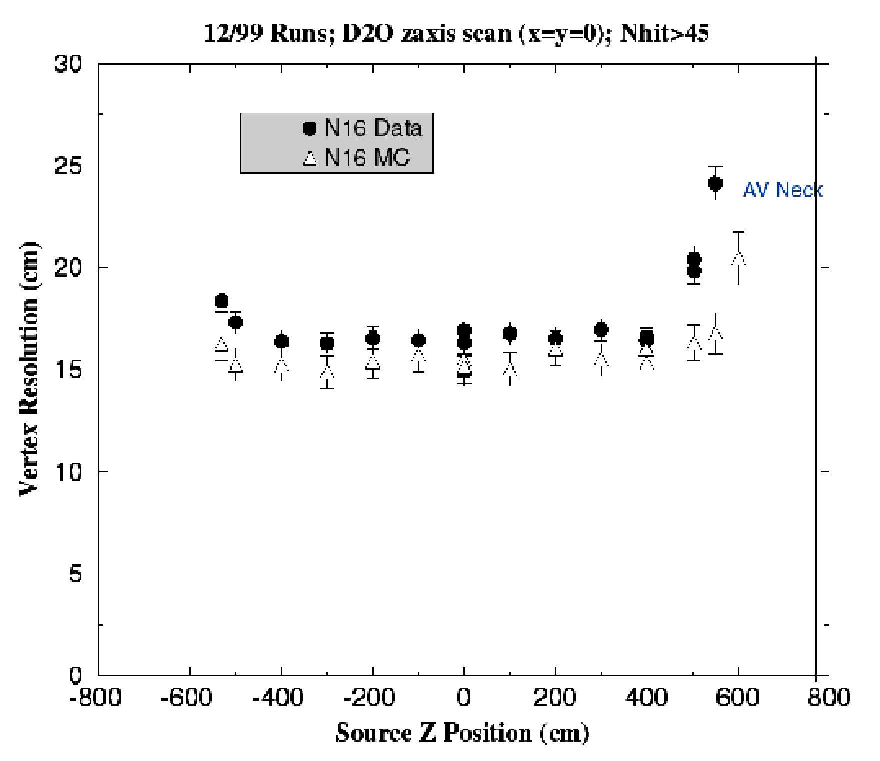


β's from ^{8}Li

γ's from ^{16}N and t(p,γ)^{4}He

SNO Event Reconstruction





Reconstruction position of ^{8}Li events

Reconstruction Resolution

Calibration

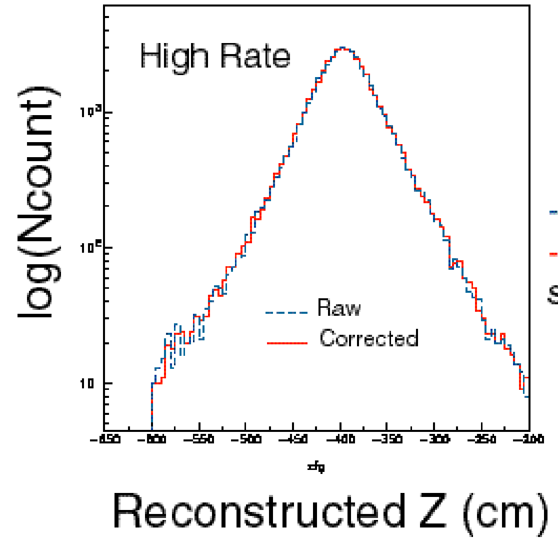
- **Electronics**
  - **Electronic Pulsers, Pulsed Light Sources**
  - **0.25 pe Threshold**
  - **Multiplicity Trigger 18 Nhit 100% efficiency by 25 (~3 MeV)**
  - **See NIM A449 (2000)**

- **CMOS Feature** Discovered with a **T**ime **S**ince **L**ast **H**it Dependence

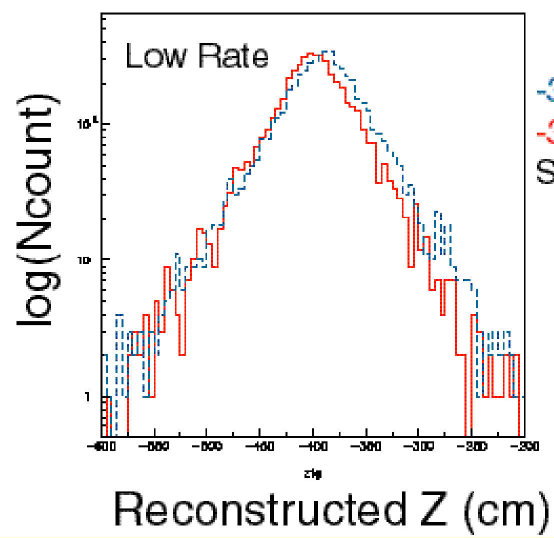
☞ **Now Corrected**

N16 source at Z=-400cm

Low Rate vs High Rate Data & Corrections

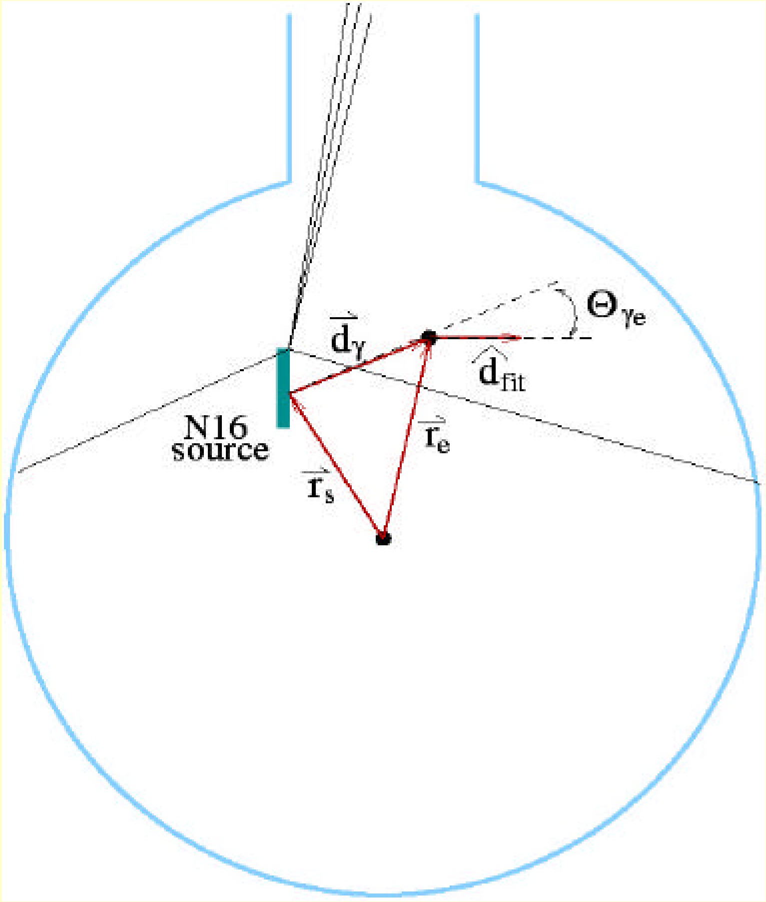


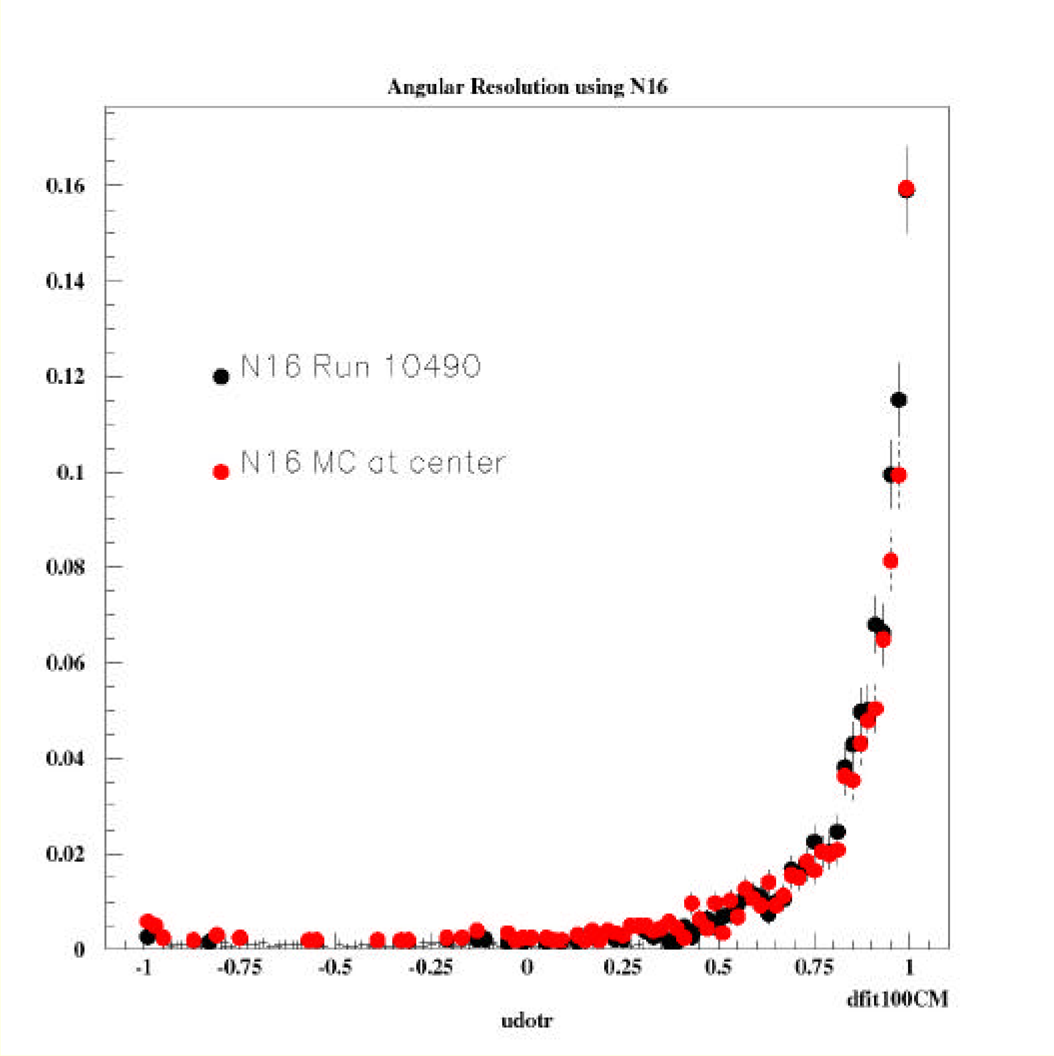
-395.9 (0.5) w/o correction
-395.5 (0.5) w correction
source at -400 cm



-389.7 (0.5) w/o correction
-398.5 (0.5) w/ correction
Source at -400 cm

Angular Resolution

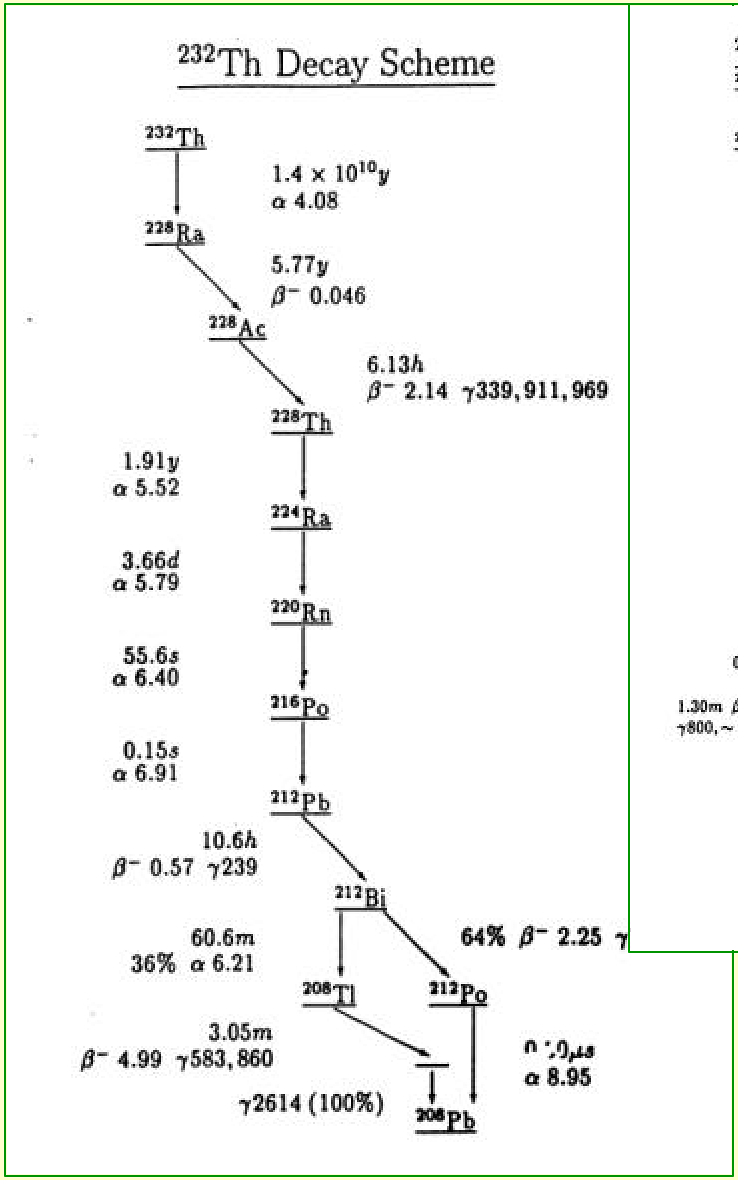


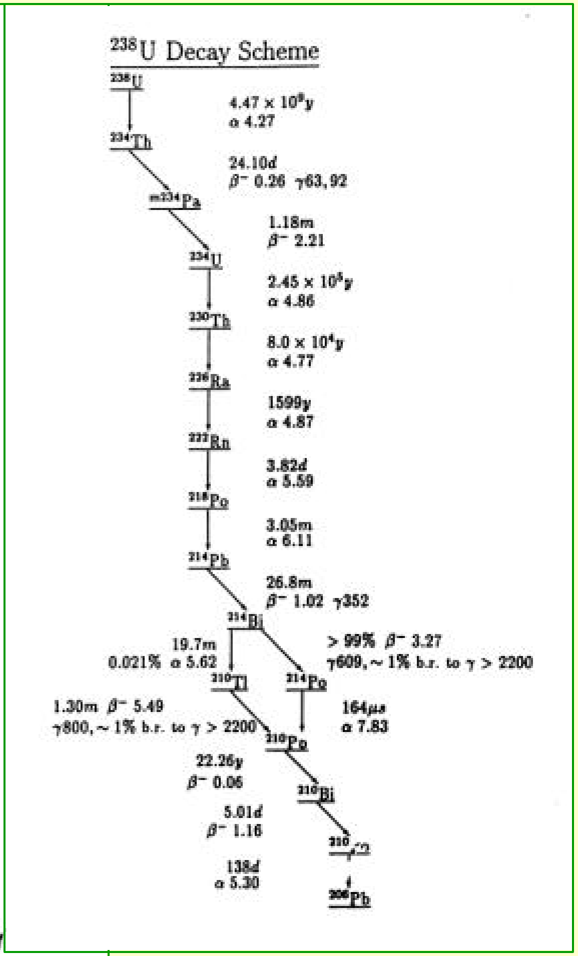


- Affects ES Extraction

☞ *Very Small Effect on Flux Extraction*

Background Radioactivity





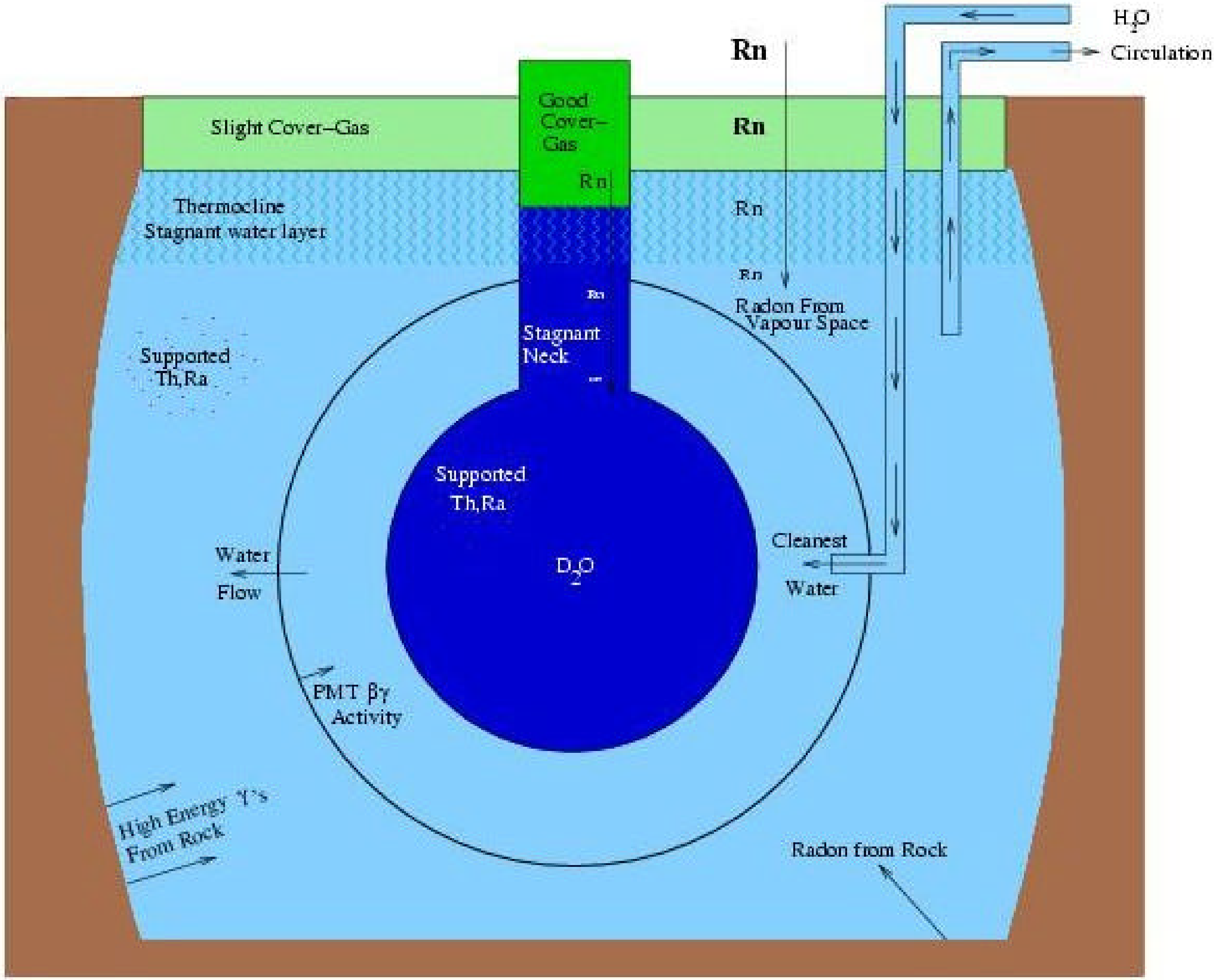
βs and γs interfere with our signals at low energies

γ's over 2.2 MeV

$\rightarrow\ d + \gamma \rightarrow n + p$

Background to NC signal

Sources of Activity in SNO Water Systems



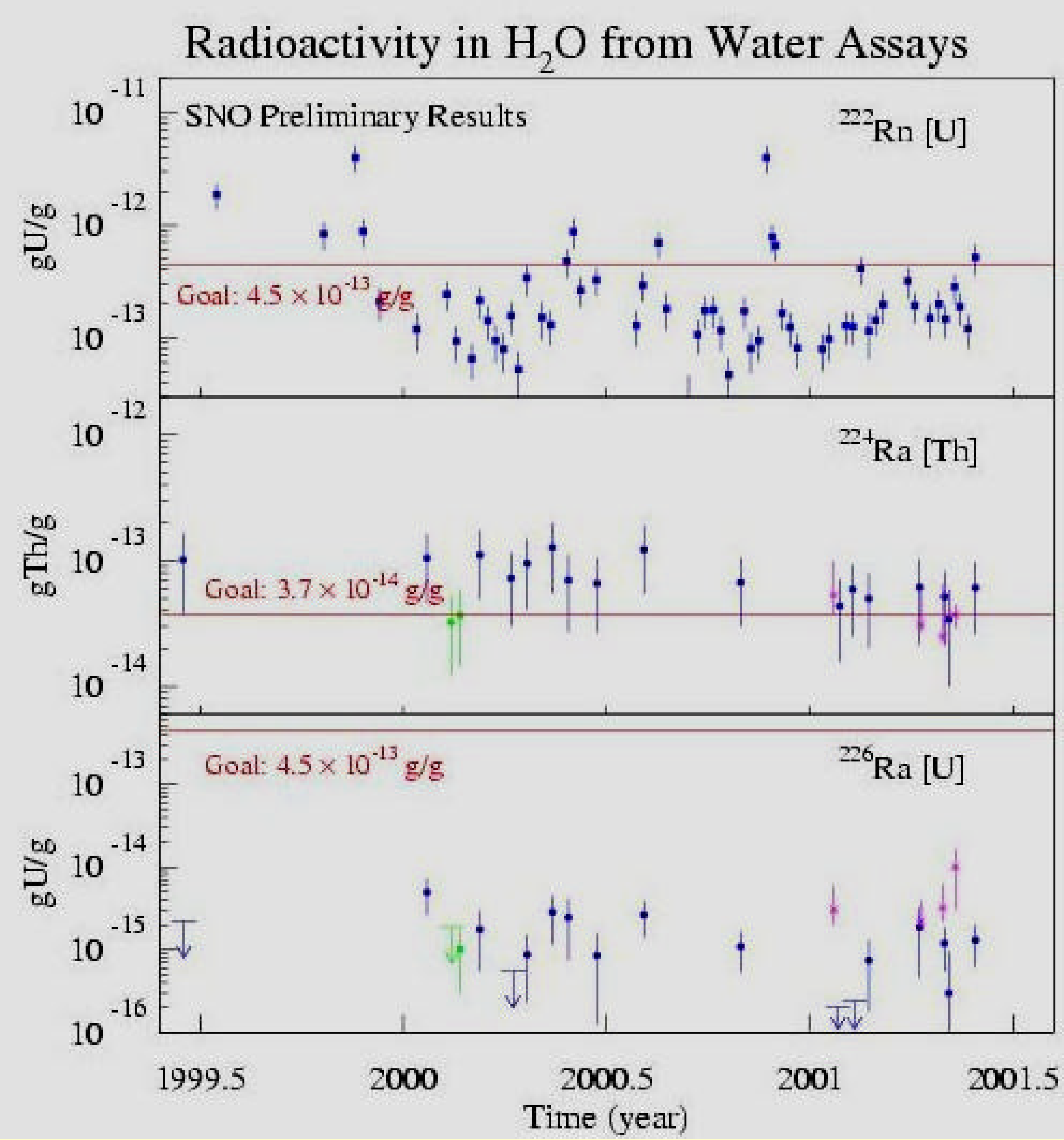
Water Purification and Assay

MnOx	^{224}Ra, ^{226}Ra extraction	→	Purification
	↪ decay products counted in electrostatic counters	→	Assay of ^{224}Ra, ^{226}Ra
HTiO	Th, Ra, & Pb extraction	→	Purification
	↪ chemically stripped and counted with βα counter	→	Assay of ^{224}Ra, ^{226}Ra, ^{228}Th
Vacuum & Membrane	Radon removal	→	Purification
De-gassing	Lucas Cells	→	Assay of ^{222}Rn
Reverse Osmosis	conc. collection	→	Purification
	liquid scintillator	→	Assay
Ion Exchange & Ultrafiltration...		→	Purification

SNO

Water Assays

H_2O



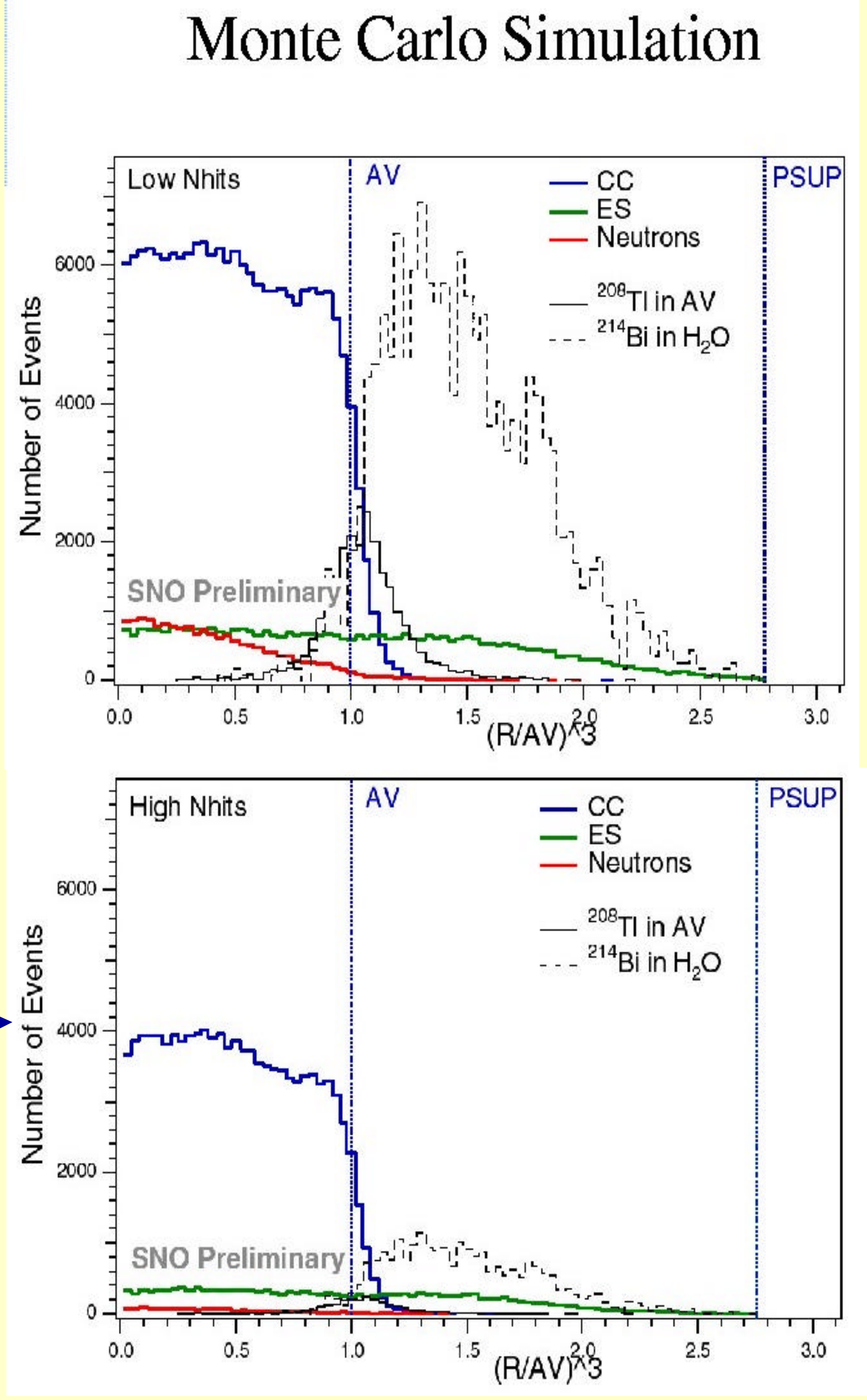
Targets are set to reduce β-γ events reconstructing inside 6m

Radial profiles

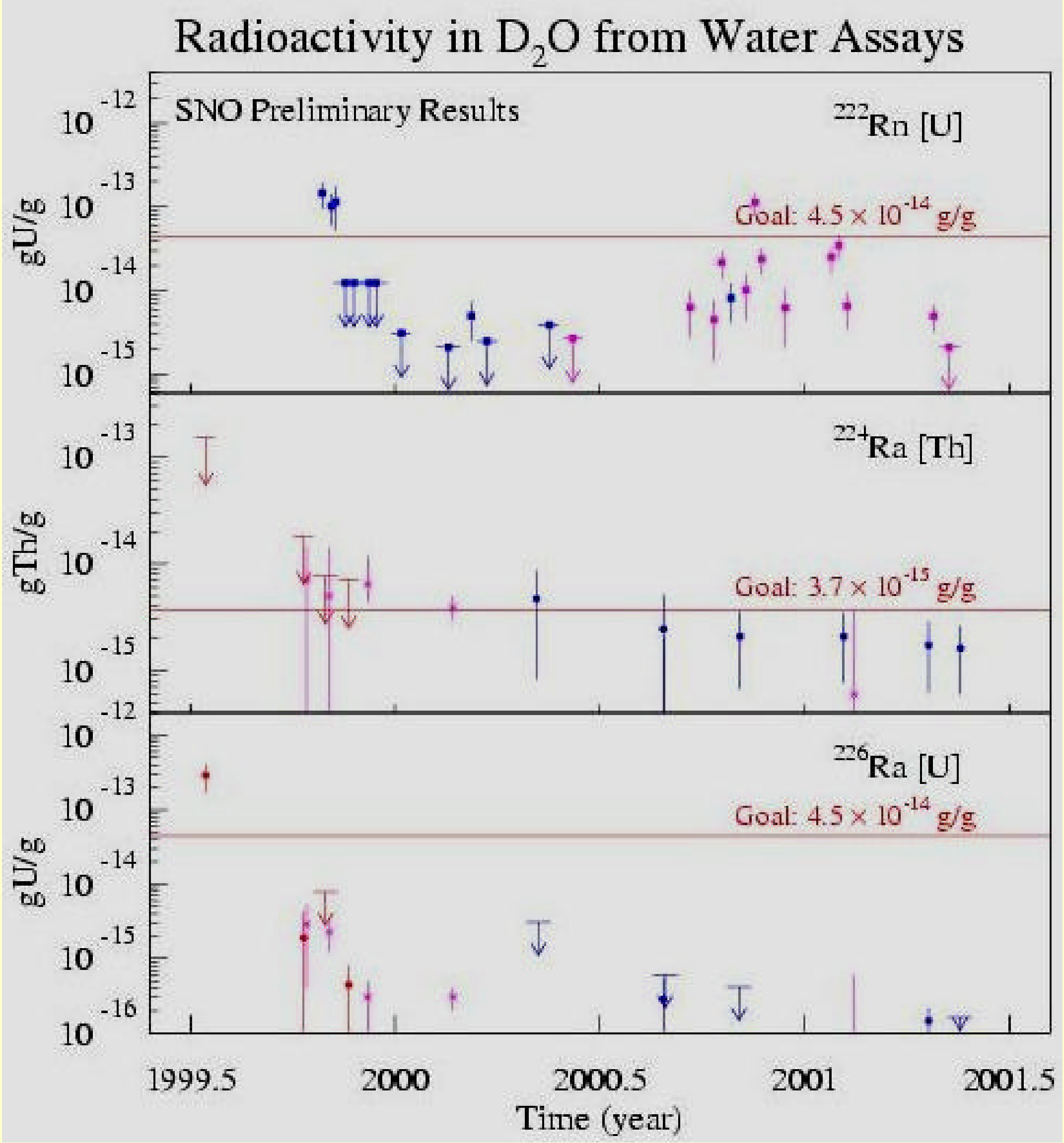
Low N_{hit}

Signals and backgrounds as a function of r^3

High N_{hit}



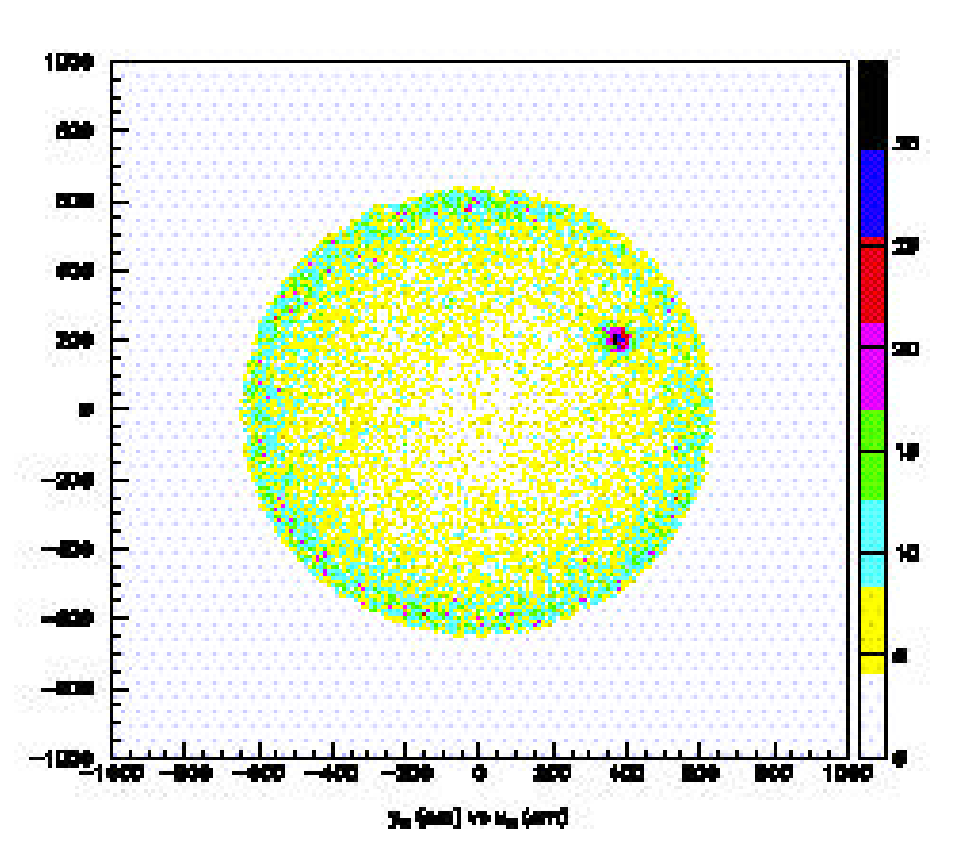
SNO
Water Assays
D_2O



Targets for D_2O represent a 5% background from $d+\gamma \rightarrow n+p$

Acrylic Vessel Backgrounds

- Direct Counting and NAA
- Encapsulated U, Th sources
- Direct Observation in Cerenkov



• Small Neutron background

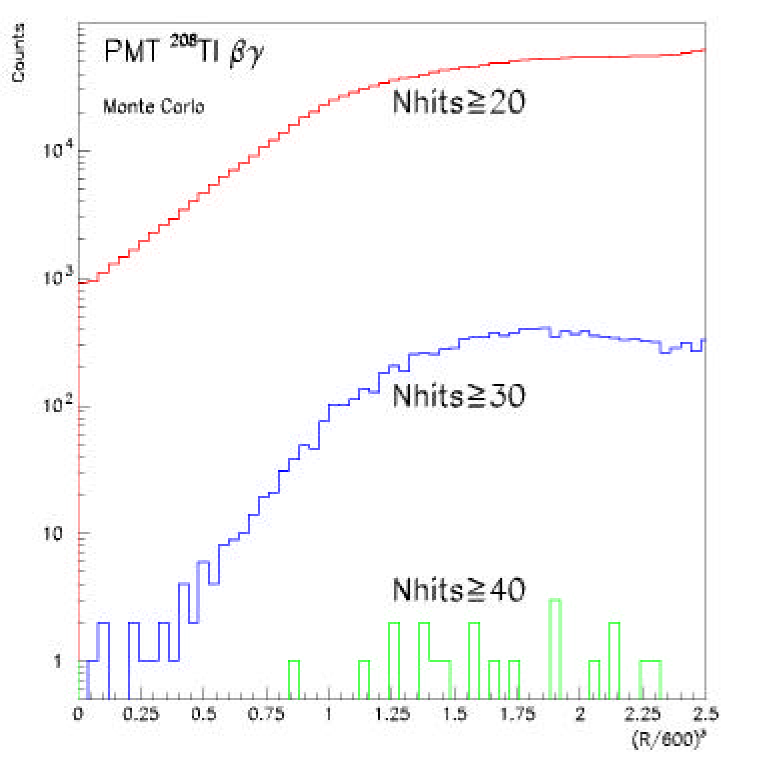
☞ Activities assayed to be <10% Targets ~0.2 ppt

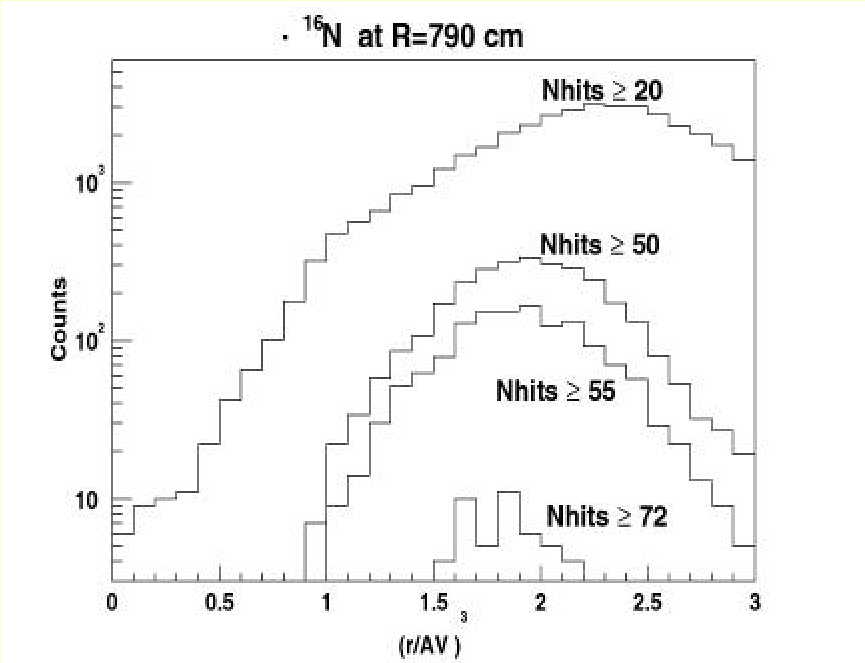
• Small Tails into Cerenkov Signals

☞ "Berkeley Blob" ~9 $^{+20}_{-5} \pm 3$ μg 'Th'

PMT β γ

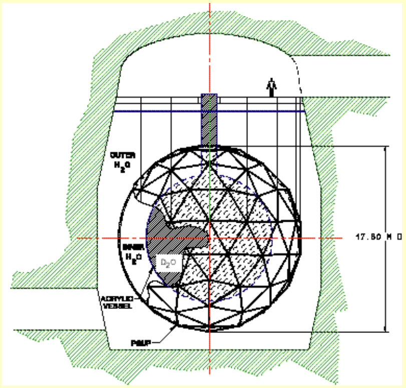
- **Direct Counting of Materials & M/C**
- **"Hot" Encapsulated U & Th Sources, ^{16}N-γ's**





- **Small Tails into Cerenkov Signals**

☞ **Limits <550cm <1/2%**

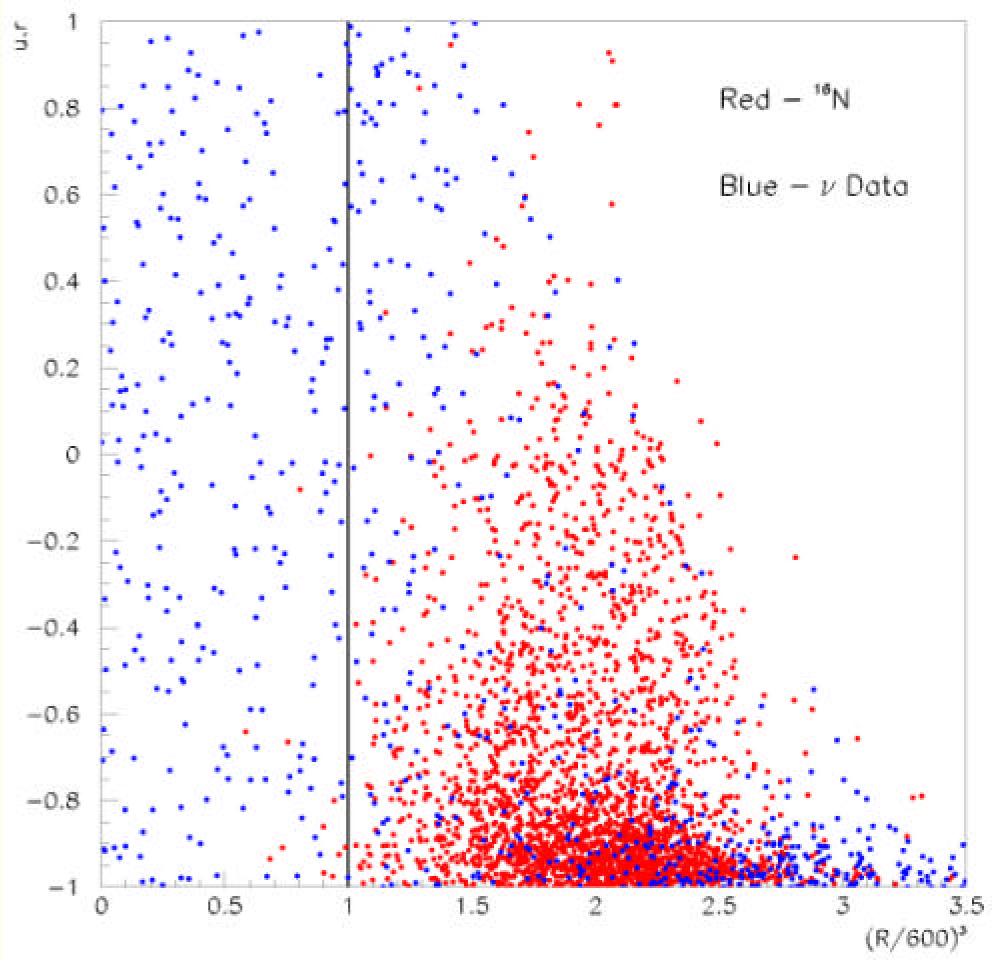


High Energy Gammas

- **From PMTs & Rock Wall - (α,γ), (α,nγ),...**
- **Empirical Estimates from Cavity Measures**
- **Direct Observation, ^{16}N Calibration γ's**

• Small Cerenkov Signals

•<2% inside 550 cm



Data Sets

- Data Period: Nov 2, 1999 → Jan 15, 2001
- Life Time: 240.9 days
- Data Set 1: Analysis Data

  ↪ Data set used to develop the data analysis procedures. ~166 days live time.
- Data Set 2: Blind Data Set

  ↪ Signal region was not looked at until all analyses complete and unified. ~75 days live time.

No statistically significant differences were found between the blind and development data sets.

Analysis Process (see M Boulay)

Data Division, Run Selection & Livetime

Calibration

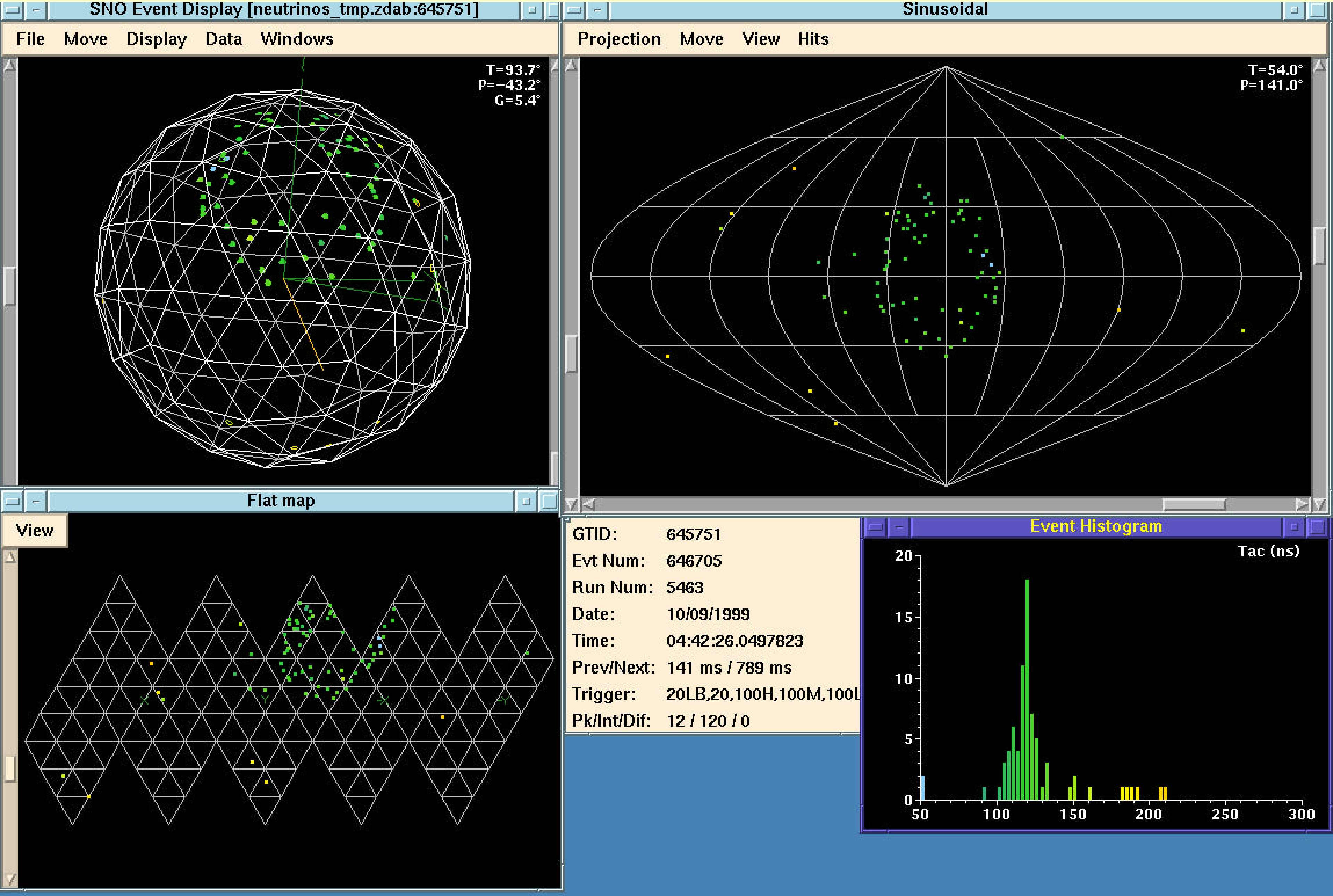
Monte Carlo Simulations

Instrumental Bckgrds Removal **D**	Instrumental Bckgrds Removal **F**
Reconstruction **P**	Reconstruction **G**

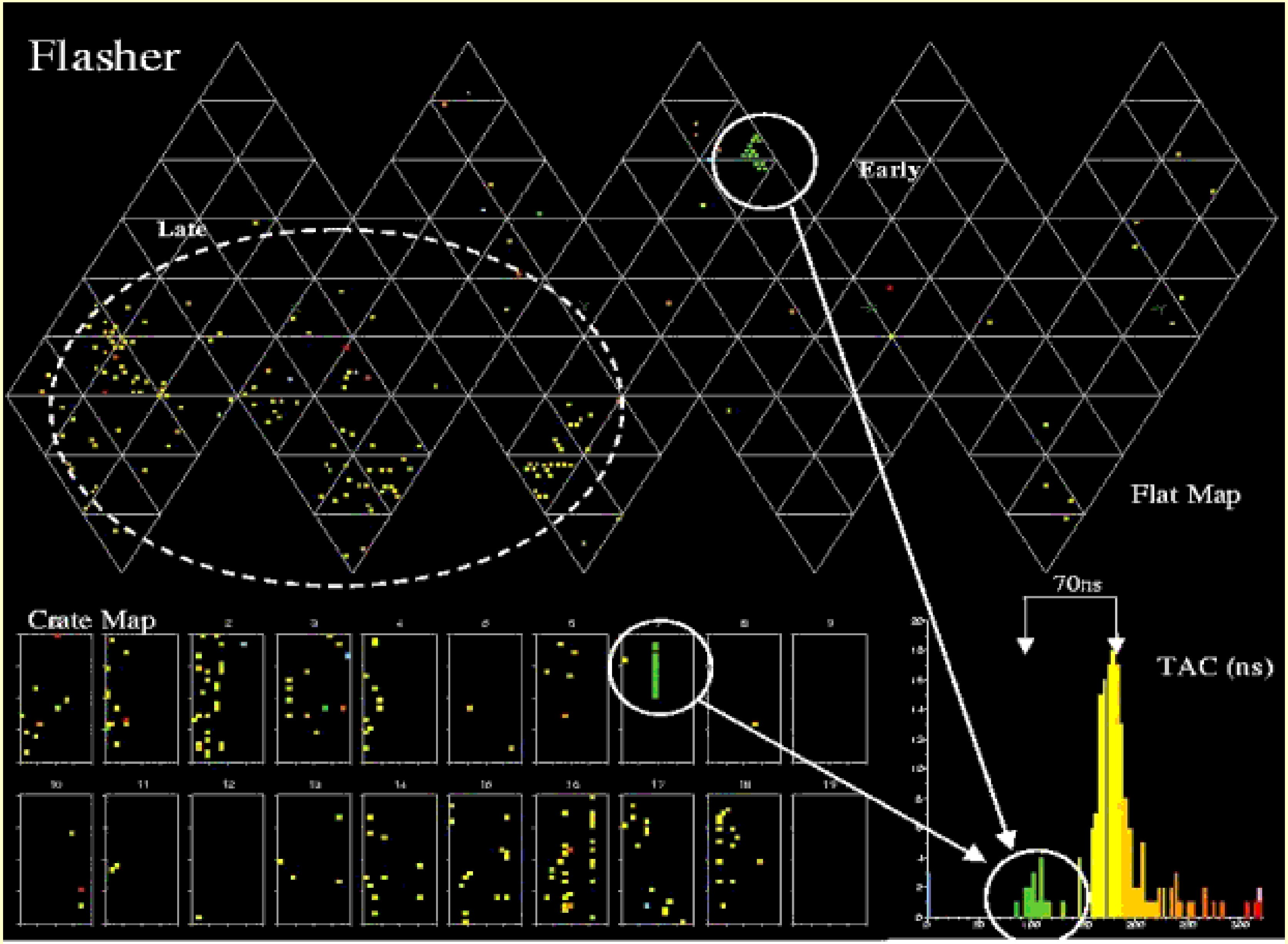
Higher Level Cuts

Signal Extraction & Background and Error Determination Tight Fiducial Volume	Signal Extraction & Background and Error Determination Variable Fiducial Volume

A Neutrino Event

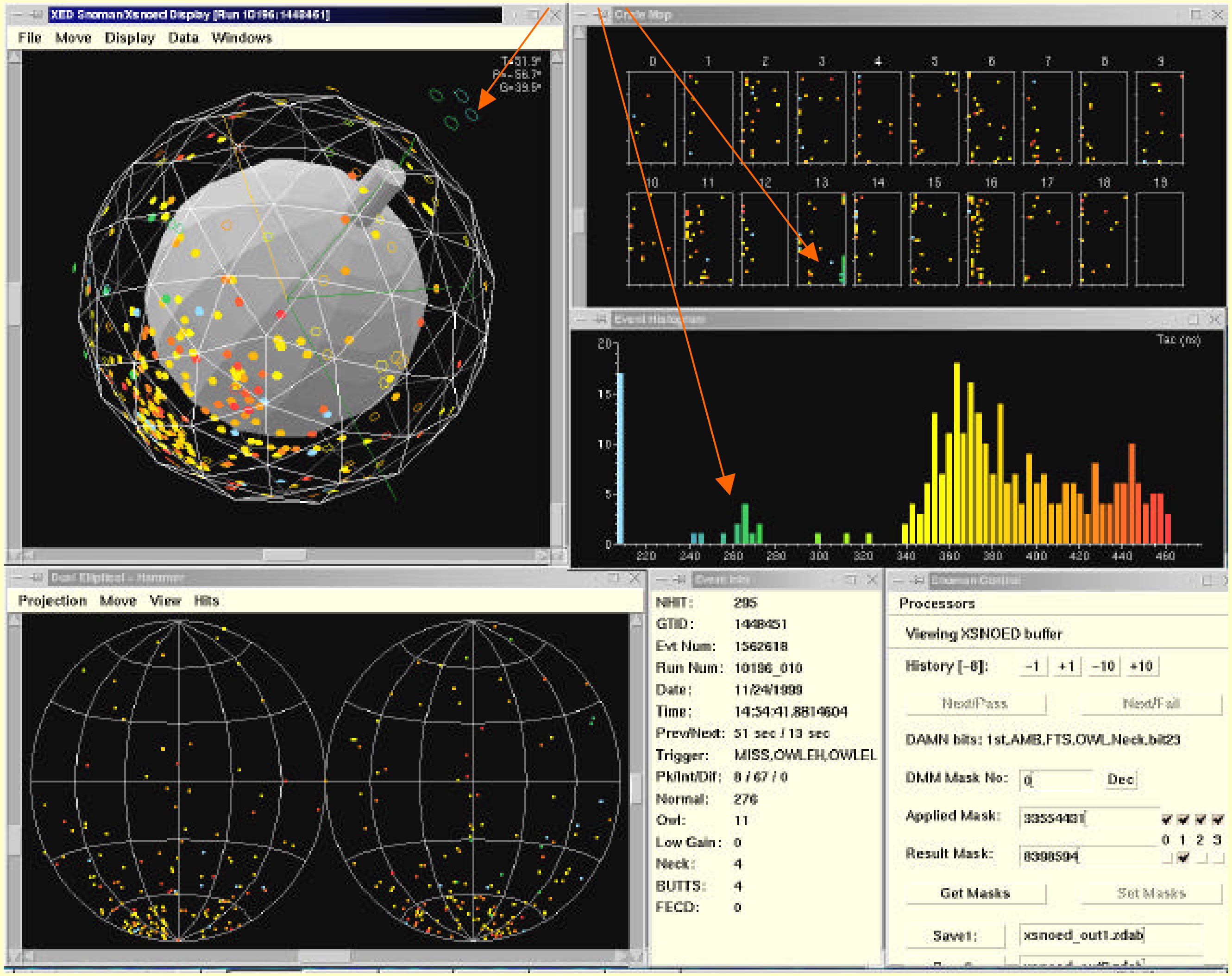


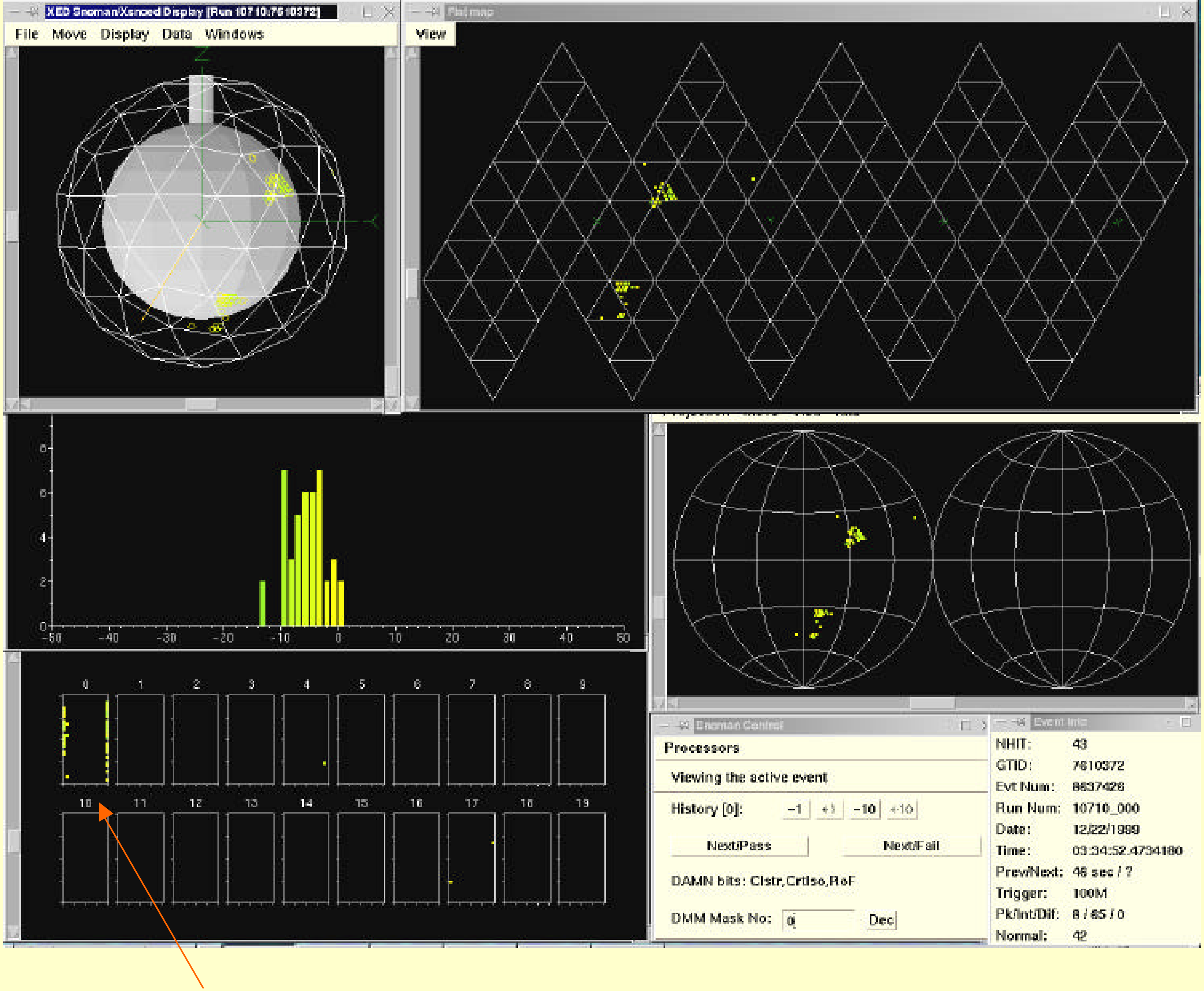
Instrumental Backgrounds



A "Neck" Event

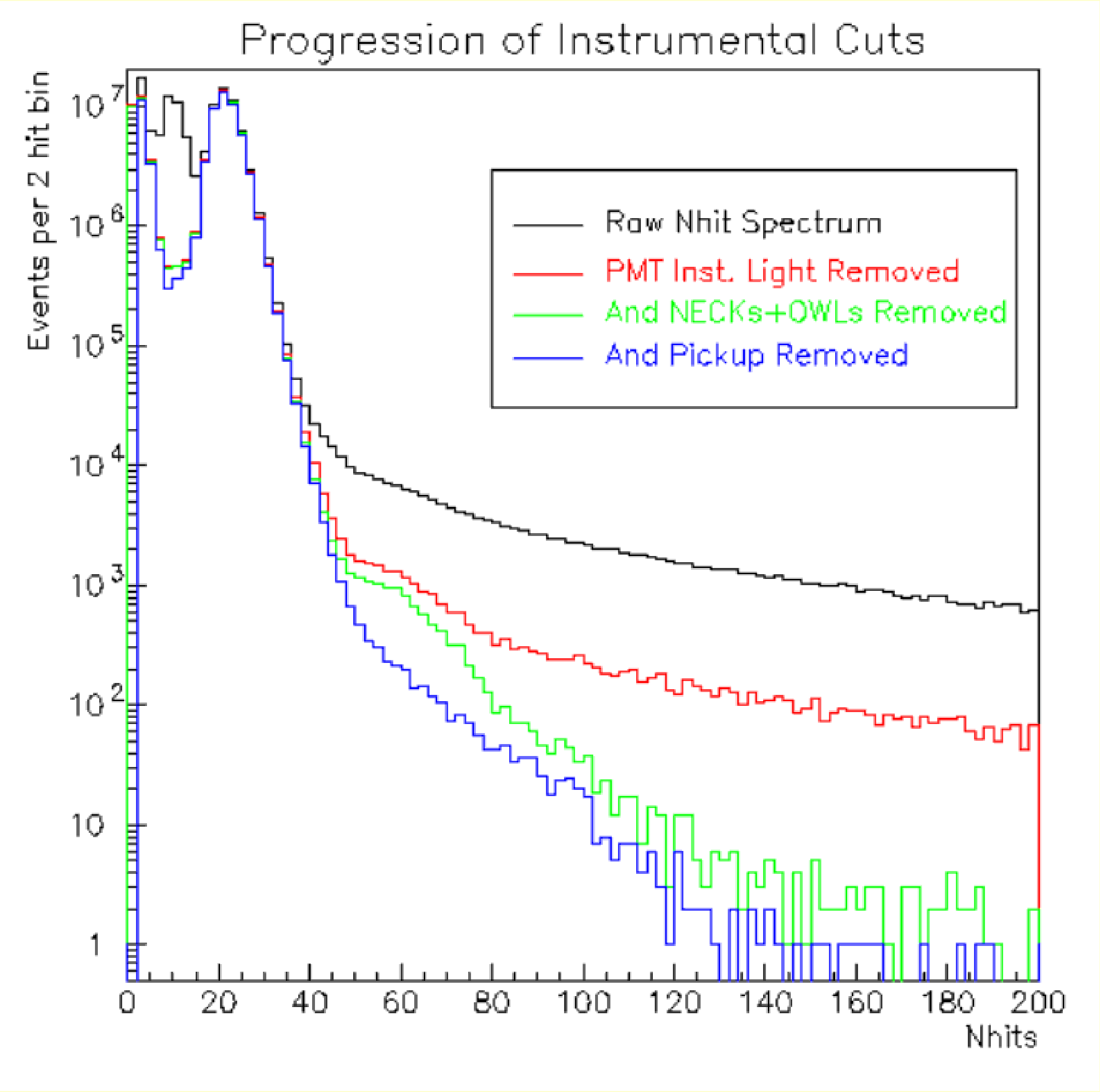
Note Neck Tubes Fired

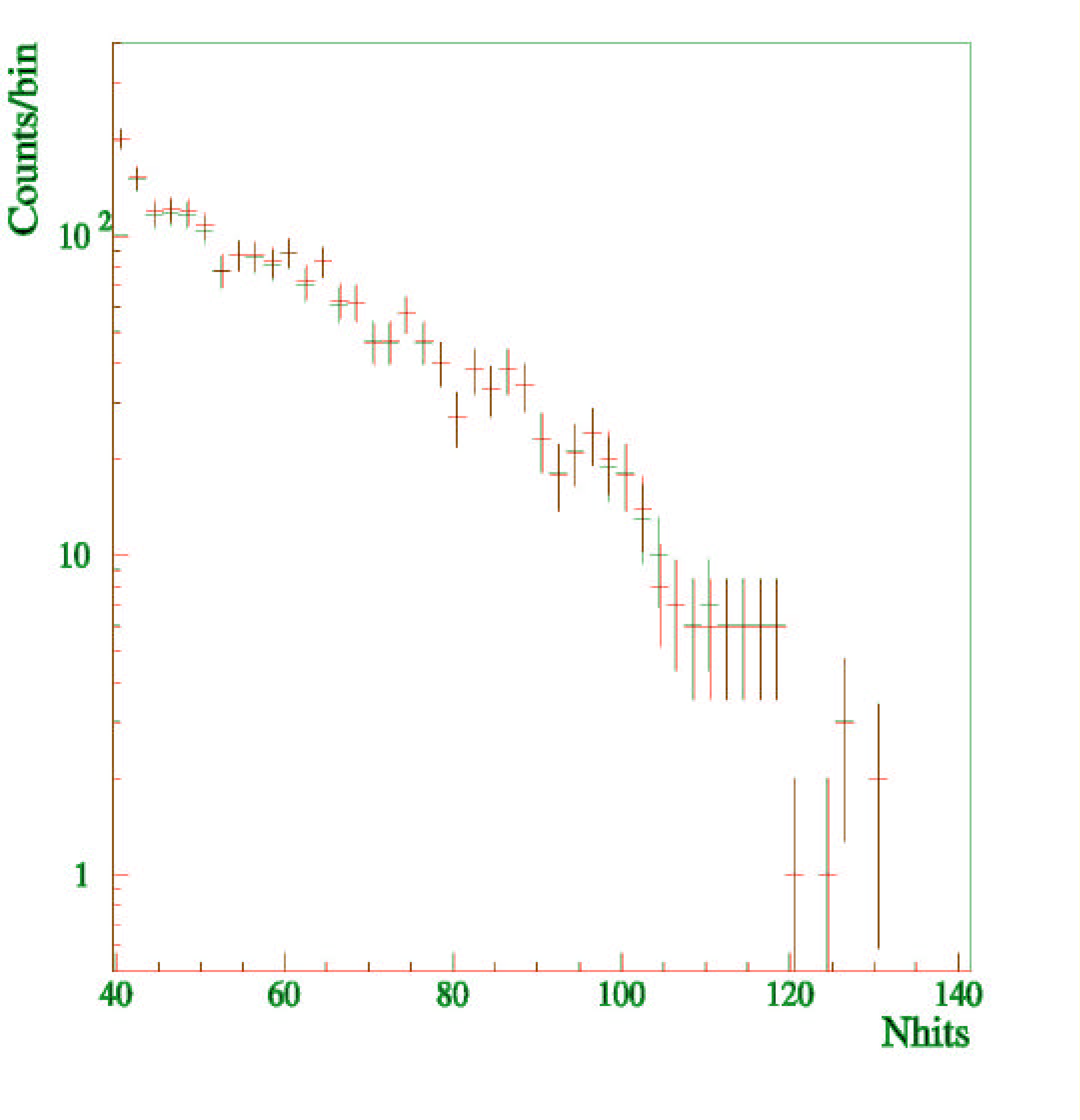




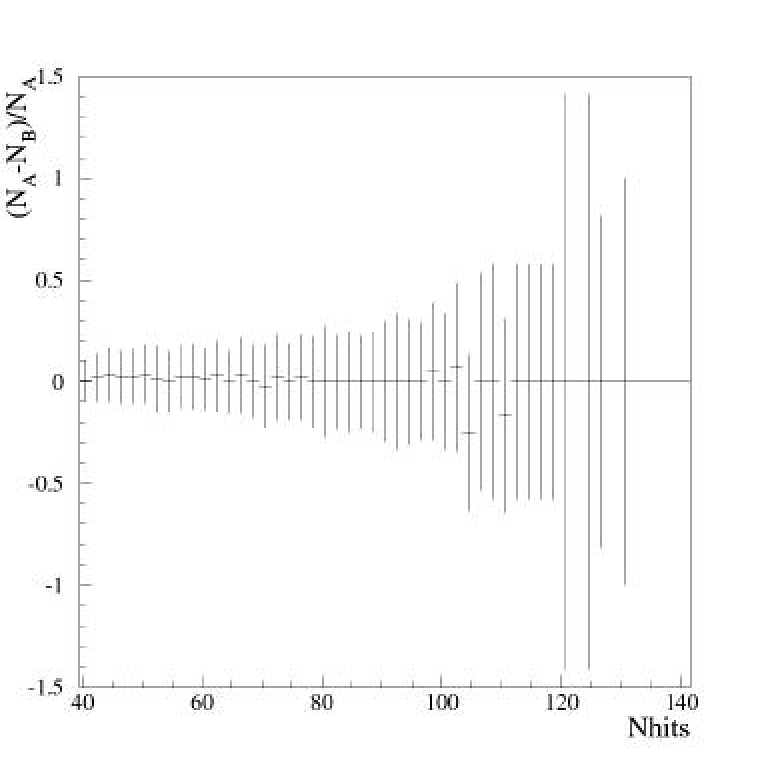
An Electronic Pickup Event

Instrumental Background Cuts



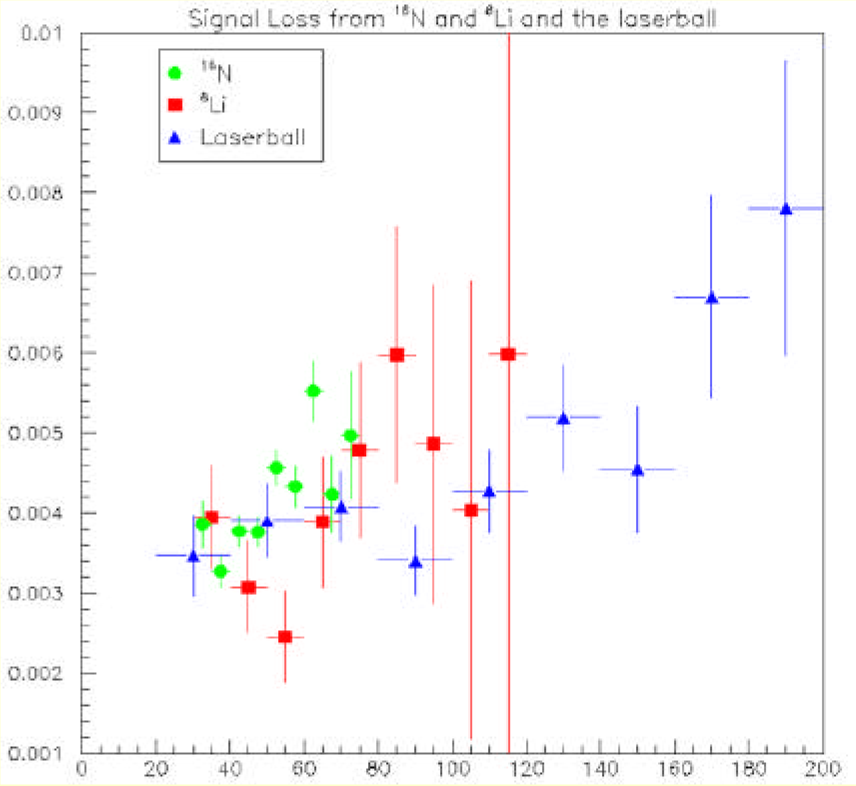


Comparison between two Instrumental Background Removal Techniques

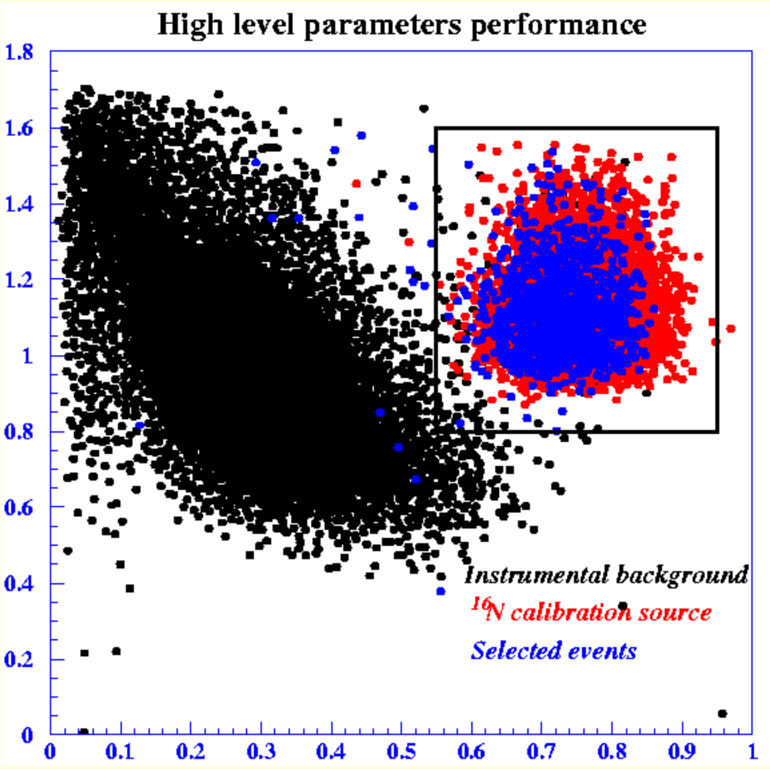


Very Small Differences Between Techniques

How do we know this worked?



Number of phototubes hit



Mean angle between phototube hits

Fraction of hits in a prompt time window

Signal loss measured with calibration sources

Contamination measured with independent cuts

Extracting the Signal

- Energy threshold set to 6.75 MeV to remove low energy radioactivity backgrounds.
- Goal is to resolve the data into contributions from the CC, ES and Neutrons.
- For each, Probability Density Functions are derived of:
  - The energy spectrum; T
  - The direction wrt to the sun; $\cos \Theta_{sun}$
  - The volume weighted radial distribution $(R/R_{AV})^3$
- Combined Maximum Likelihood used to extract individual components

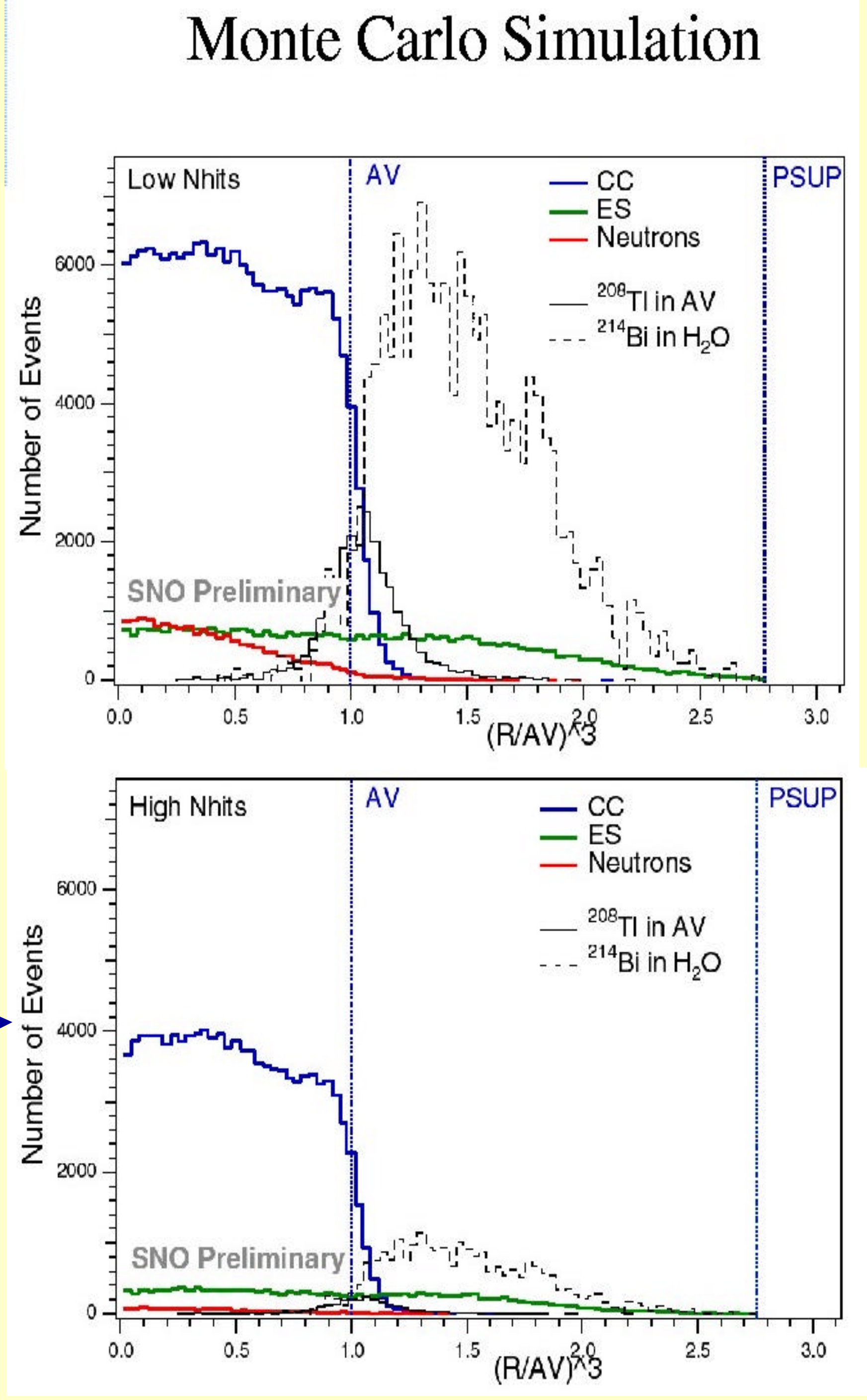
$$\Rightarrow \begin{cases} \text{CC} = 975.4 \pm 39.7 \text{ events} \\ \text{ES} = 106.1 \pm 15.2 \text{ events} \\ \text{neutrons} = 87.5 \pm 24.7 \text{ events} \end{cases}$$

Radial profiles

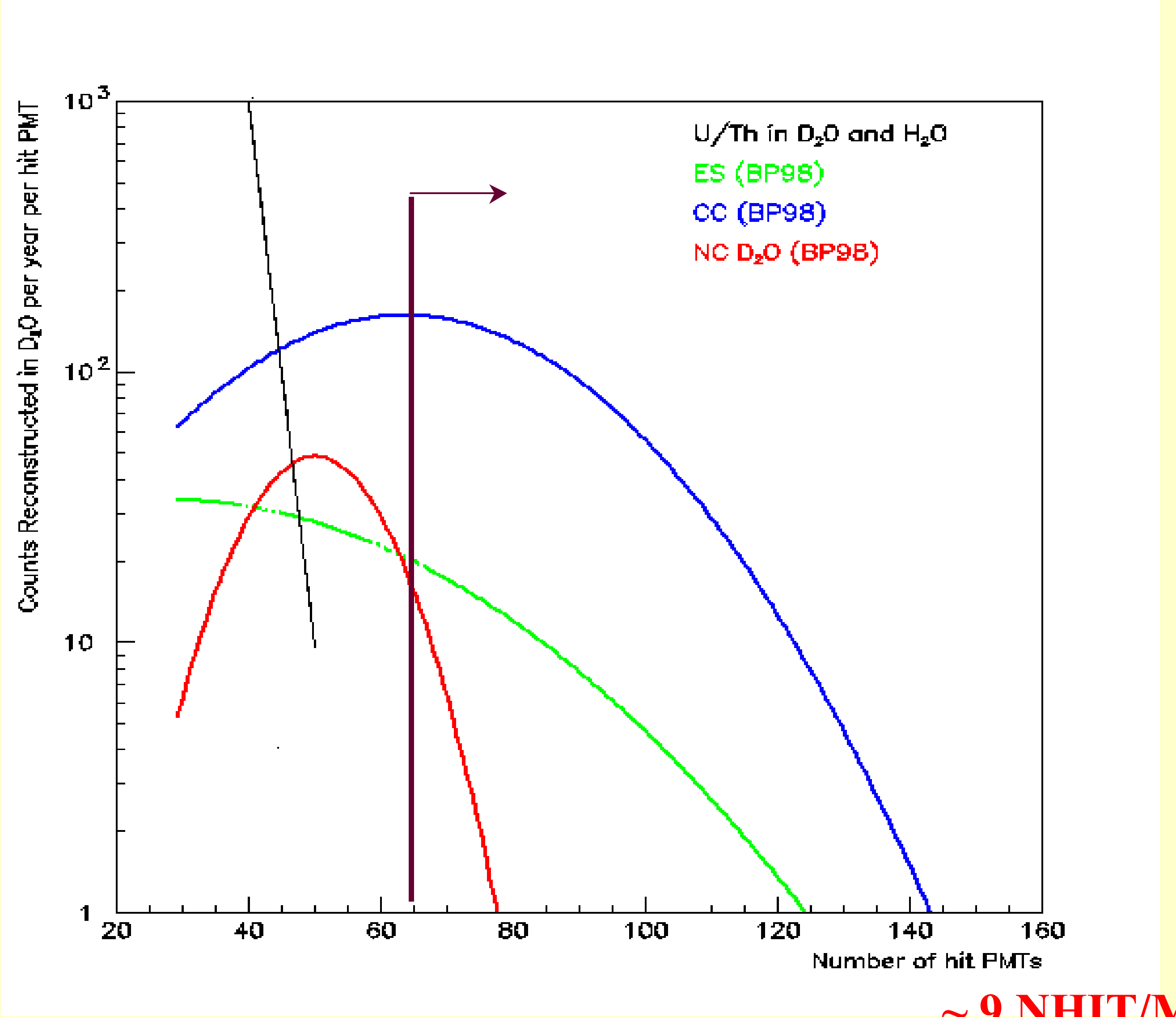
Low N_{hit}

High N_{hit}

Signals and backgrounds as a function of r^3



Signals in SNO



~ 9 NHIT/MEV

Distributions

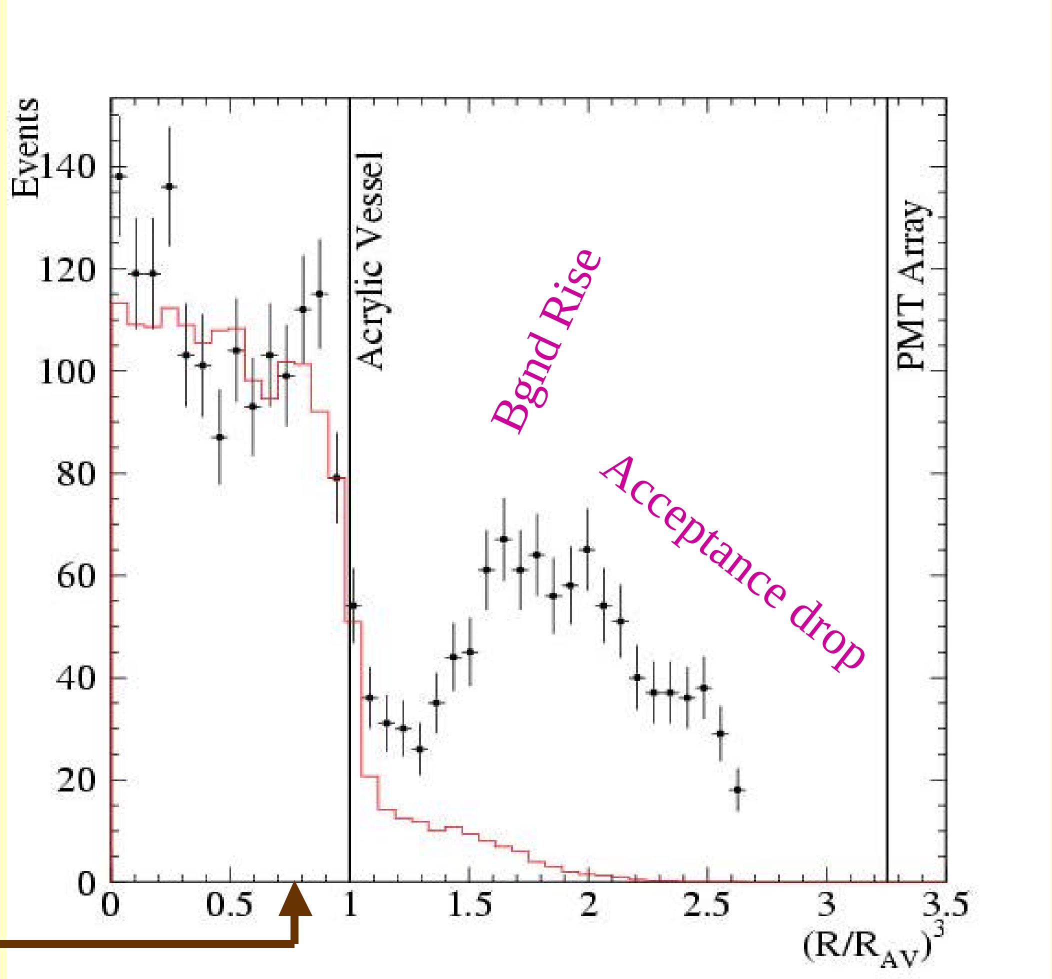
Radial Distribution Nhit ³ 65

(very small neutrons, low energy backgrounds)

Edge of AV is quite sharp.

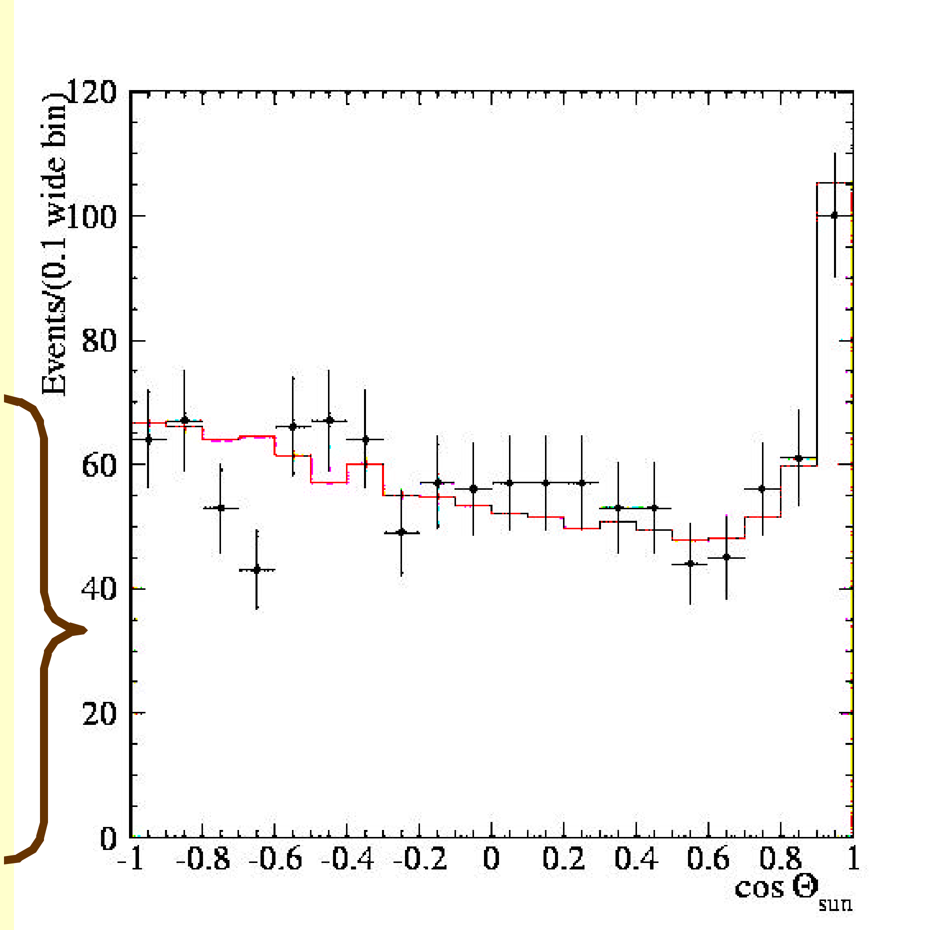
➥ Events from D_2O clearly identified.

Fiducial cut set to R=5.5m

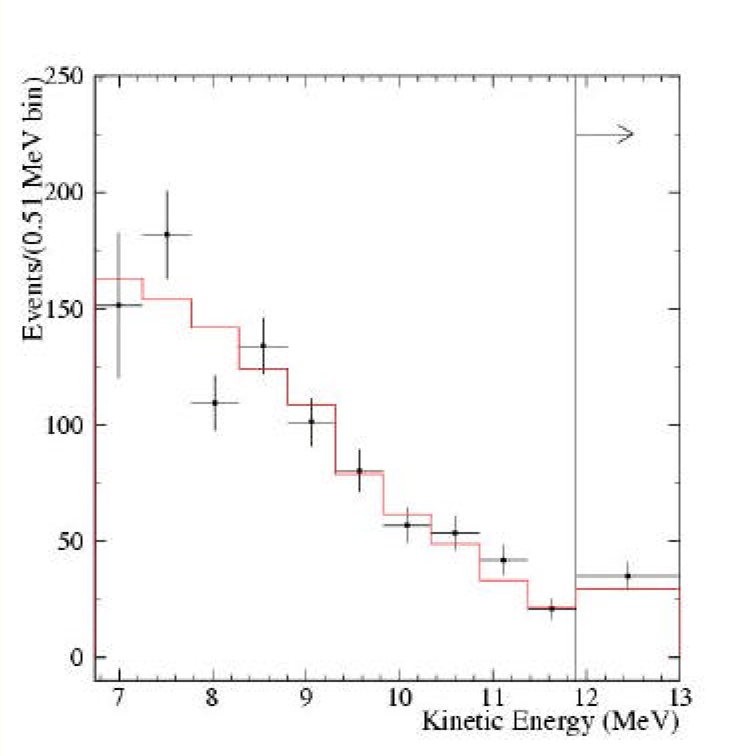


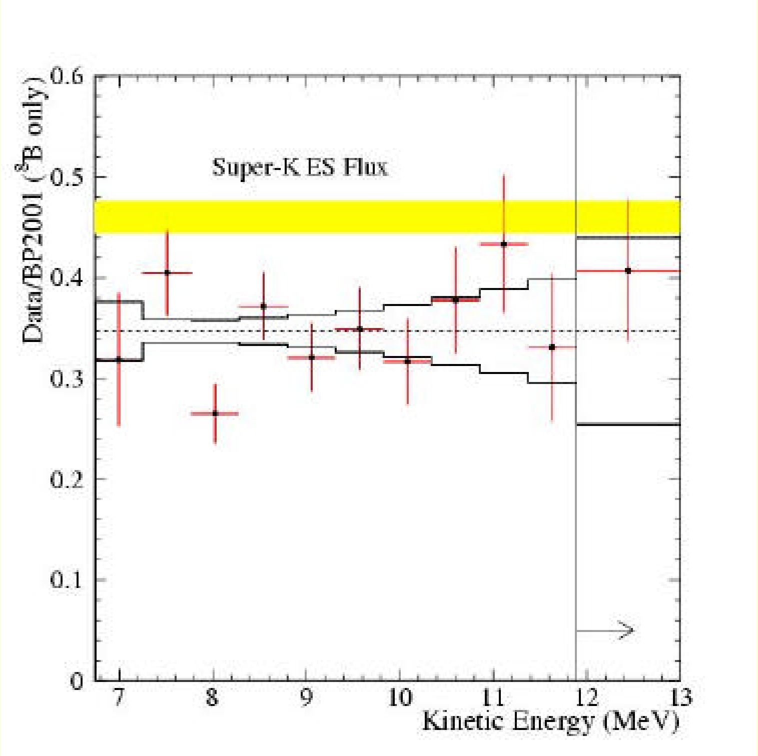
Direction of Events with respect to the SUN

Component	Angular Distribution
ES	Points from the sun
CC	~ 1- 0.3 $\cos\Theta_{sun}$
Neutrons	Isotropic
Bgnds	Isotropic



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.

Systematic Errors for Fluxes

Error Source	**CC error (%)**	**ES error (%)**
Energy scale	-5.2, +6.1	-3.5, +5.4
Energy resolution	±0.5	±0.3
Non-linearity	±0.5	±0.4
Vertex shift	±3.1	±3.3
Vertex resolution	±0.7	±0.4
Angular resolution	±0.5	±2.2
High Energy γ's	-0.8, +0.0	-1.9, +0.0
Low energy background	-0.2, +0.0	-0.2, +0.0
Instrumental background	-0.2, +0.0	-0.6, +0.0
Trigger efficiency	0.0	0.0
Live time	±0.1	±0.1
Cut acceptance	-0.6, +0.7	-0.6, +0.7
Earth orbit eccentricity	±0.1	±0.2
^{17}O, ^{18}O	0.0	0.0
Experimental uncertainty	-6.2, +7.0	-5.7, +6.8
Cross-section	3.0	0.5
Solar Model	-16, +20	-16, +20

Charged Current and Elastic Scattering Fluxes

for No Oscillation Hypothesis

- **Absolute Flux (assuming pure ν_e for ES, in $10^6\ cm^{-2}\ s^{-1}$)**

$$\Phi^{CC}(^8B) = 1.75 \pm 0.07\ (\text{stat})\ ^{+0.12}_{-0.11}\ (\text{sys.}) \pm 0.05\ (\text{theor})$$

$$\Phi^{ES}(^8B) = 2.39 \pm 0.34\ (\text{stat})\ ^{+0.16}_{-0.14}\ (\text{sys.})$$

Oscillation Test Independent of Solar Model

- **Super-Kamiokande finds***

$$\Phi^{ES}(^8B) = 2.32 \pm 0.03\ (\text{stat})\ ^{+0.08}_{-0.07}\ (\text{sys.})$$

CC is lower Than ES !

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

Charged Current vs Elastic Scattering Rates

- **SNO:** CC vs ES (Units $10^6\,cm^{-2}\,s^{-1}$)

$$\Phi^{ES}_{SNO} - \Phi^{CC}_{SNO} = 0.64 \pm 0.40 \quad \Rightarrow 1.6\sigma \text{ effect}$$

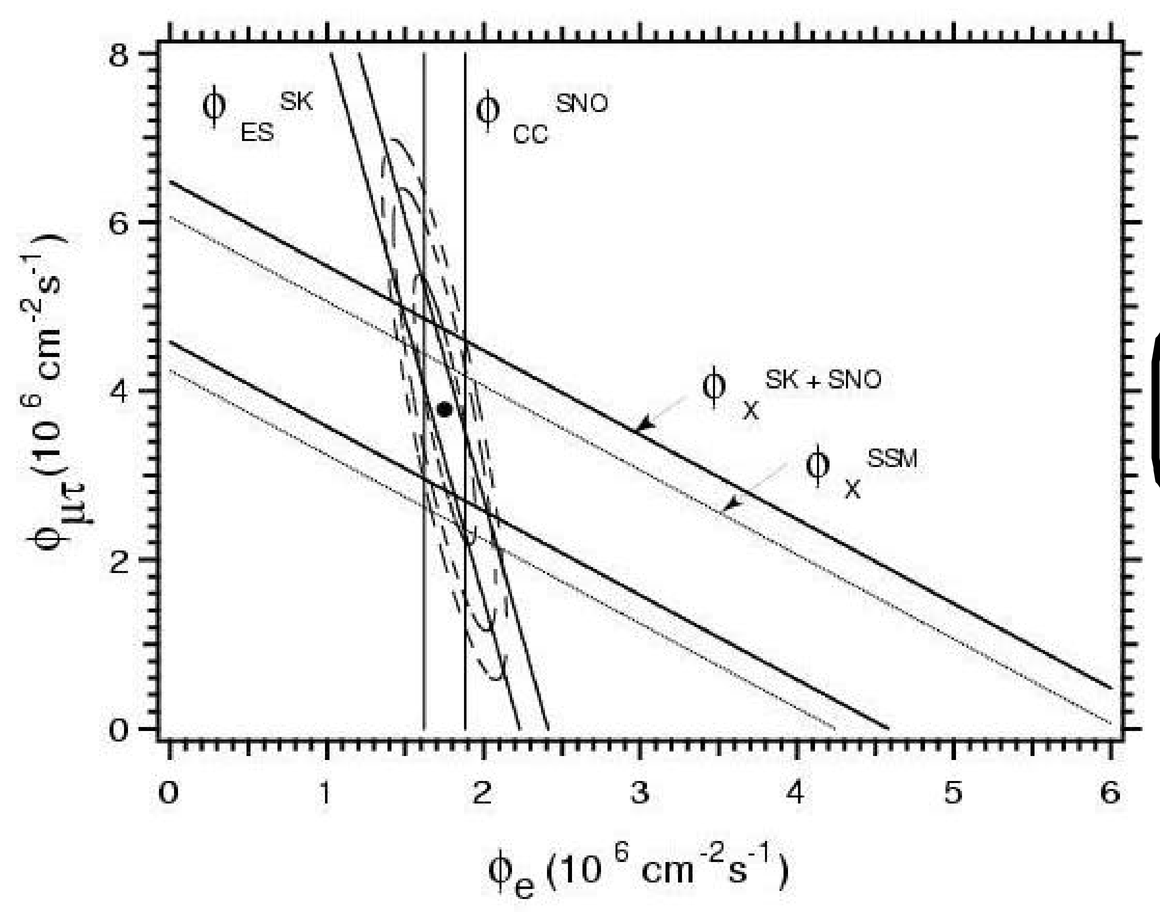
- CC at **SNO** vs ES at **SK**

$$\Phi^{ES}_{SK} - \Phi^{CC}_{SNO} = 0.57 \pm 0.17 \quad \Rightarrow \underline{3.3\sigma \text{ effect !!}}$$

99.9% c.l.

Strong Evidence for Neutrino Oscillations

Neutrino Oscillations



Total ^{8}B flux is

5.44 ± 0.99 ´ $10^{6}\ cm^{-2}s^{-1}$

Note: this is in excellent agreement with the BPB01 prediction of $5.01^{+1.01}_{-0.81}$

Flux of non-electron neutrinos is 68% of total

The CC result from SNO combined with the ES result from SK gives clear evidence for the oscillation of electron- neutrinos to mu- and/or tau- neutrinos (or anti-neutrinos).

Comparison with Standard Solar Model: BPB01

- Total Flux

$$\Phi_{SNO}\,(^8B) = 5.44 \pm 0.99 \times 10^6\ cm^{-2}s^{-1}$$

$$\Phi_{SSM}\,(^8B) = 5.01\ ^{+1.01}_{-0.81} \times 10^6\ cm^{-2}s^{-1}$$

- CC Flux (ν_e) Relative to BPB01

$$R^{CC}\,(^8B) = 0.347 \pm 0.029$$

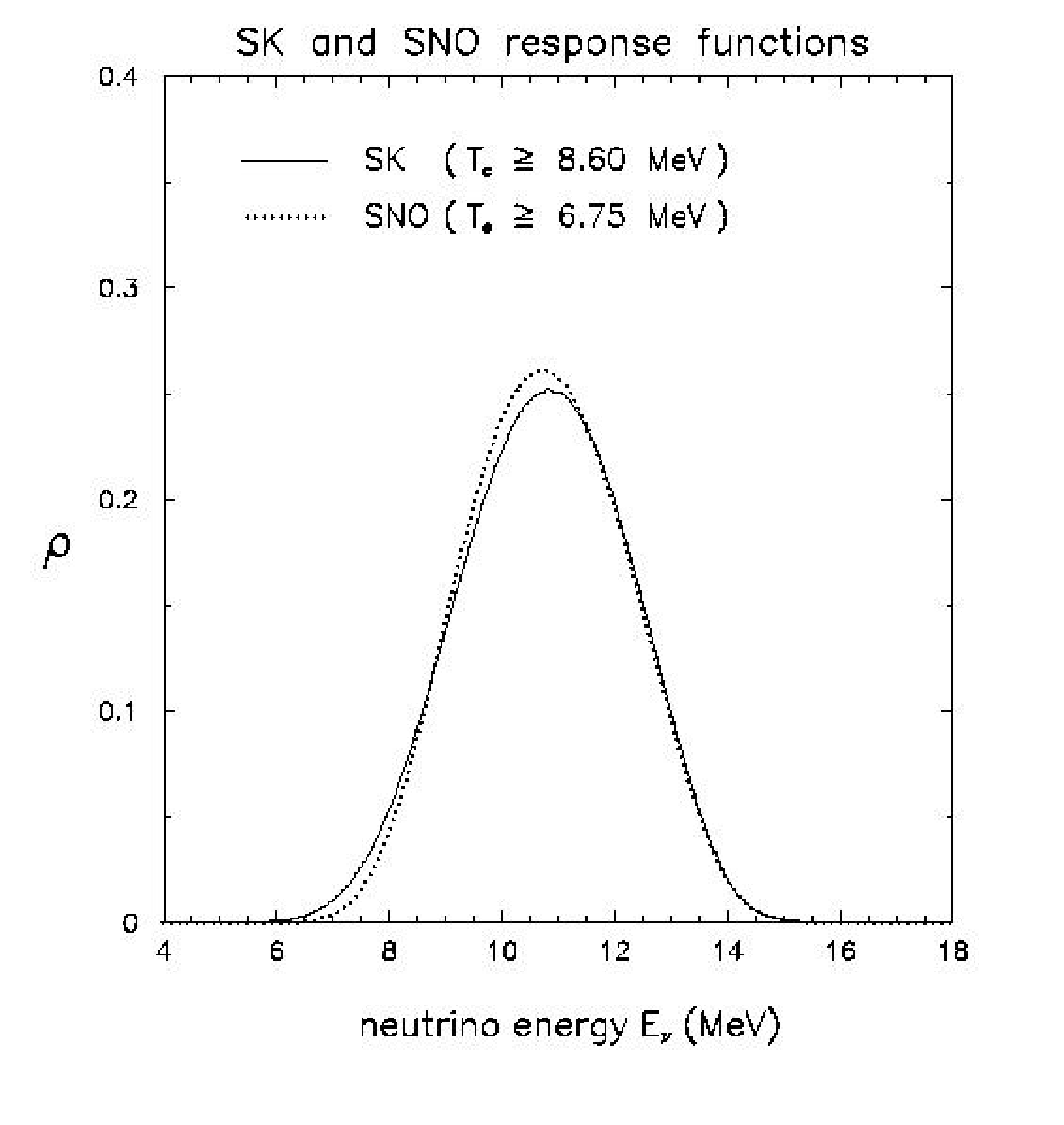
Constraints on Oscillation Scenarios

- If oscillation with mixing solely to a sterile neutrino is occurring the SNO CC - derived ^8B flux above a threshold of 6.75 MeV will be essentially identical with the integrated Super-Kamiokande ES - derived ^8B flux above a threshold of 8.6 MeV.

⤷ Correcting for the ES threshold the flux difference is

0.53 ± 0.17, or $3.1\ \sigma$

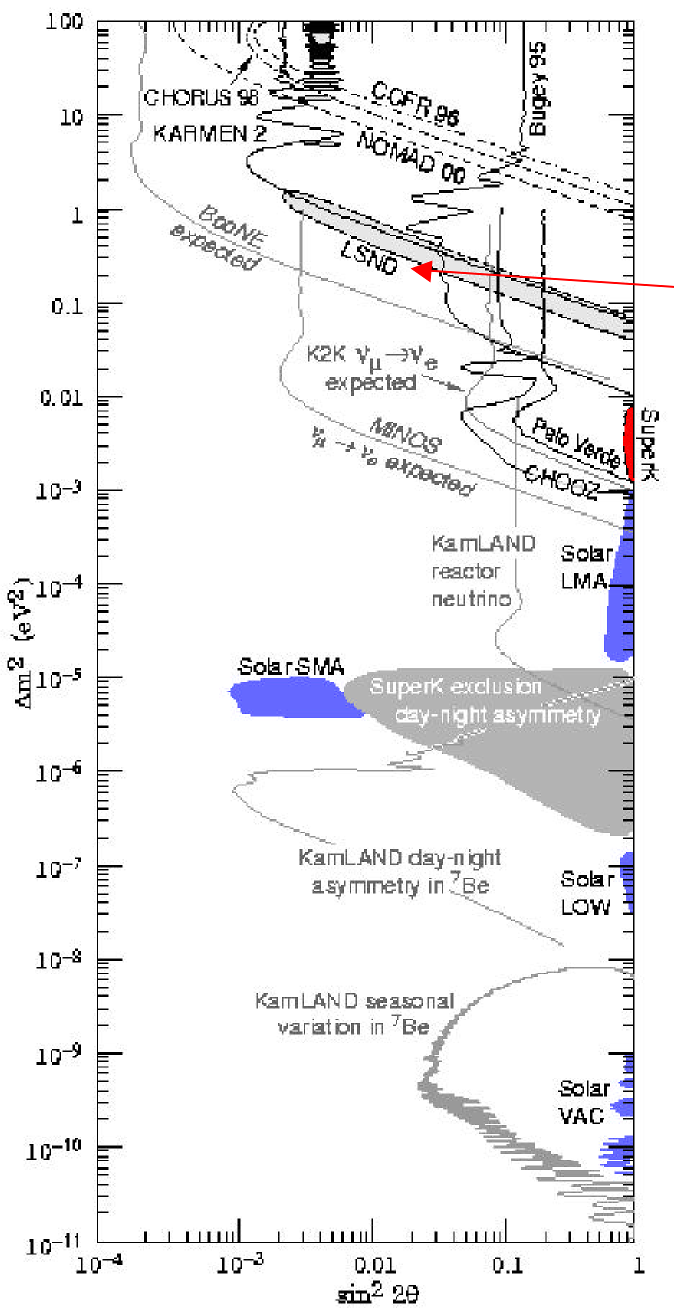
→ **Therefore the hypothesis of oscillations solely to sterile neutrinos is excluded at the 3.1 s level.**



Fogli et al.

Hep-ph/0106247

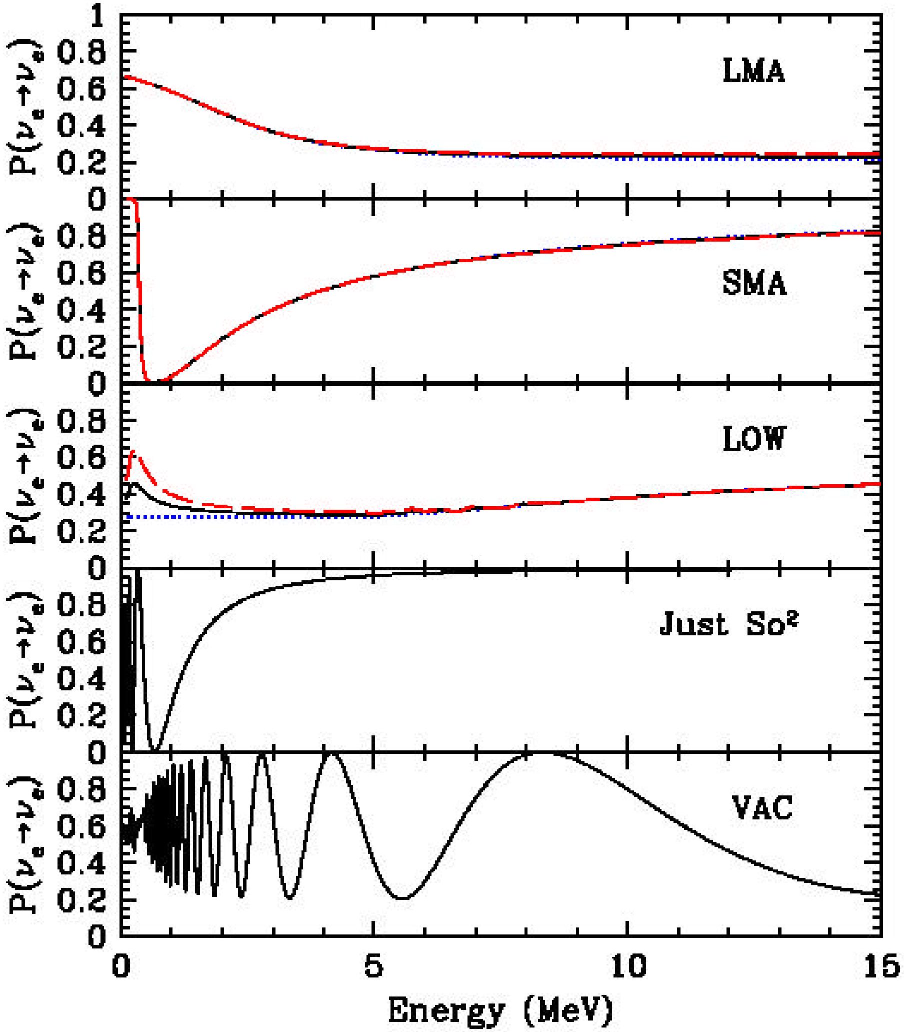
Particle Data Group 2000

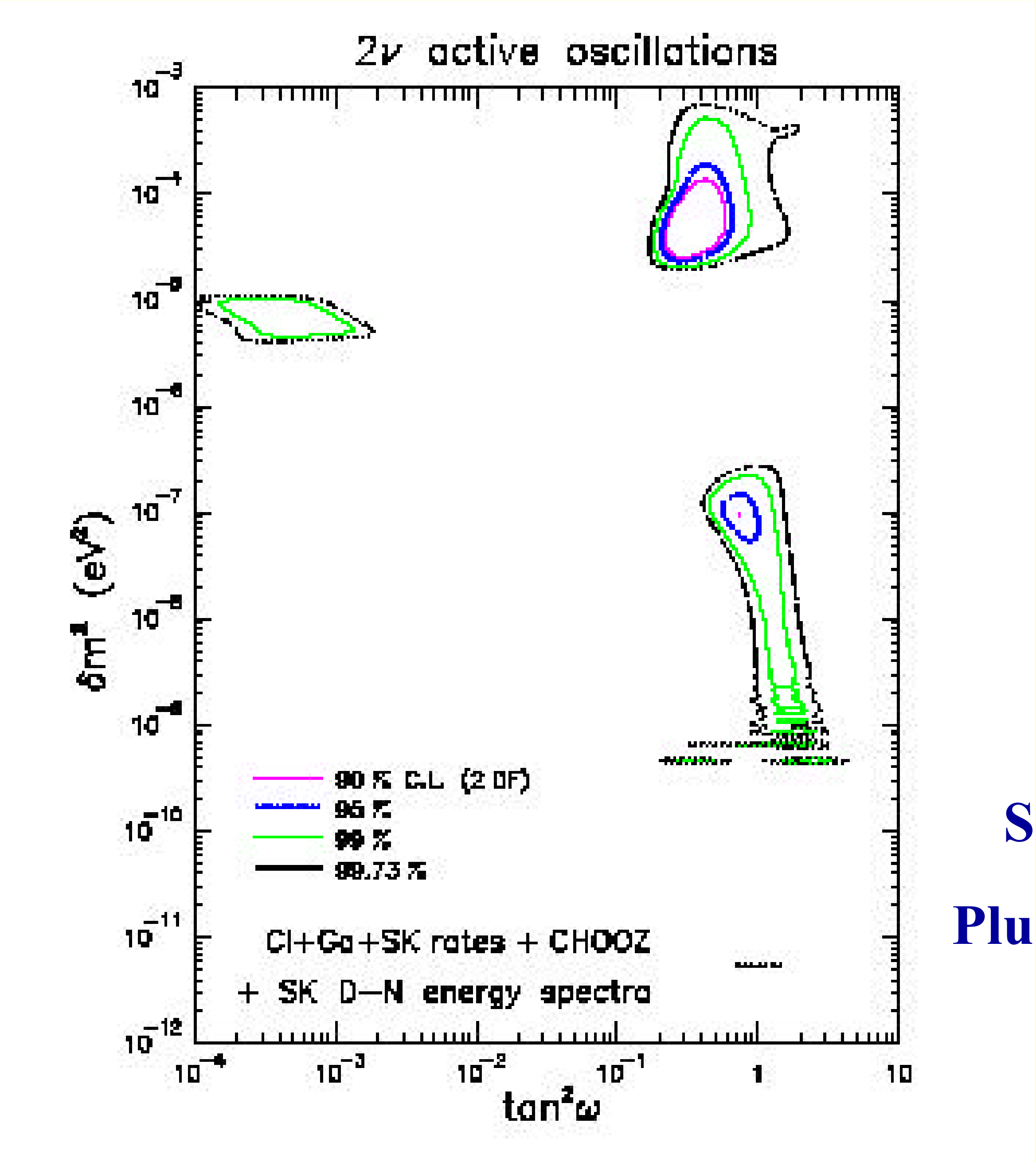


?? $\nu_\mu \to \nu_e$

$\nu_\mu \to \nu_\tau$

MSW Effects + Vacuum Oscillations for Solar Neutrinos





Fogli et al.

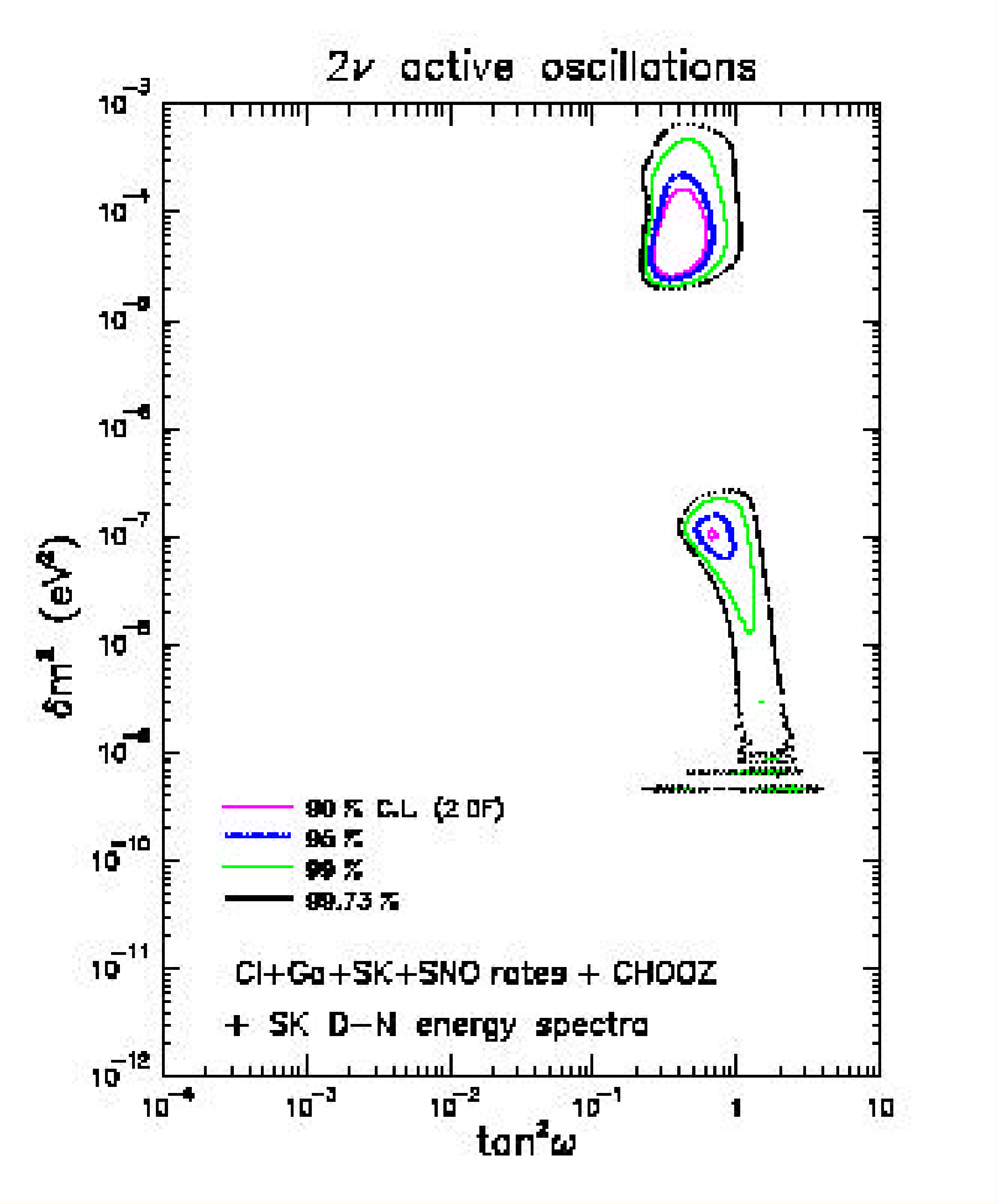
hep-ph/0106247

Pre - SNO

Using Standard

Solar Model fluxes

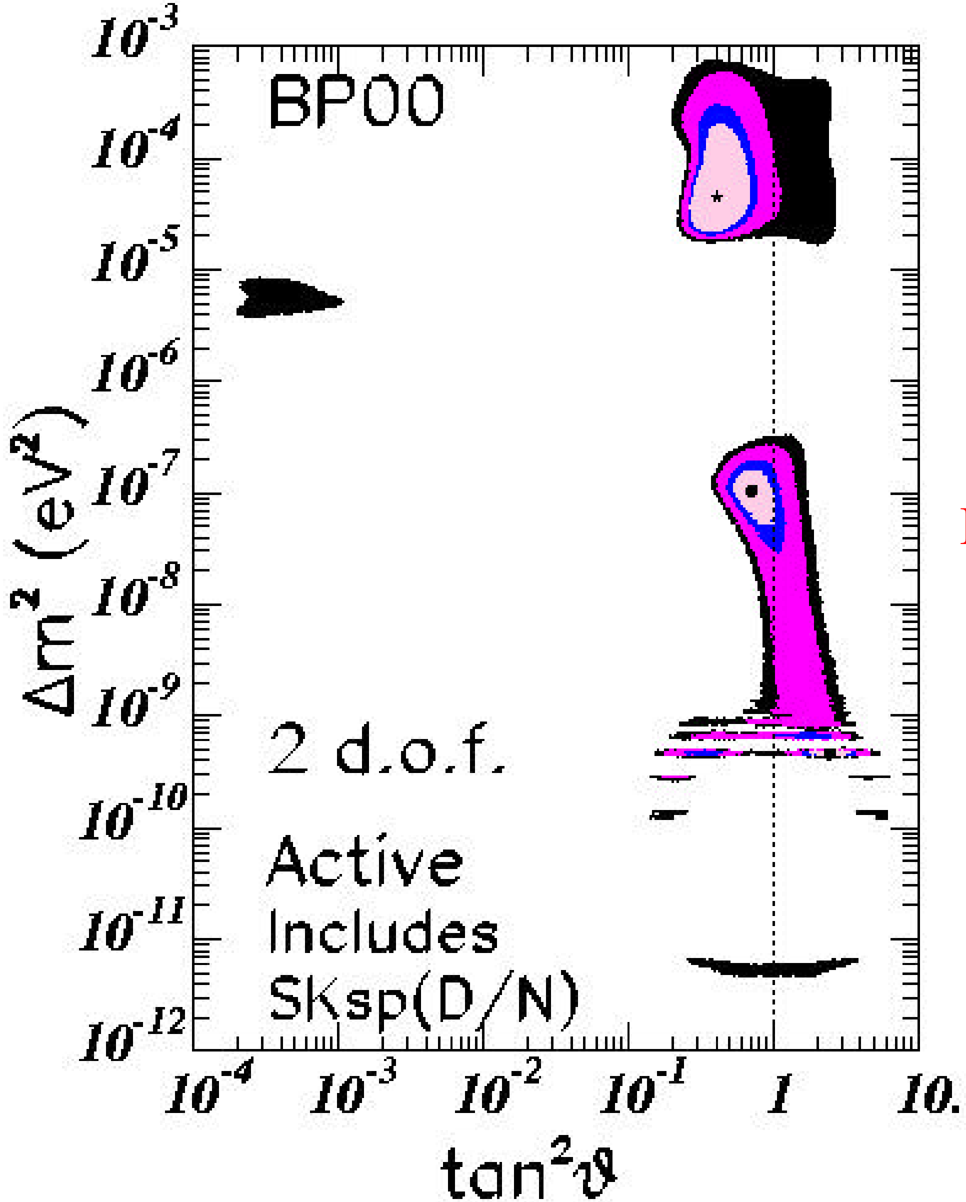
Plus other experiments



Fogli et al.

hep-ph/0106247

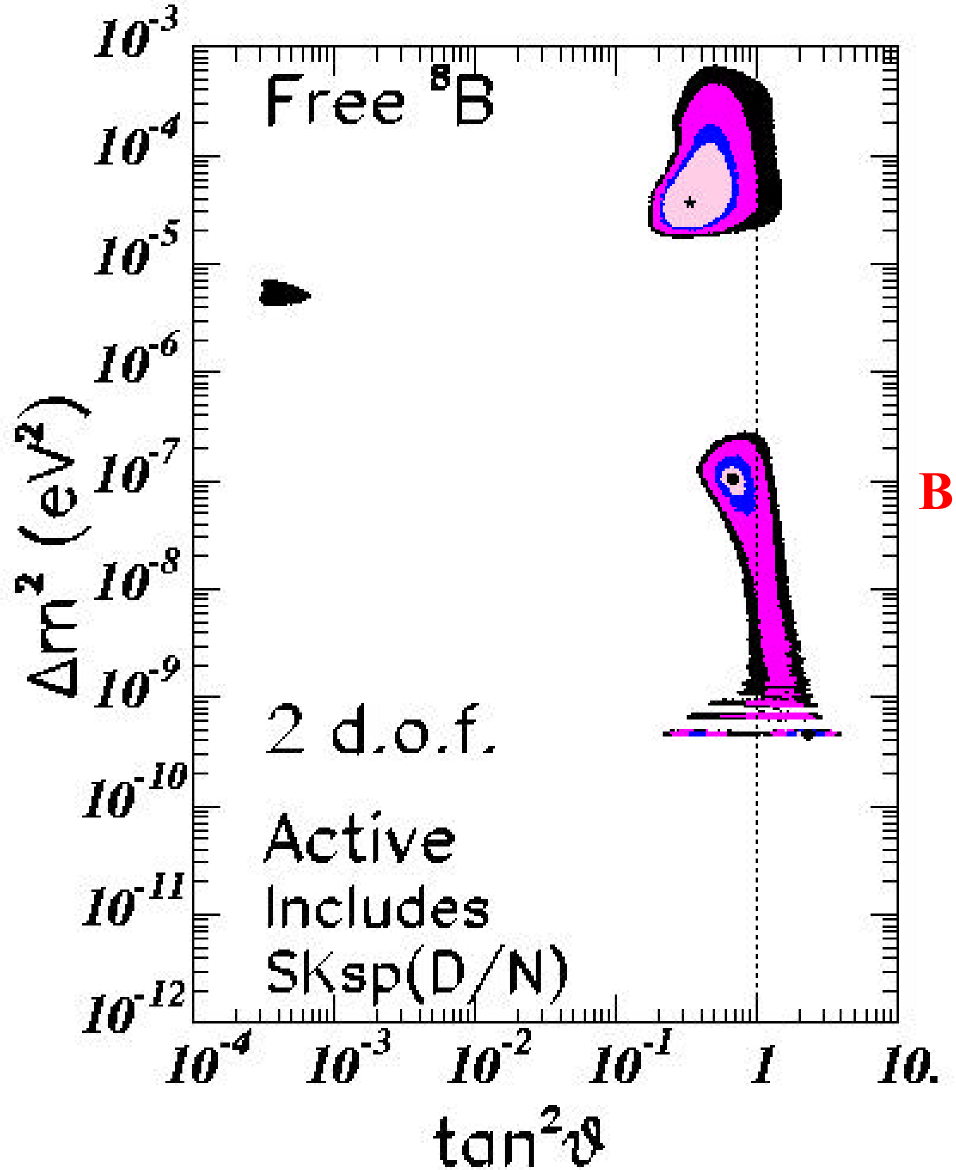
Post - SNO



Bahcall, Gonzales-Garcia

and Pena-Garay

hep-ph/0106258



Bahcall, Gonzales-Garcia and Pena-Garay hep-ph/0106258

Cosmological Implications

These results plus analyses suggest:

$(\Delta m_{e\mu})^2 \lessapprox 10^{-3}\ eV^2$ <u>or</u>

$(\Delta m_{e\tau})^2 \lessapprox 10^{-3}\ eV^2$

Limits on ν_e mass give: $m(\nu_e) < 2.8\ eV$

Assuming the hypothesis of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations in atmospheric neutrinos: $(\Delta m_{\mu\tau})^2 \approx 3 \times 10^{-3}\ eV^2$

Σ neutrino masses: $0.05 < \sum_{e\mu\tau} m < 8.4\ eV$

➥ limit on mass fraction of neutrinos in the universe: $0.001 < \Omega_\nu < 0.18$

Physics Program

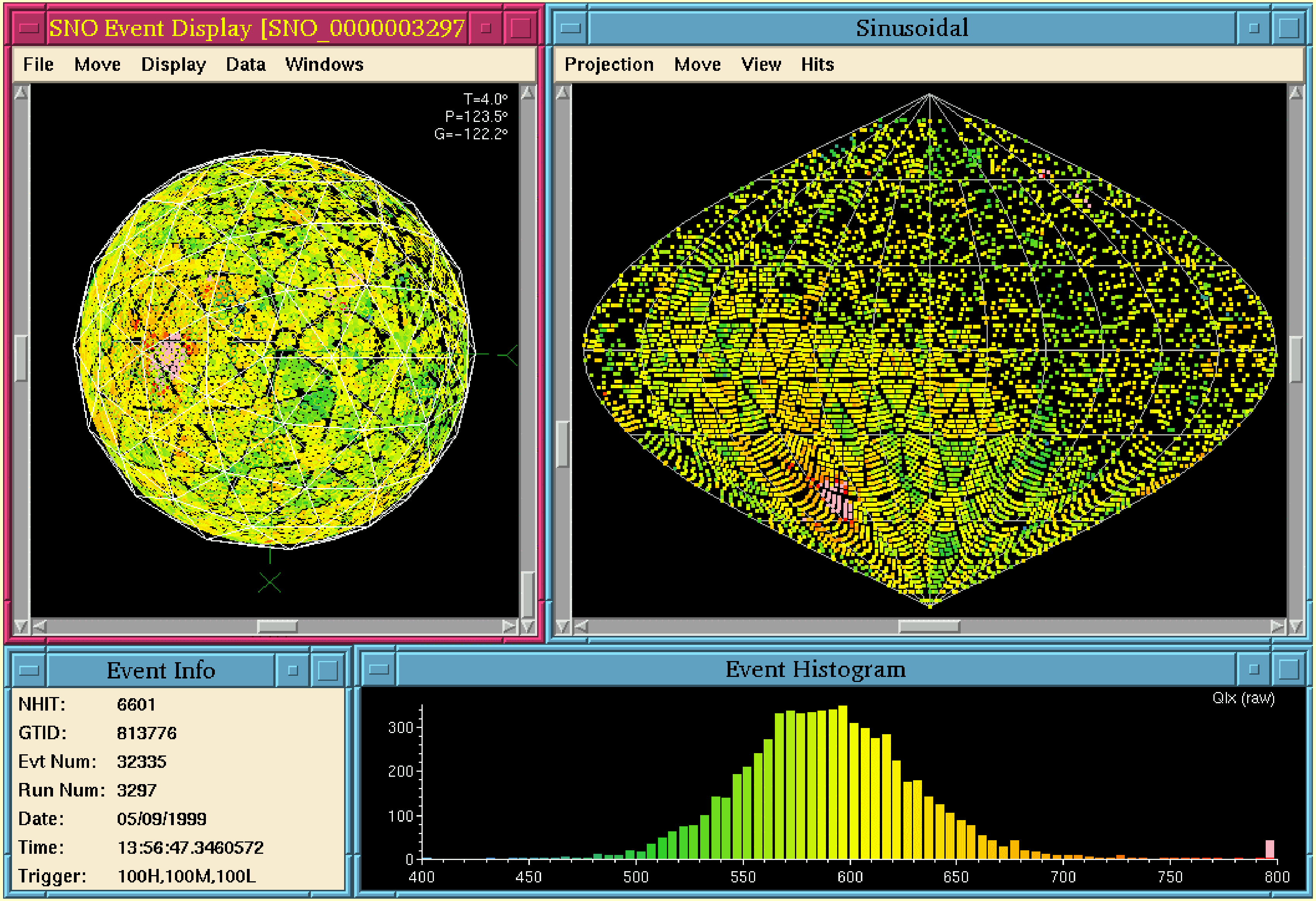
- **Solar Neutrinos**
  - → Electron Neutrino Flux
  - → Total Neutrino Flux
  - → Charged Current Energy Spectrum
  - → Day/Night effects
  - → Seasonal variations

- **Atmospheric Neutrinos & Muons**
  - → Downward going cosmic muon flux
  - → Upward going muons and angular dependence

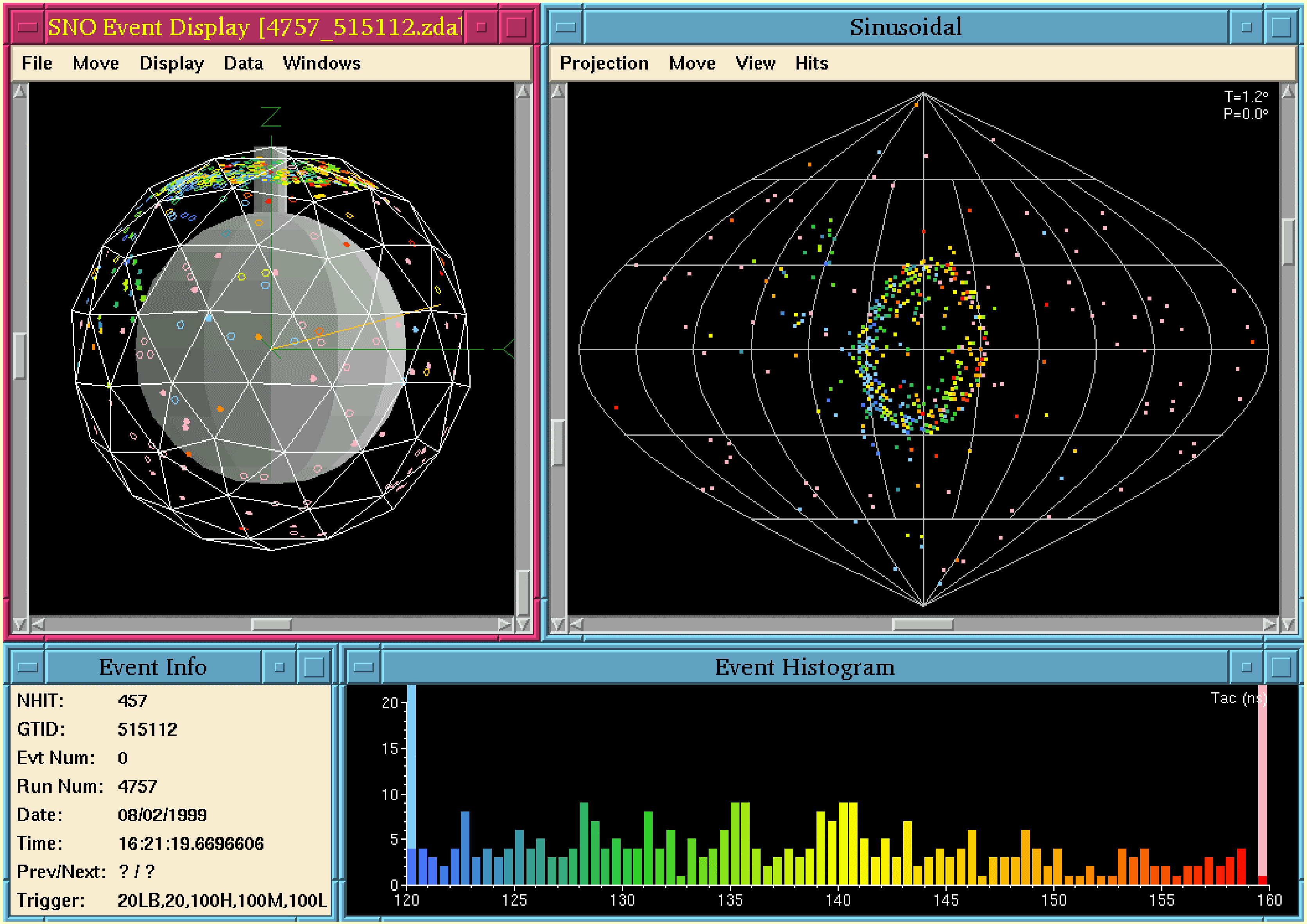
- **Supernova Watch**

- **Antineutrinos, proton decay…**

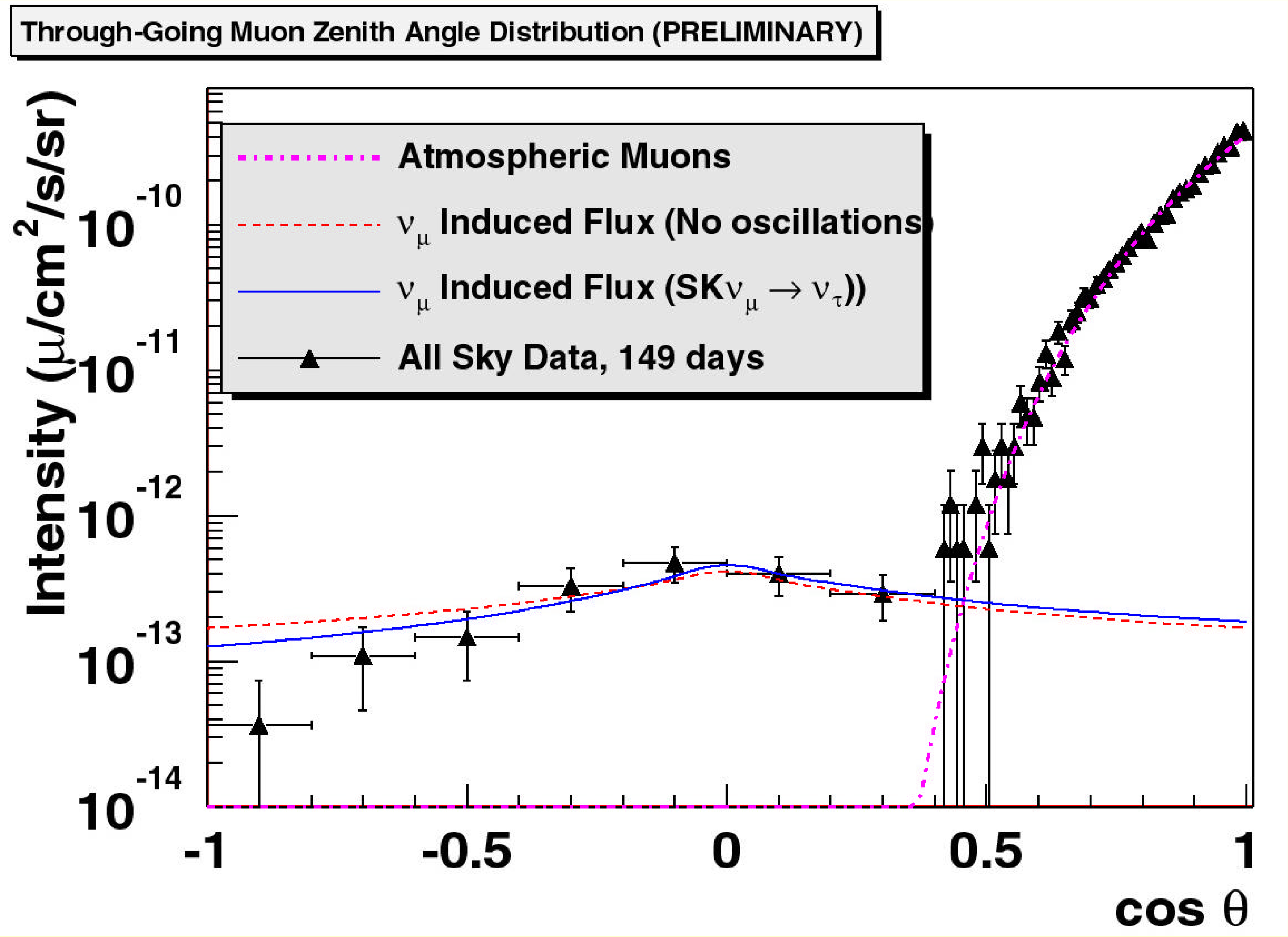
SNO Cosmic Ray Muon Event (Charge)



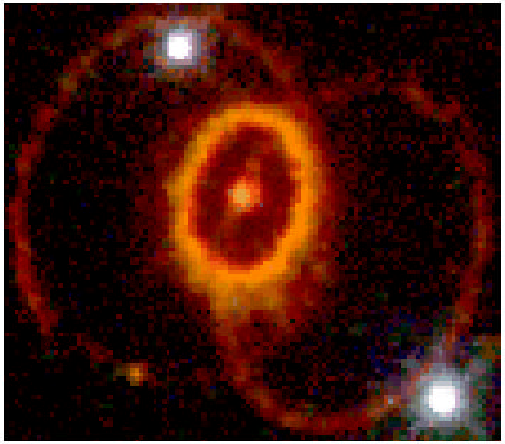
SNO Atmospheric Neutrino Candidate



Muon Analysis



SNO and Supernovae



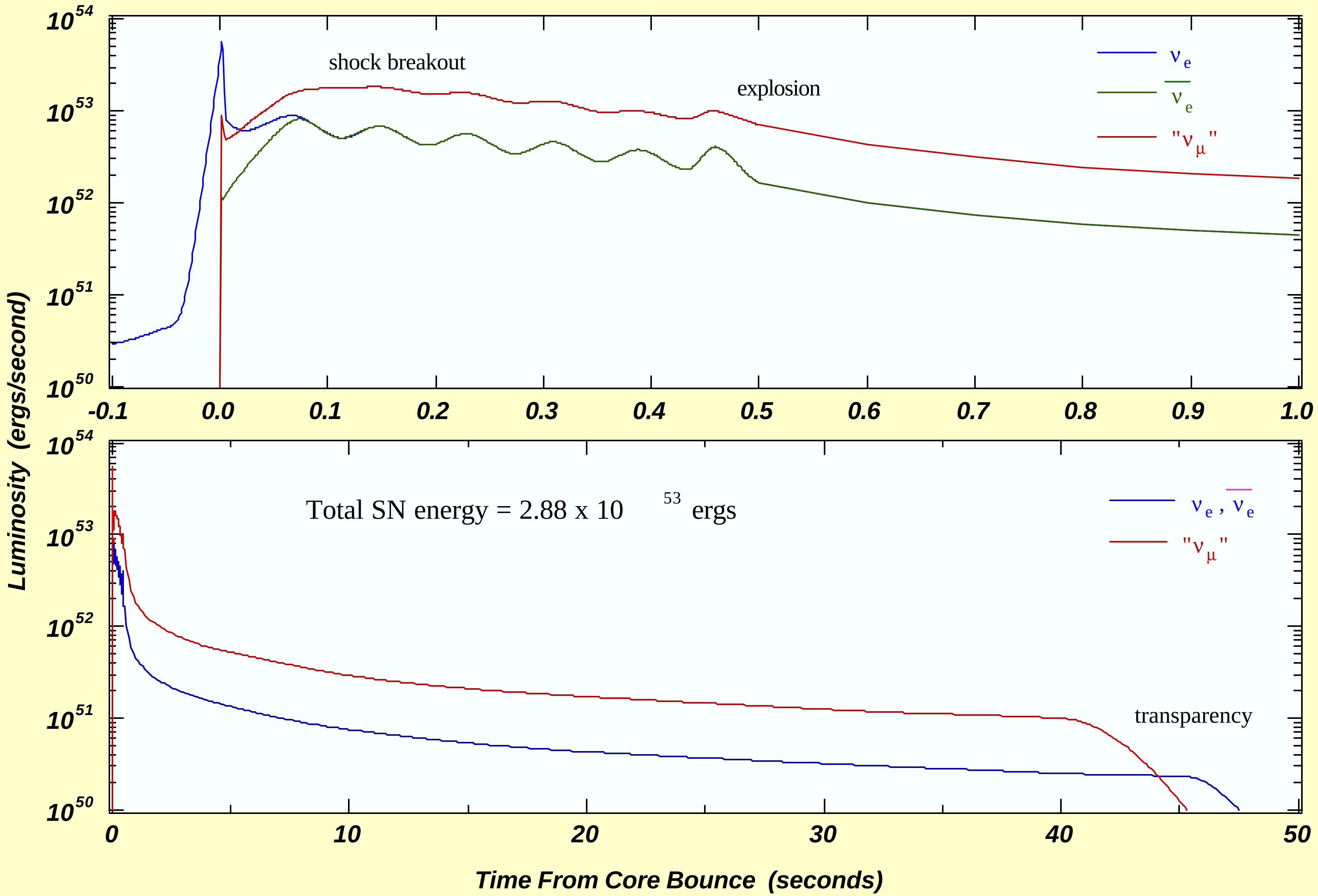
SN1987A

Estimates of supernovae in our galaxy range from 1 in 10 years to 1 in 30 years.

- The SNO Data Acquisition System has a 100 kHz burst mode.
- If there is a supernova during it's lifetime, SNO will:
  - Measure the initial ν_e burst (will detect ~1000 events at 10kpc).
  - Measure all types of neutrinos via neutral current interaction
  - Measure the energy spectrum of ν_e.

Supernova Neutrino Luminosity Spectrum

Using the model of Burrows et al. (1992)



Conclusions

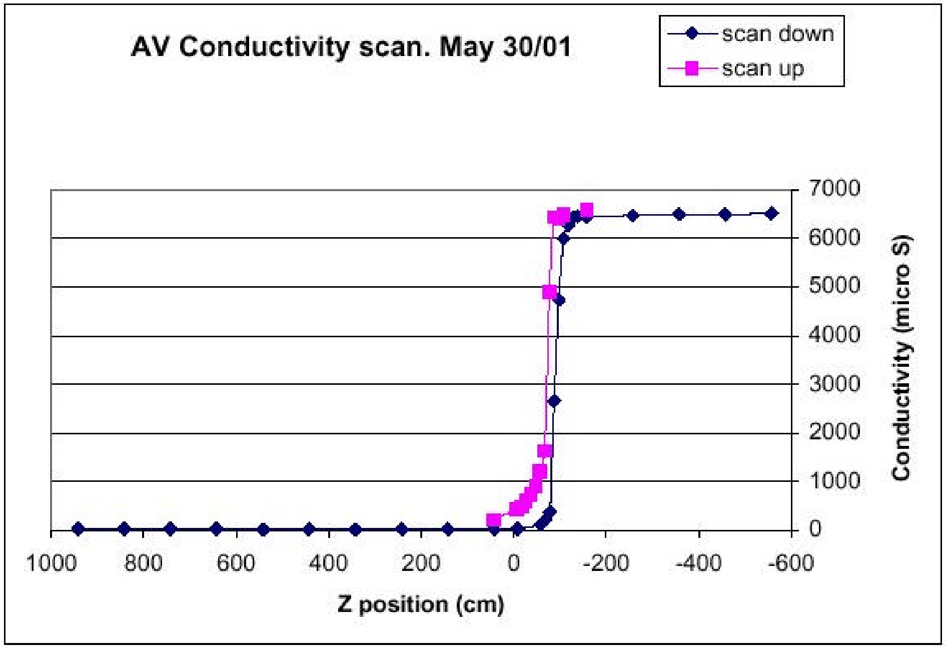
- The SNO detector is taking very nice data. Phase I is complete.
- The CC rate is low compared to the ES rates as measured by SNO and SK. This provides strong evidence for ν_e oscillations, independent of solar models.
- Oscillation solely to sterile neutrinos is strongly disfavored.
- These results provide the first direct indication of solar neutrinos of type other than ν_e .
- These results provide the first measurement of the total flux of active ^8B neutrinos from the Sun. The flux agrees well with the SSM predictions.

Outlook

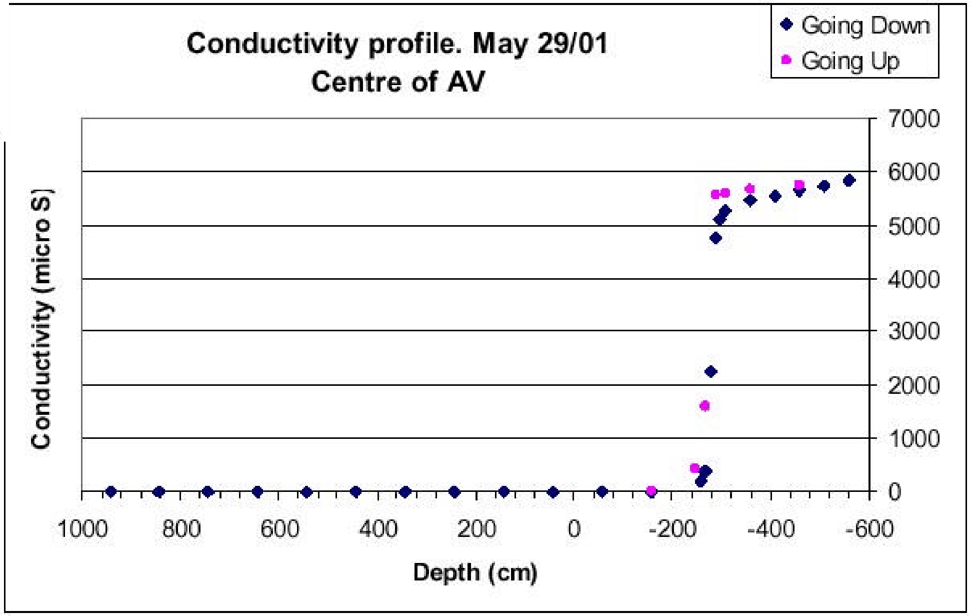
- Analysis tools all in place. Work will continue on other topics and we plan to release other papers soon. E.g..
  - → Day/night and seasonal effects
  - → NC rate in pure D_2O phase
  - → Muons, Atmospheric neutrinos…
  - → Supernova Watch
- Phase II with NaCl in detector is just starting. The plan is to run in that configuration for 8 months to a year.
- Water radioactivity numbers are low. This will be maintained during the NaCl phase.

Phase II Underway!!

NaCl Injected into D_2O. Calibrations in Progress.



Conductivity Measurements Taken During Salt Addition



CFI PROPOSAL: INTERNATIONAL UNDERGROUND SCIENCE FACILITY AT SNO

$30 M FOR: - DEVELOPMENT SPACE FOR NEW EXPERIMENTS
- SPACE FOR PICASSO + OTHER INTERNATIONAL PROJECTS
- RESEARCH & DEVELOPMENT LABORATORY ON SURFACE