First Physics Results from the Sudbury Neutrino Observatory

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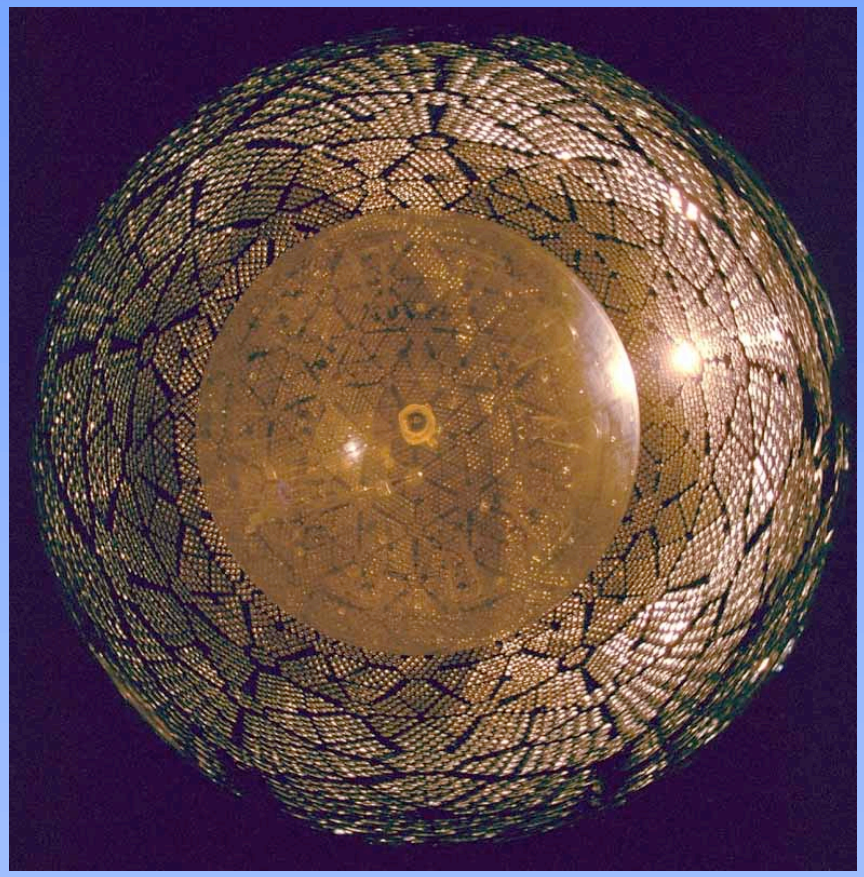
for the SNO Collaboration

June 18, 2001

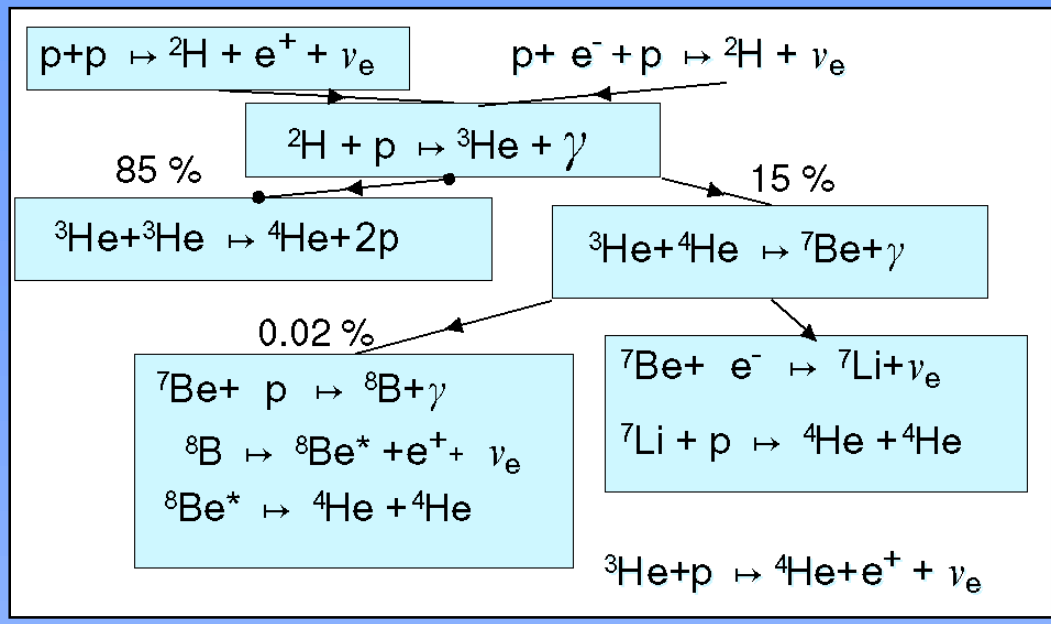
Sudbury Neutrino Observatory

- Introduction & Summary
- Detector Response & Data Analysis
- Results & Implications
- Outlook for SNO & other Experiments



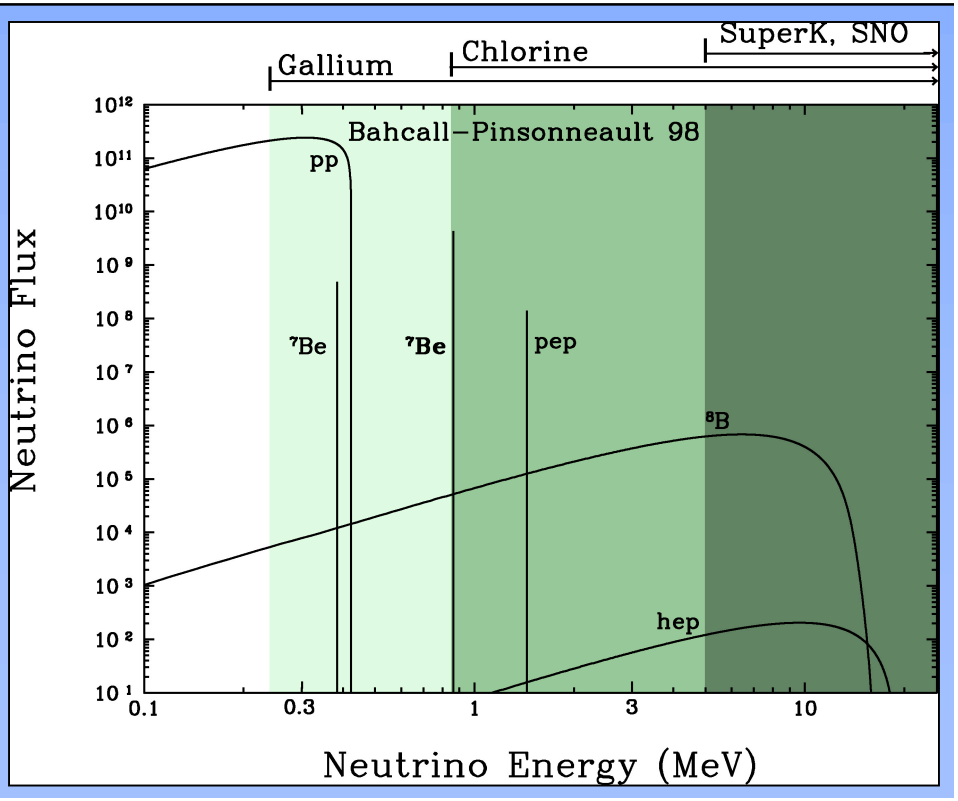
The Solar Neutrino Problem

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



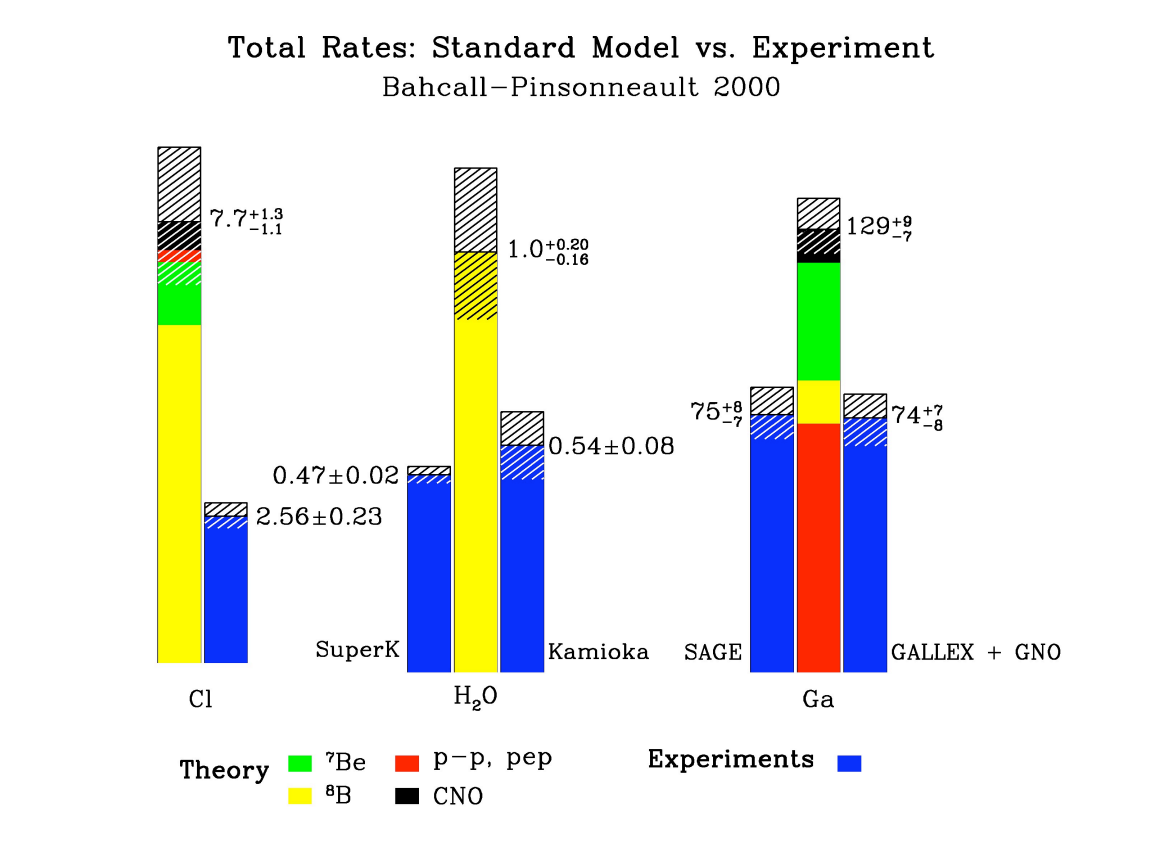
- **"…to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars."**
- **Phys. Rev. Lett. 12, 300 (1964); Phys. Rev. Lett. 12, 303 (1964)**

  Bahcall and Davis



The Solar Neutrino Problem

- Subsequent 35 years have seen five experiments all measure a deficiency of solar neutrinos



Either

Solar Models are Incomplete or Incorrect

Or

Neutrinos Undergo Flavor Changing Oscillations

The Sudbury Neutrino Observatory

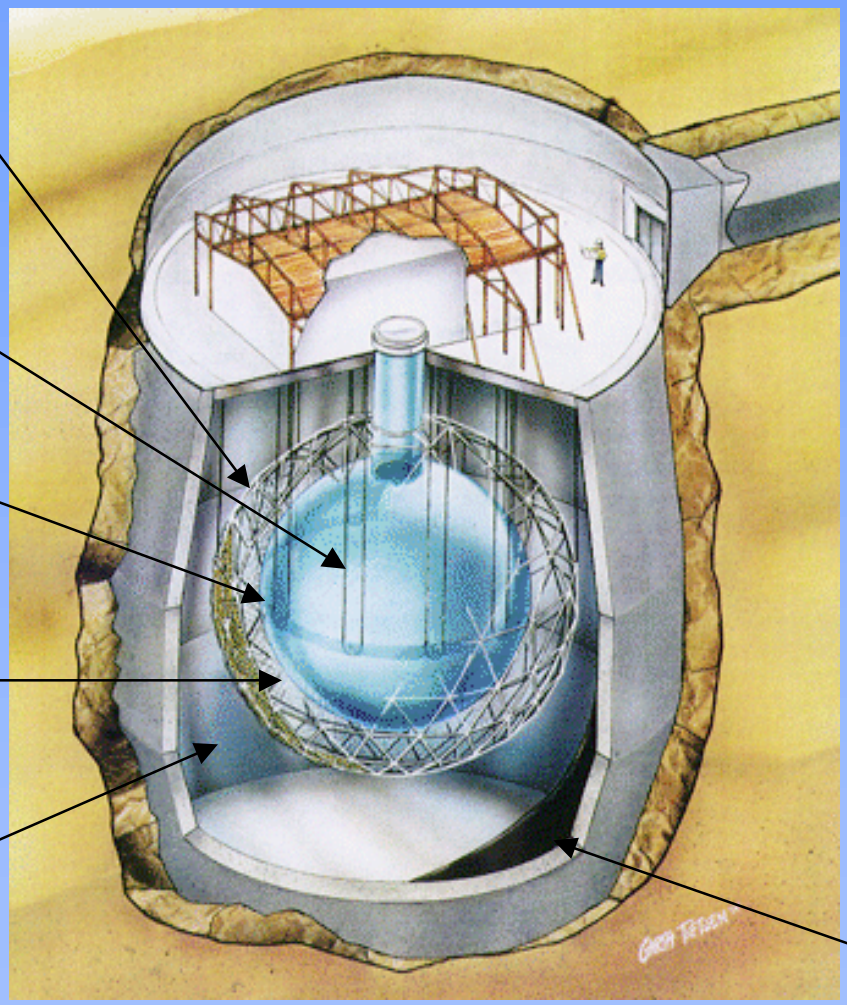
17.8 m Diameter Support Structure for 9456 PMTs, 56% coverage

1006 Metric Tons D_2O

12.01 m Diameter Acrylic Vessel

1700 Metric Tons Inner Shielding H_2O

5300 Tons Outer Shield H_2O



Clean Room Construction

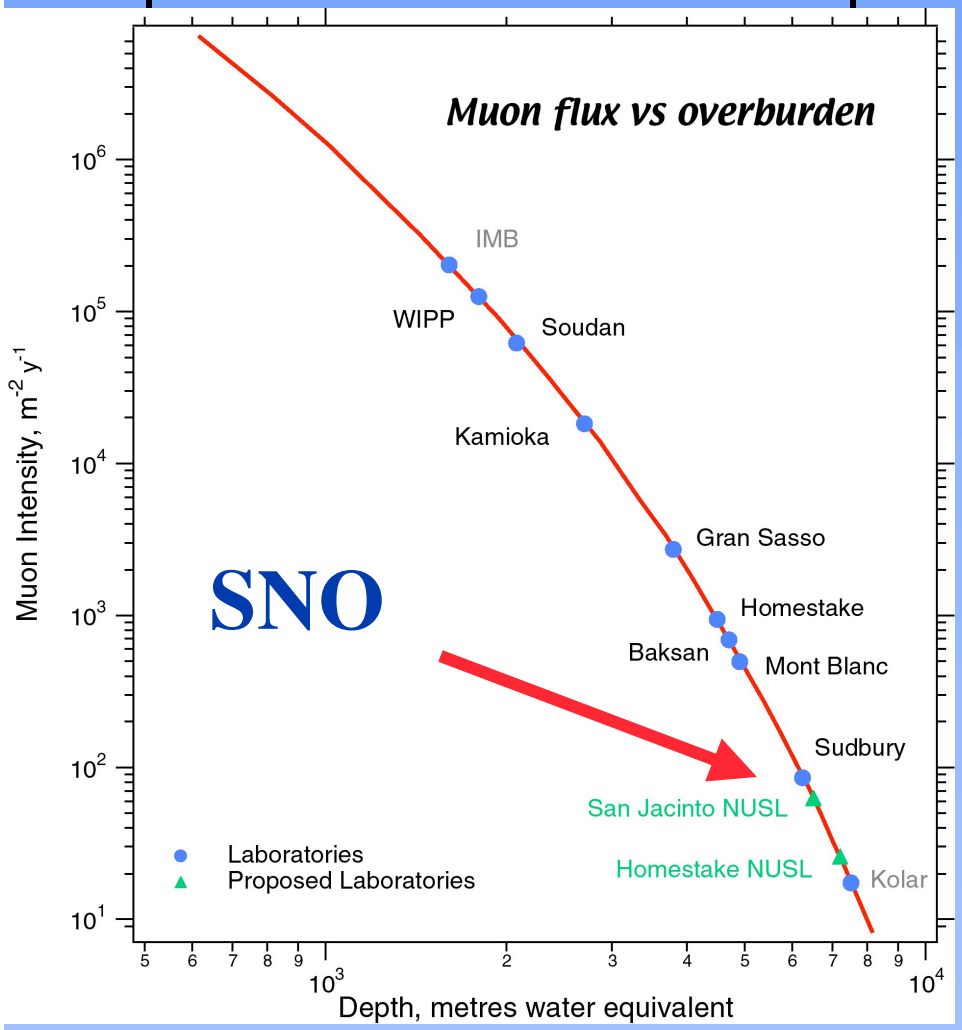
Ultra-low Activity Components

Ultra-Pure Water

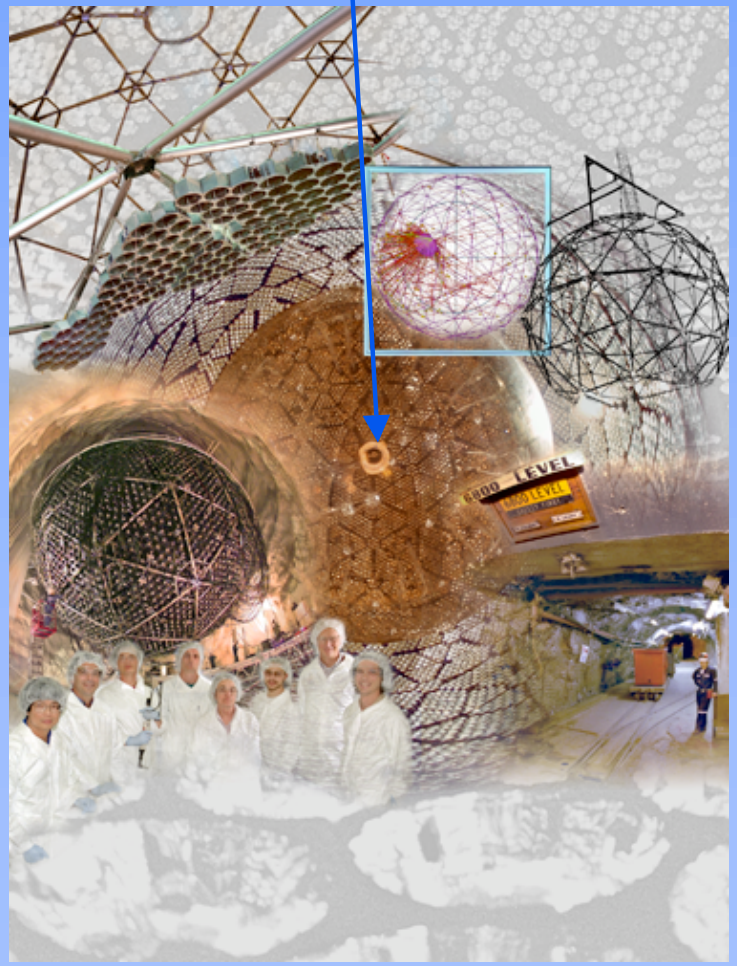
Urylon Liner and Radon Seal

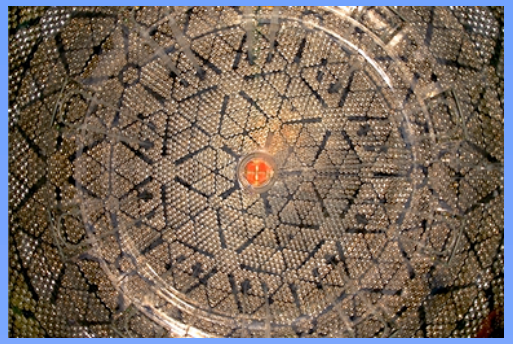
NIM A449, 127 (2000)

2092 m to Surface



"Lowest Background" Laboratory On Earth





Physics Program for SNO

- Charged Current
  $\nu_e + d \rightarrow e^- + p + p$
  $E_{thresh} = 1.4$ MeV

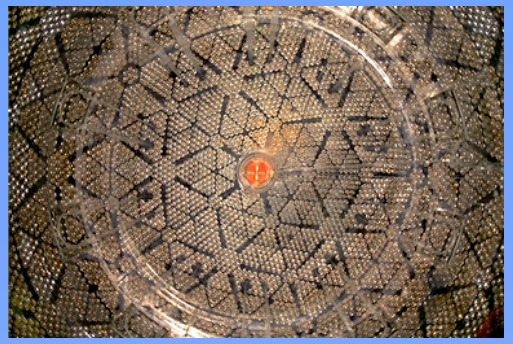
- Elastic Scattering
  $\nu_x + e^- \rightarrow \nu_x + e^-$

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

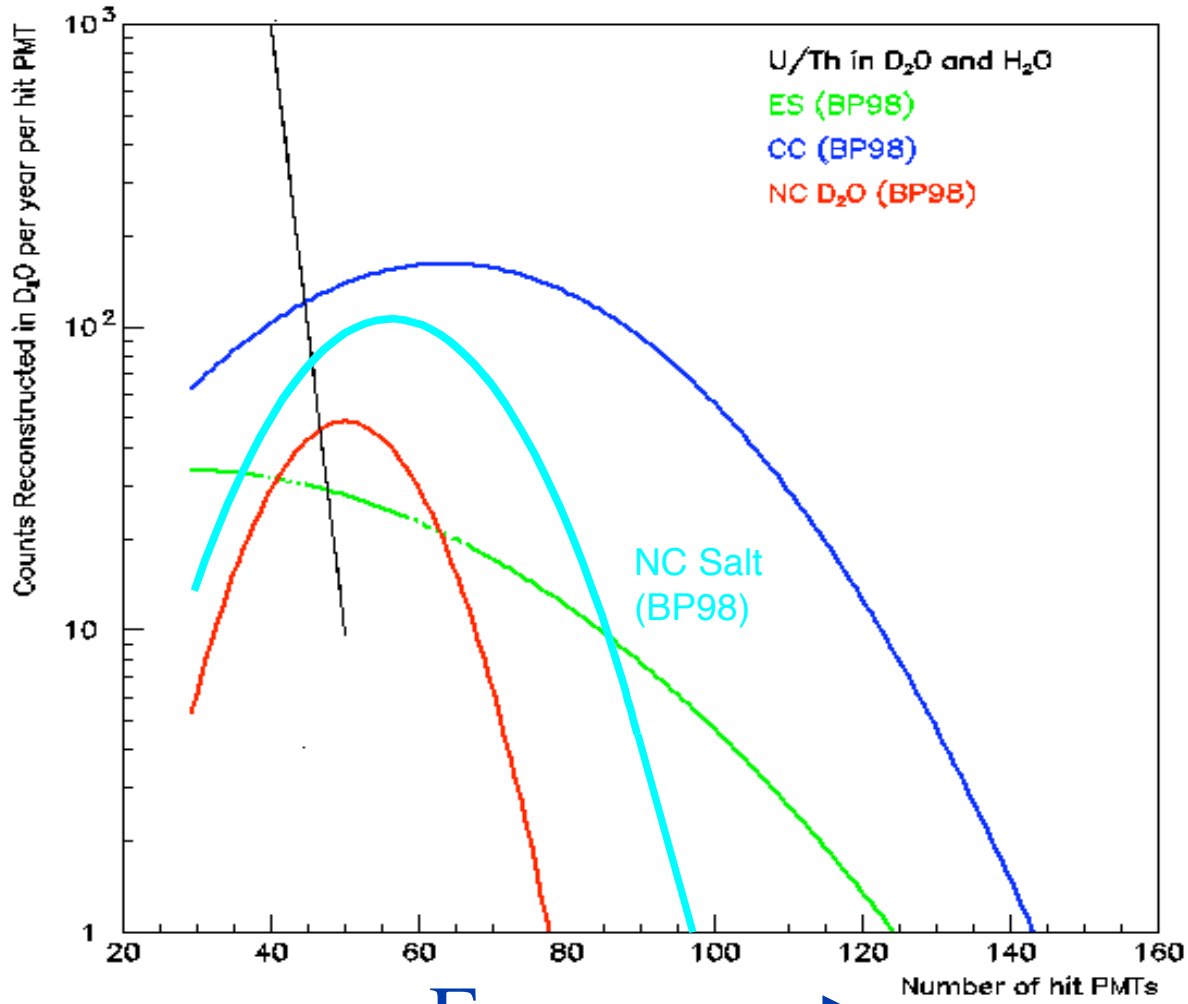
- Pure D_2O
  CC, ES, reduced NC
  (6.25 MeV, $\eta_n \sim 24\%$)

- D_2O + NaCl
  CC, ES, enhanced NC
  (~8.6 MeV, $\eta_n \sim 86\%$
  ~45% above threshold)

- D_2O + NCDs (^{3}He Prop. Counters)
  Concurrent CC & NC, ES
  ($\eta_n \sim 45\%$)



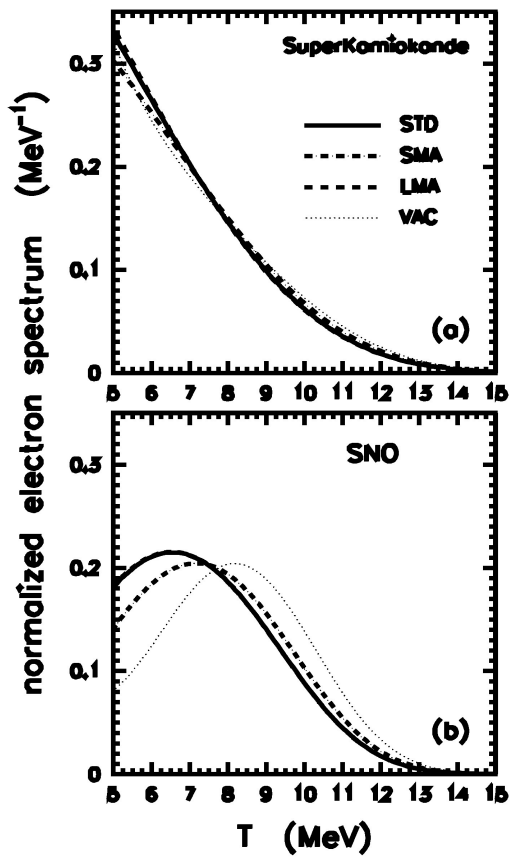
Physics Program for SNO



Energy →

SNO's Major Signals

- **Spectra distortions to ES and CC**



ES

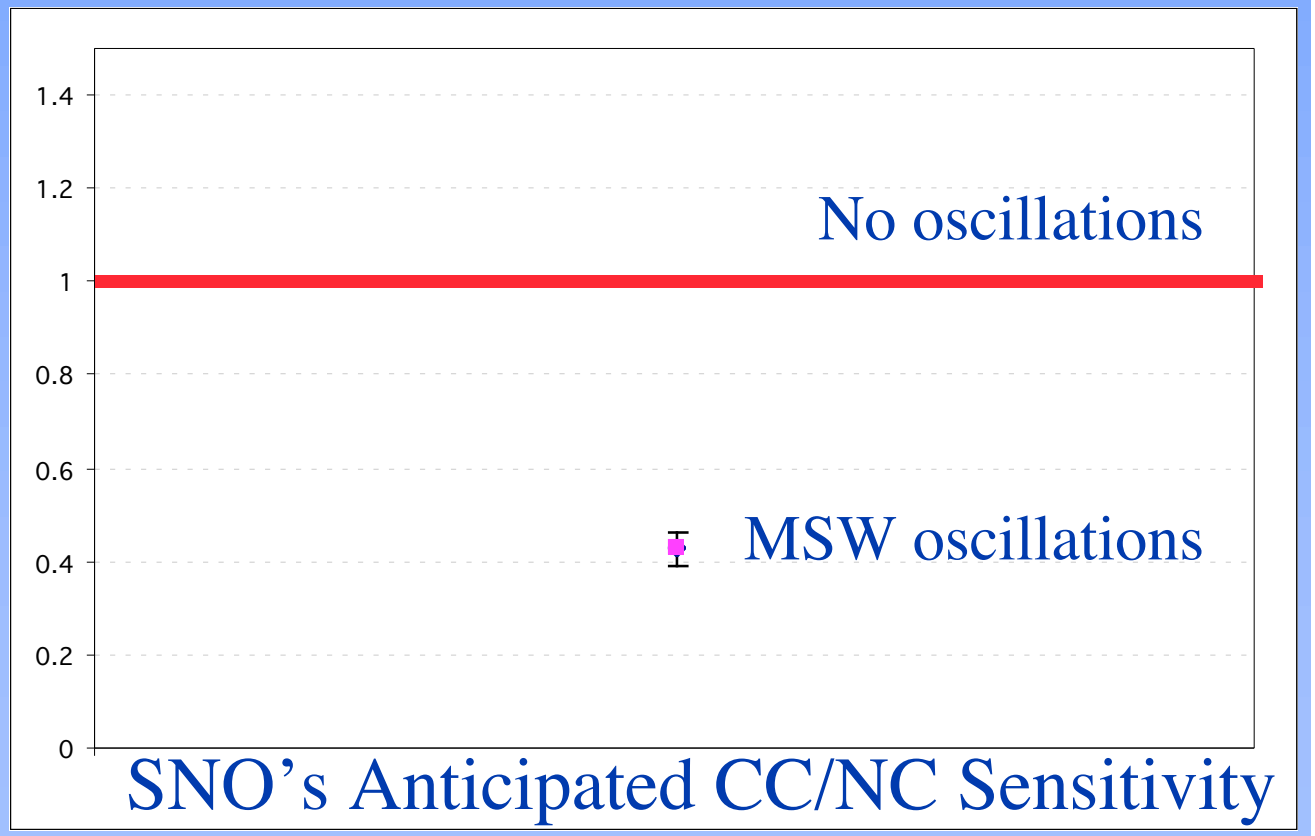
CC

Bahcall *et al.*

SNO's Major Signals

$$\frac{CC}{NC} = \frac{\phi_e}{\phi_e + \phi_\mu + \phi_\tau}$$

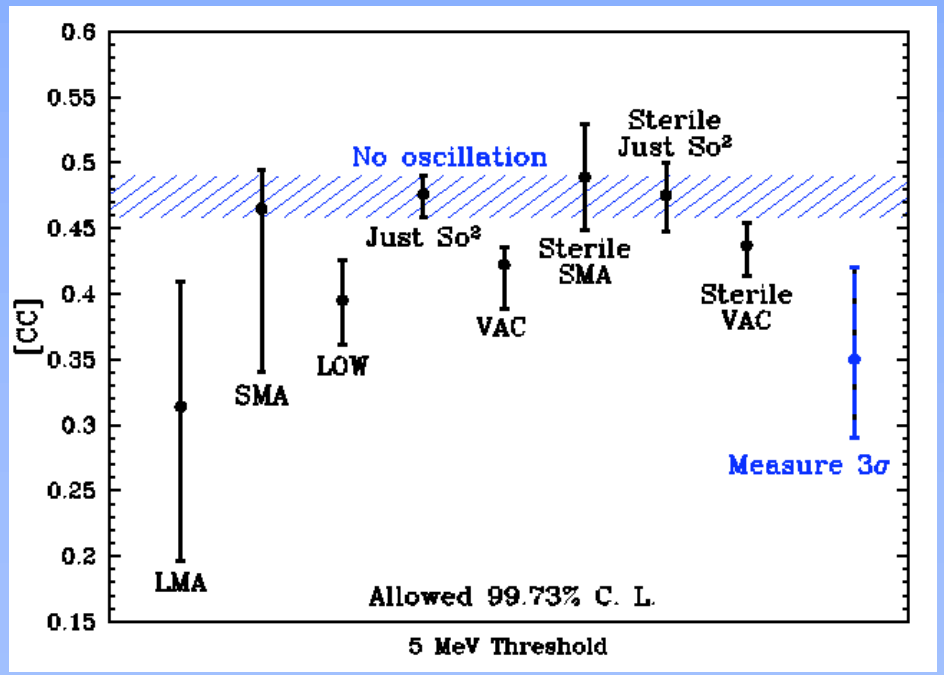
$$\frac{\frac{CC_{exp}}{NC_{exp}}}{\frac{CC_{theory}}{NC_{theory}}}$$



SNO's Major Signals

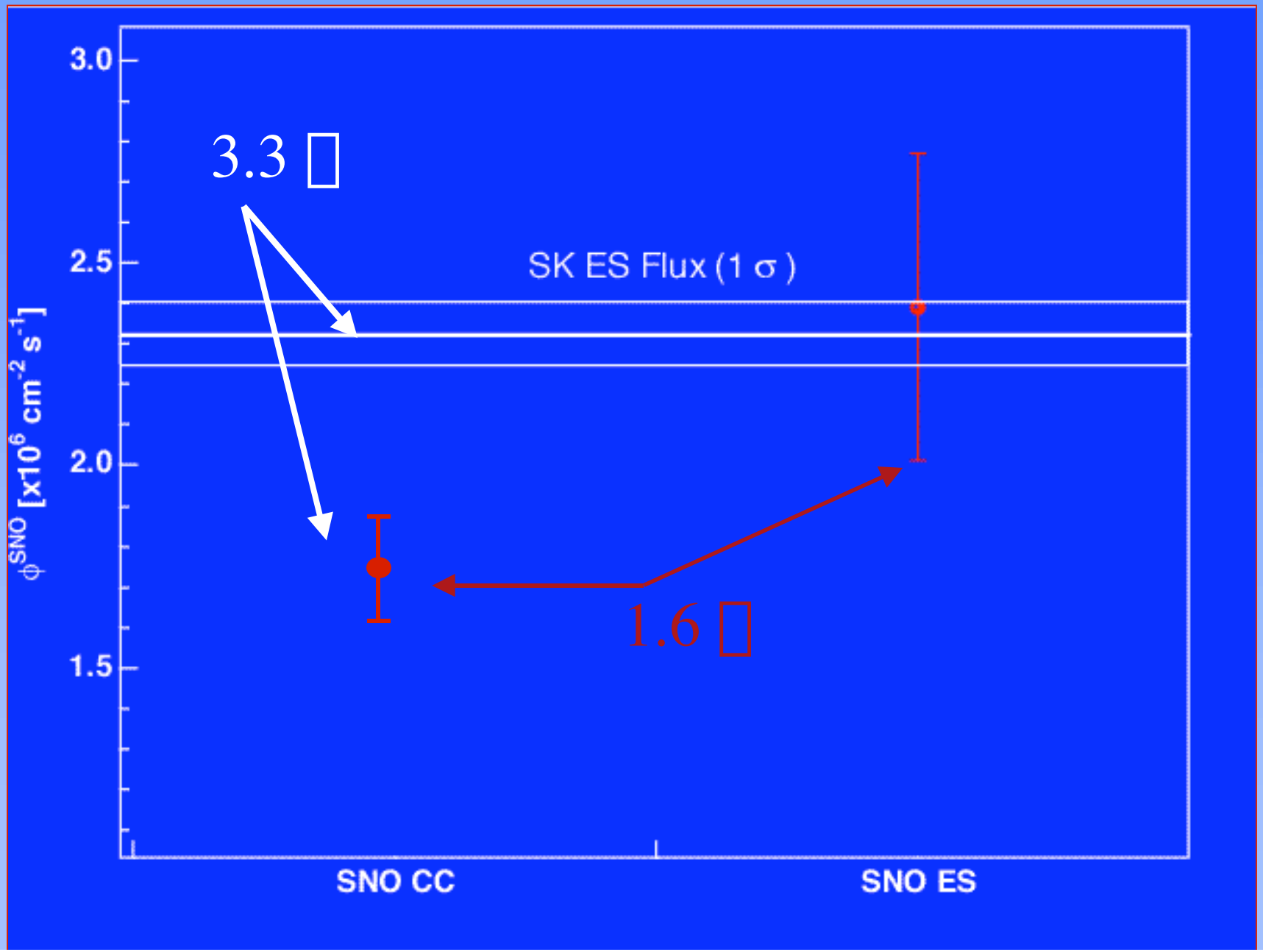
Elastic Scattering also *measures* other Neutrino Flavors

$$\frac{CC}{ES} = \frac{\phi_e}{\phi_e + 0.156(\phi_\mu + \phi_\tau)}$$



Bahcall et al.

Evidence for Solar Neutrino Oscillations



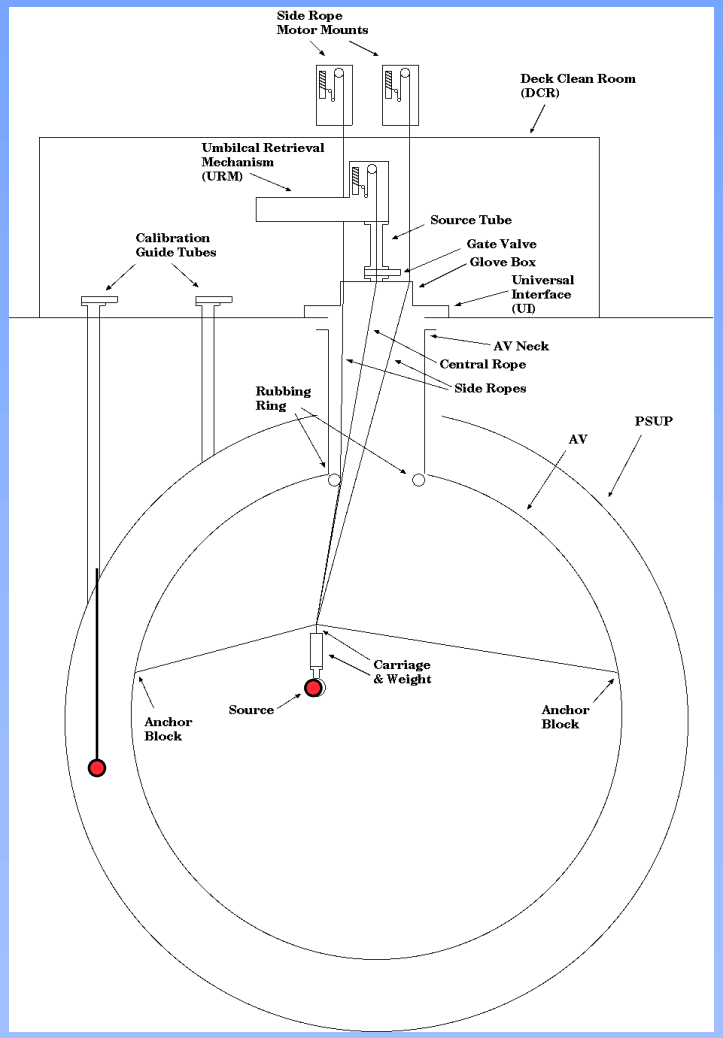
Calibration, Detector Response and Data Analysis

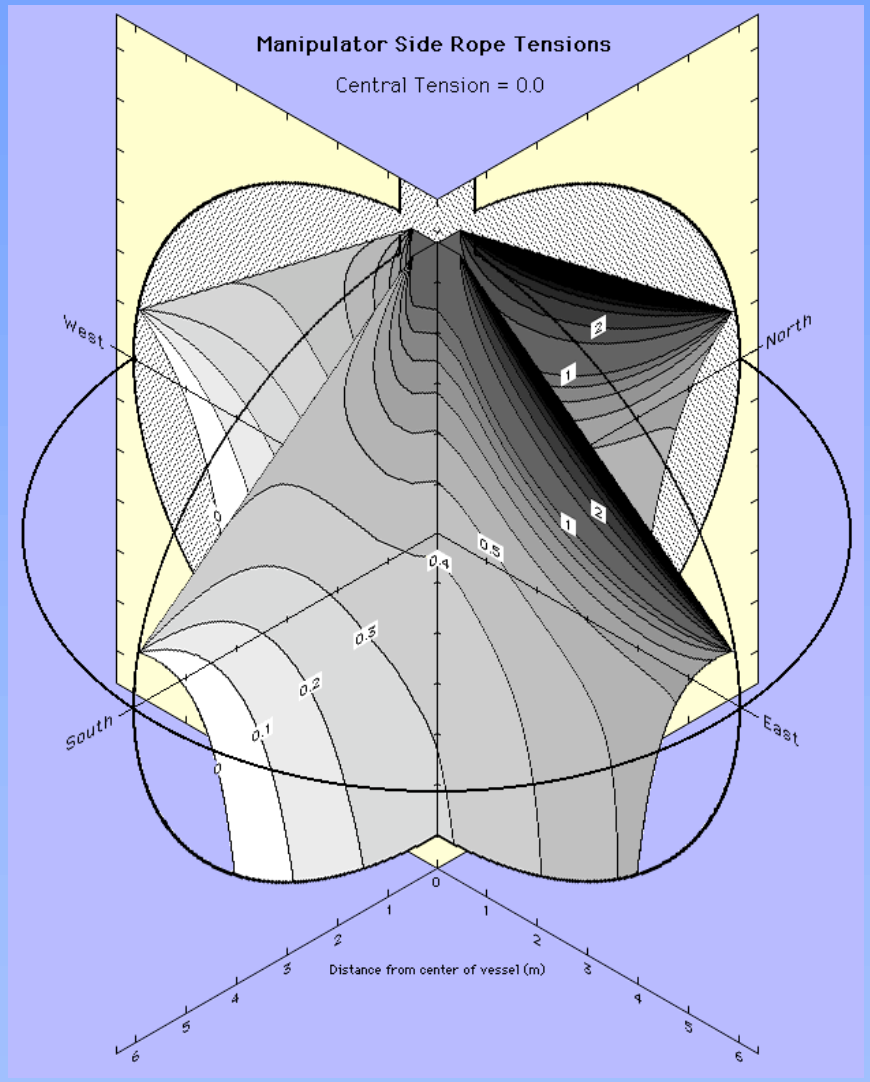
- Optical Calibration
- Energy Response
- Event Reconstruction
  - Position resolution
  - Angular resolution
  - Energy resolution
- Detector Response
- Monte Carlo Simulations

- Livetime
- D_2O Isotopic Purity
- Instrumental Backgrounds
- Low Energy Physics Backgrounds
  - D_2O
  - Acrylic Vessel
  - H_2O & PMT
- High Energy γrays

Do Everything at least two ways

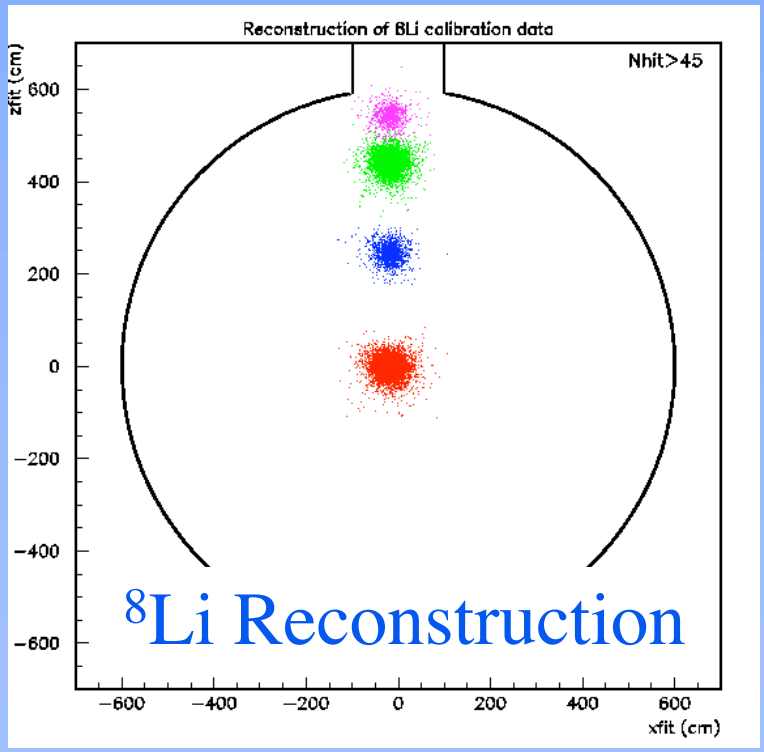
Calibration Systems

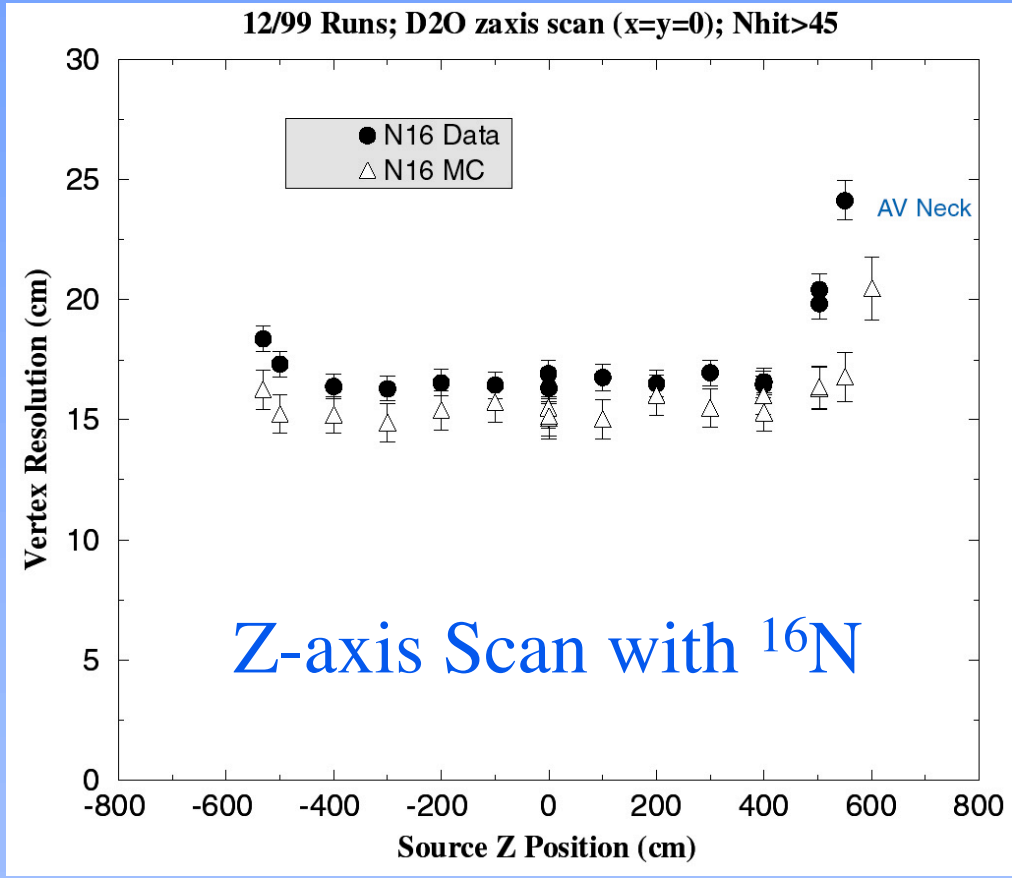




Event Reconstruction

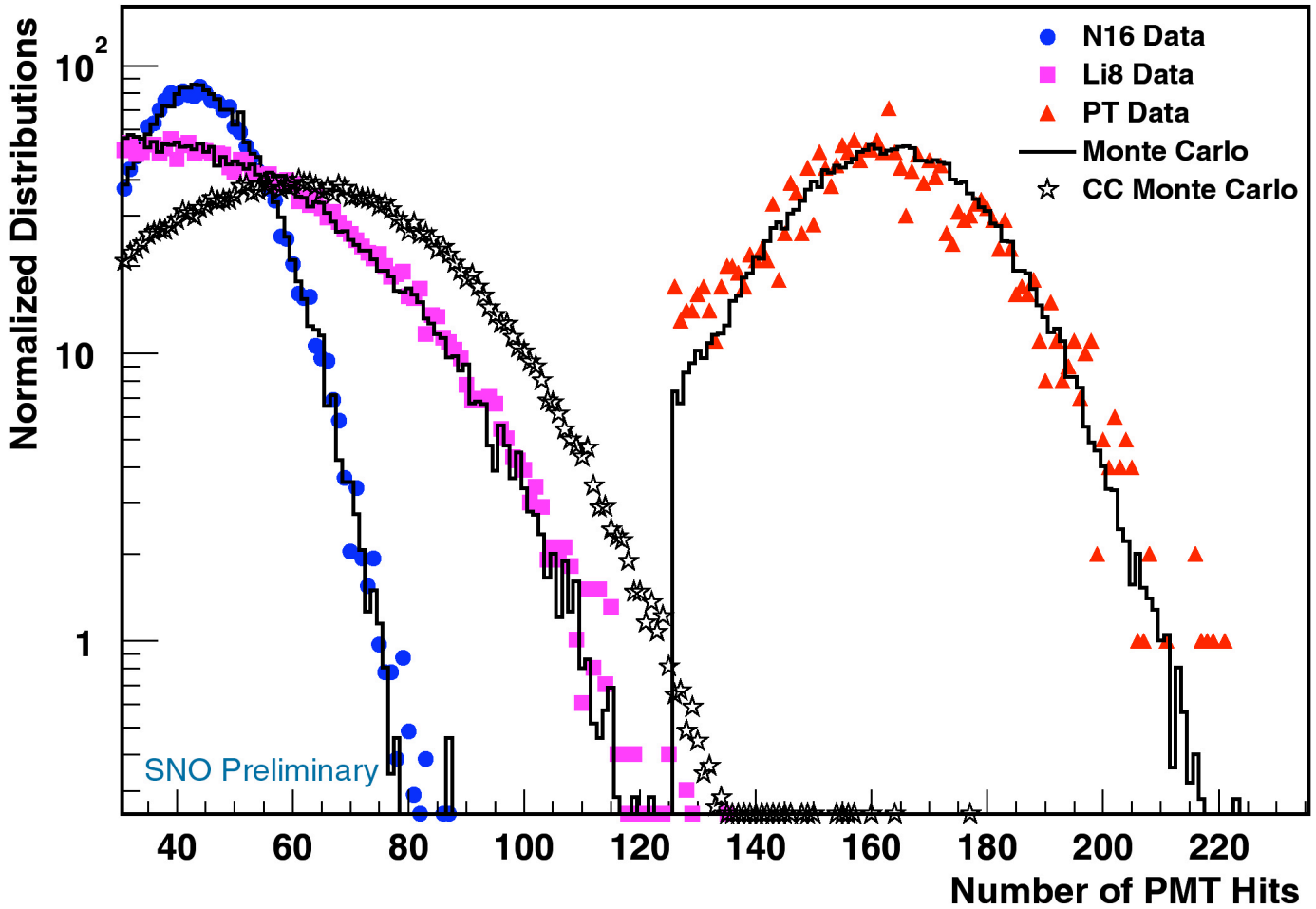
- Calibrated with:
  ^{16}N β's and ^{8}Li β's throughout D_2O
  ^{16}N β's in H_2O





Vertex resolution =16 cm

SNO's Energy Response at the Center of the Detector



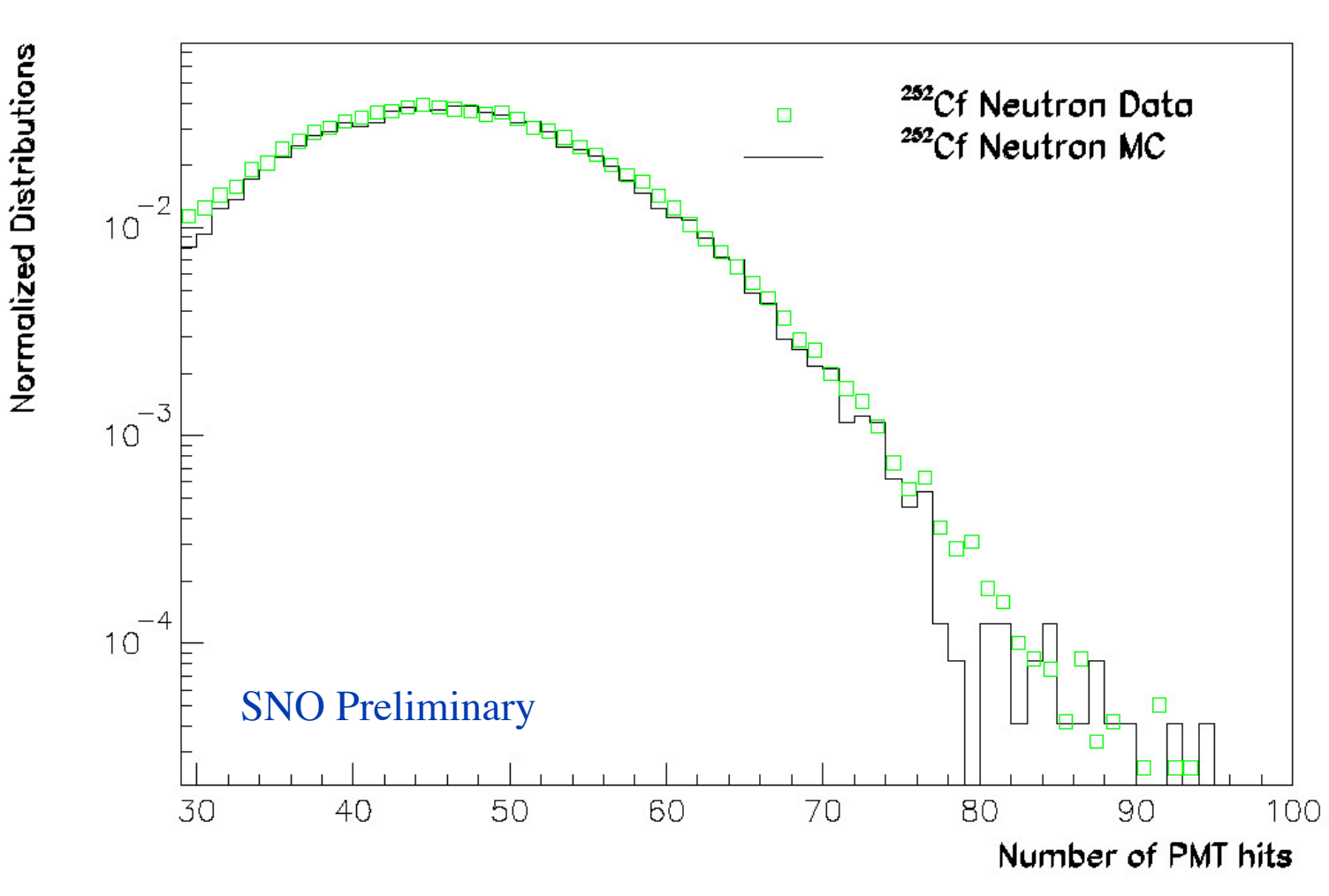
6.13 MeV

~14 MeV

19.8 MeV

1% E/E ~ 3%

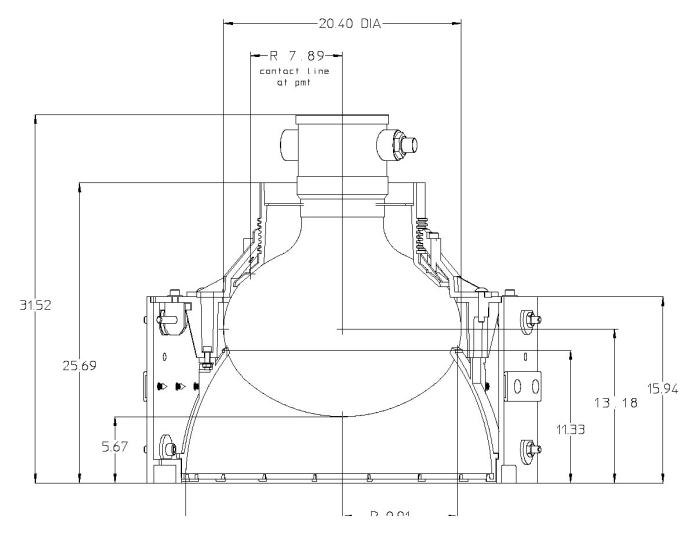
Energy Response to Neutrons throughout the Detector



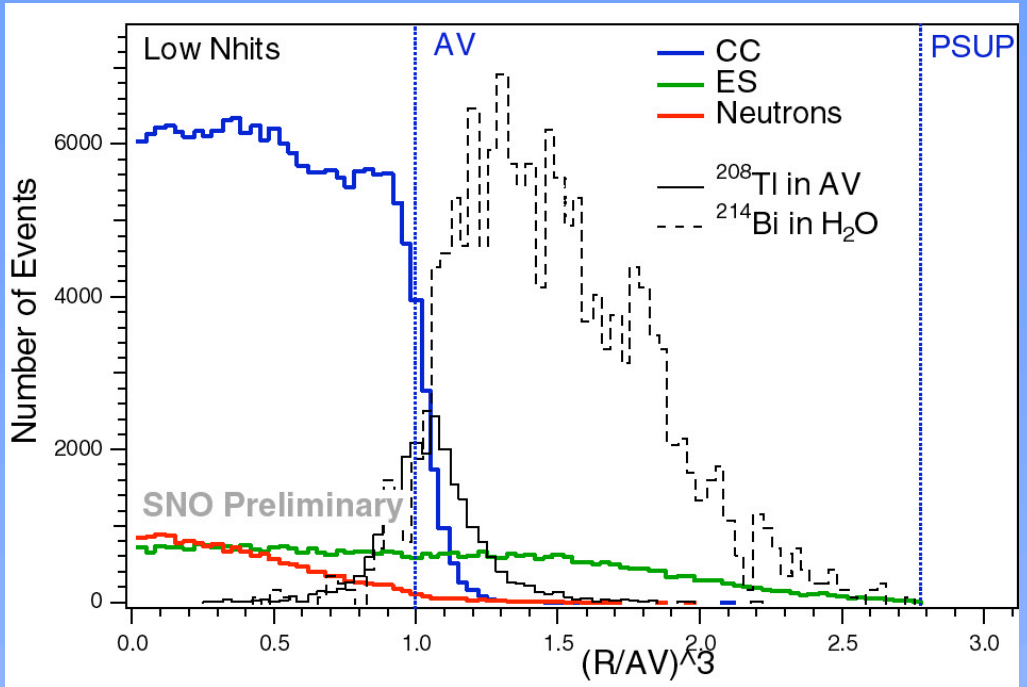
6.25 MeV capture

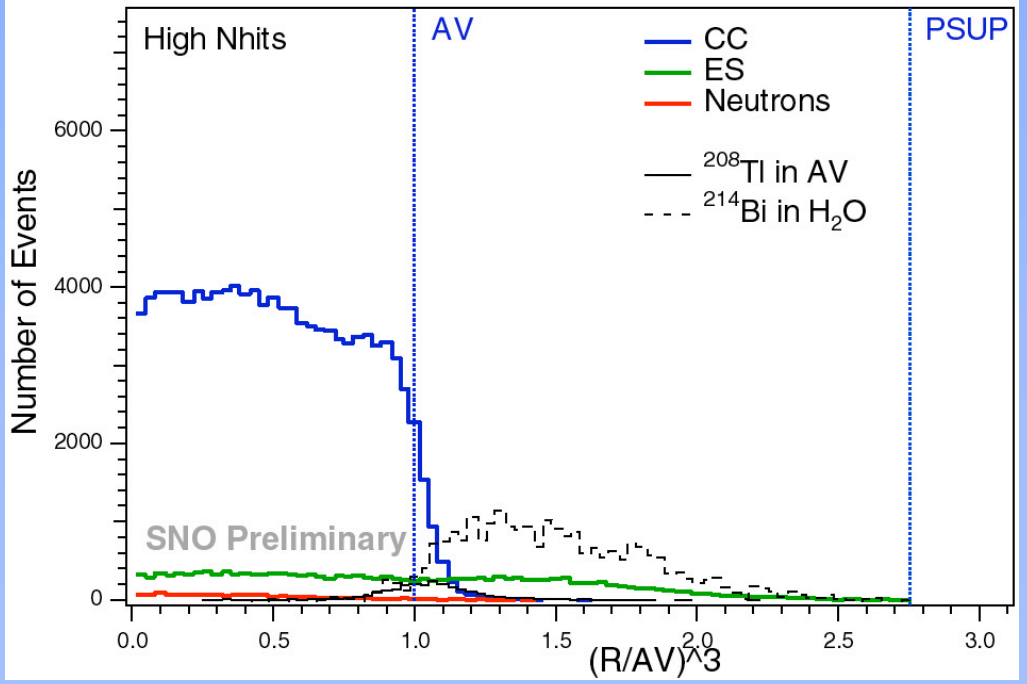
SNO's Monte Carlo Model

- **Photon Generation, Transport and Detection**
- **Detector Geometry, Status and Conditions**



x 10,000

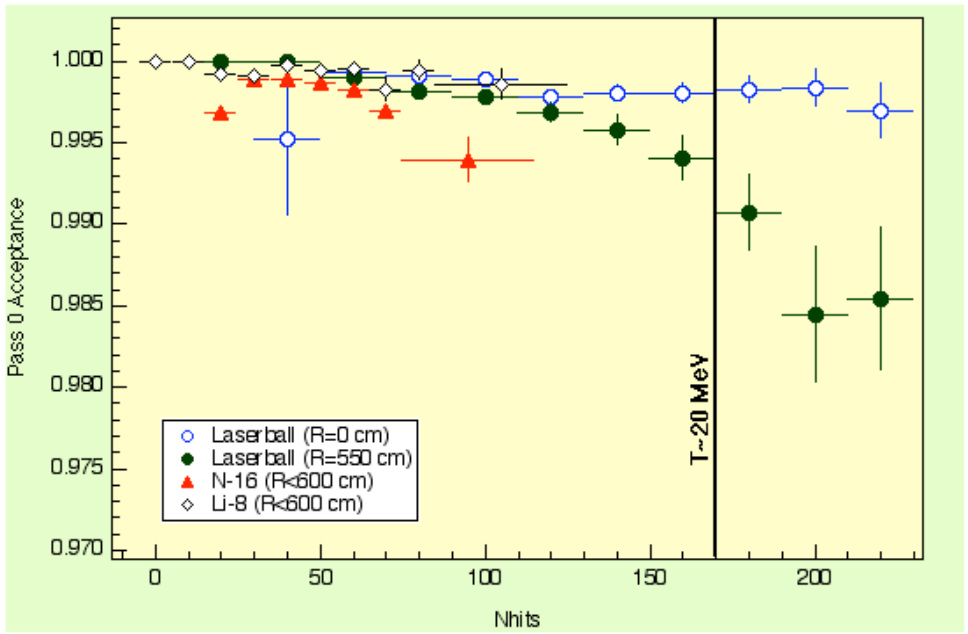


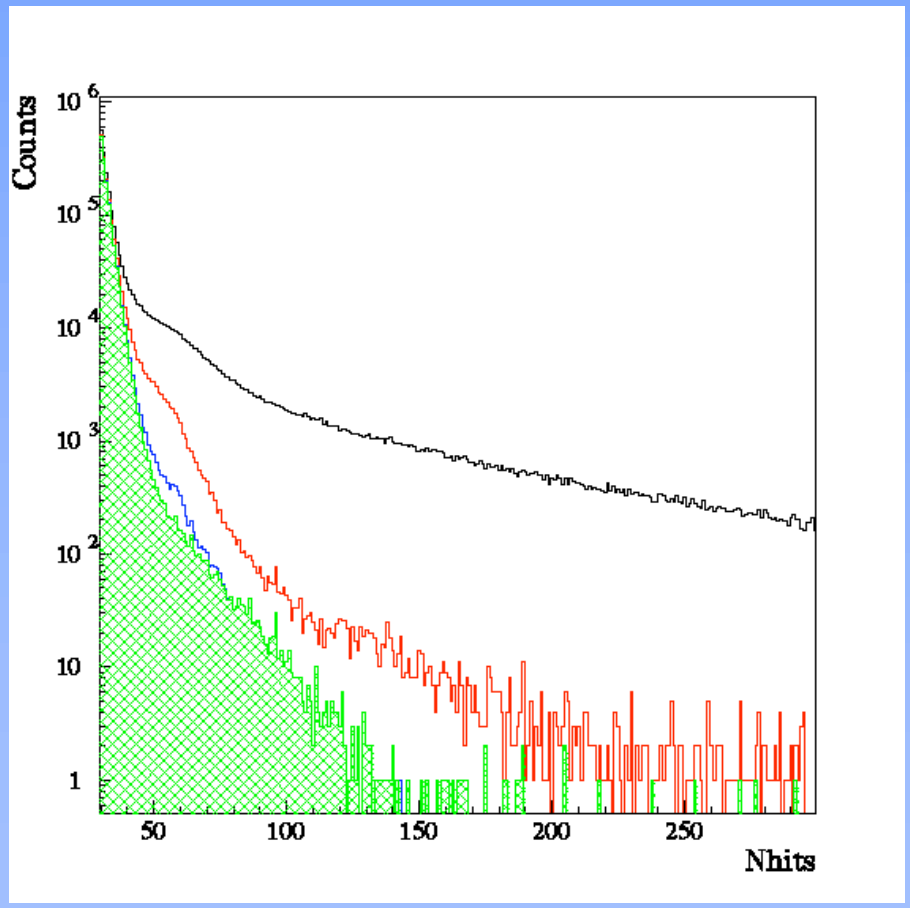


Instrumental Background Removal

Acceptance

- measured with ^{16}N and ^{8}Li sources
- 0.9962 +0.0073/-0.0063



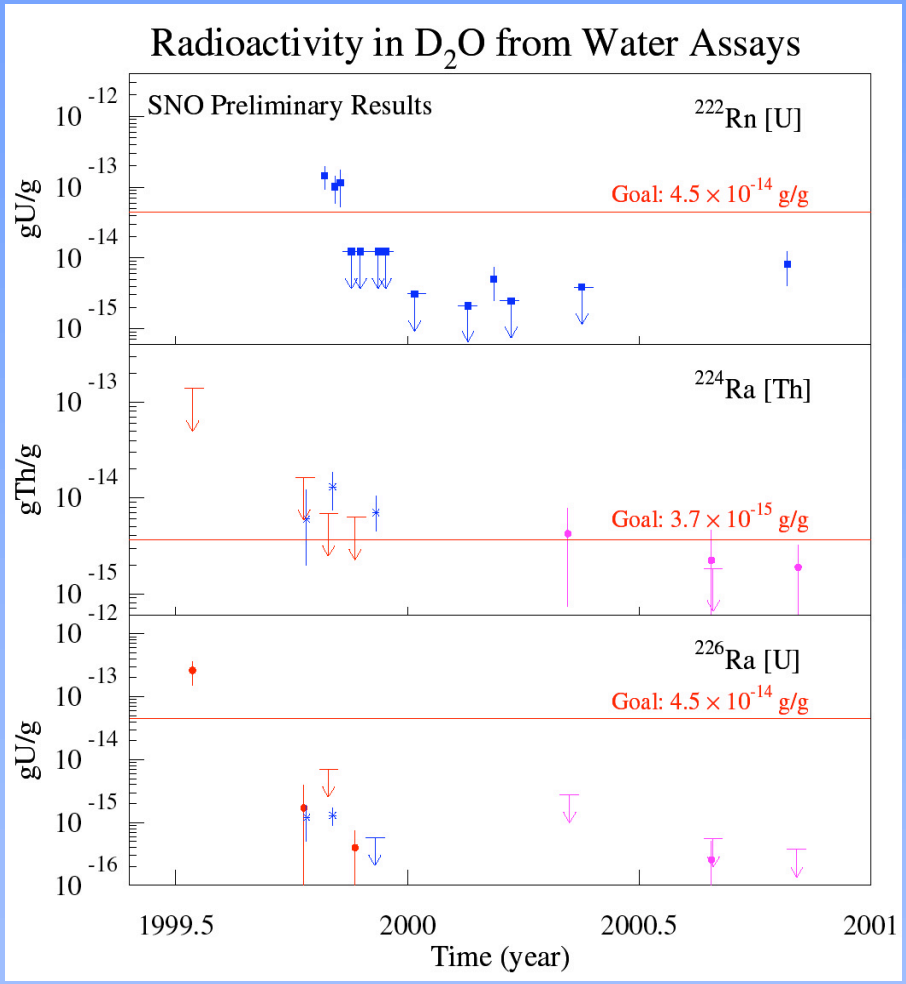


Residual Contamination

- bifurcated analysis + handscanning
- < 0.2%

D_2O Backgrounds

Measured both by Radioassay and Cerenkov light at ~10^{-15} g/g!



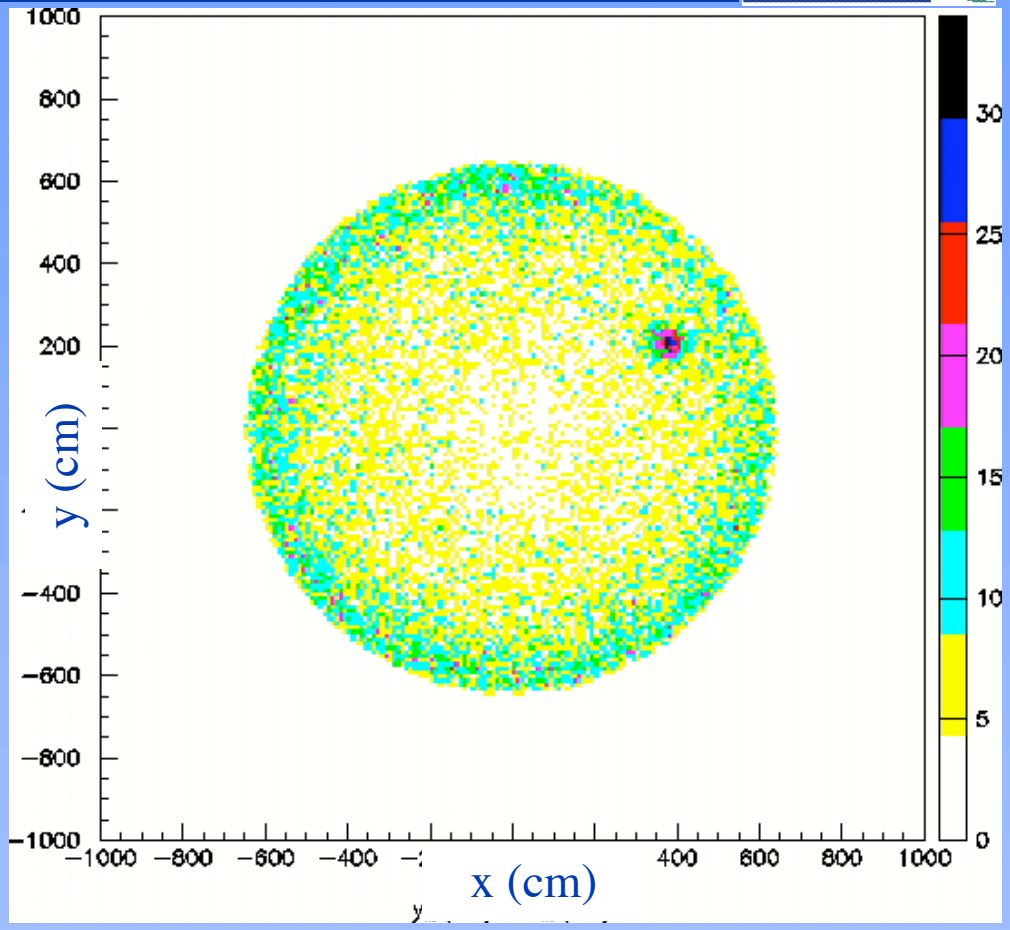
Target Levels would produce 1 neutron/day or 10% SSM

Acrylic Vessel Backgrounds

Activities assayed are
<10% Targets ~0.2 ppt

Or ~ 6 μg Th or U

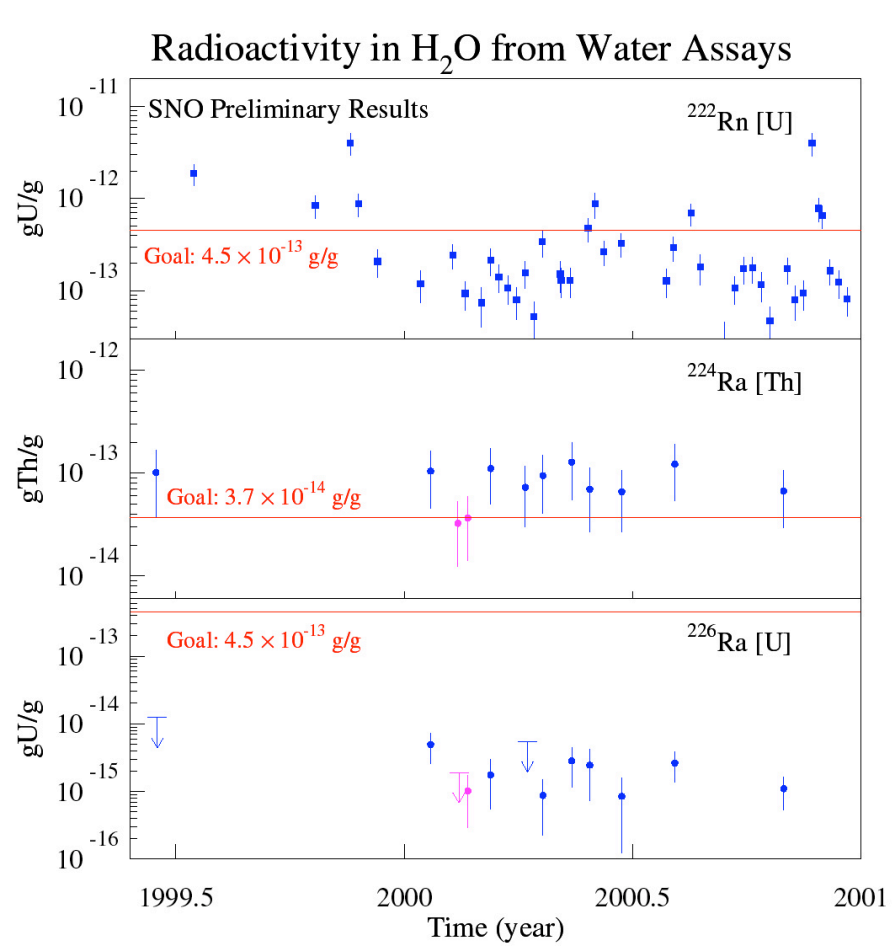
Original Target was
60 μg Th or U



☞ "Berkeley Blob"

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

H_2O and PMT Backgrounds



Radioassay and *in situ* Cerenkov Measurements

Signal Extraction

- **"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

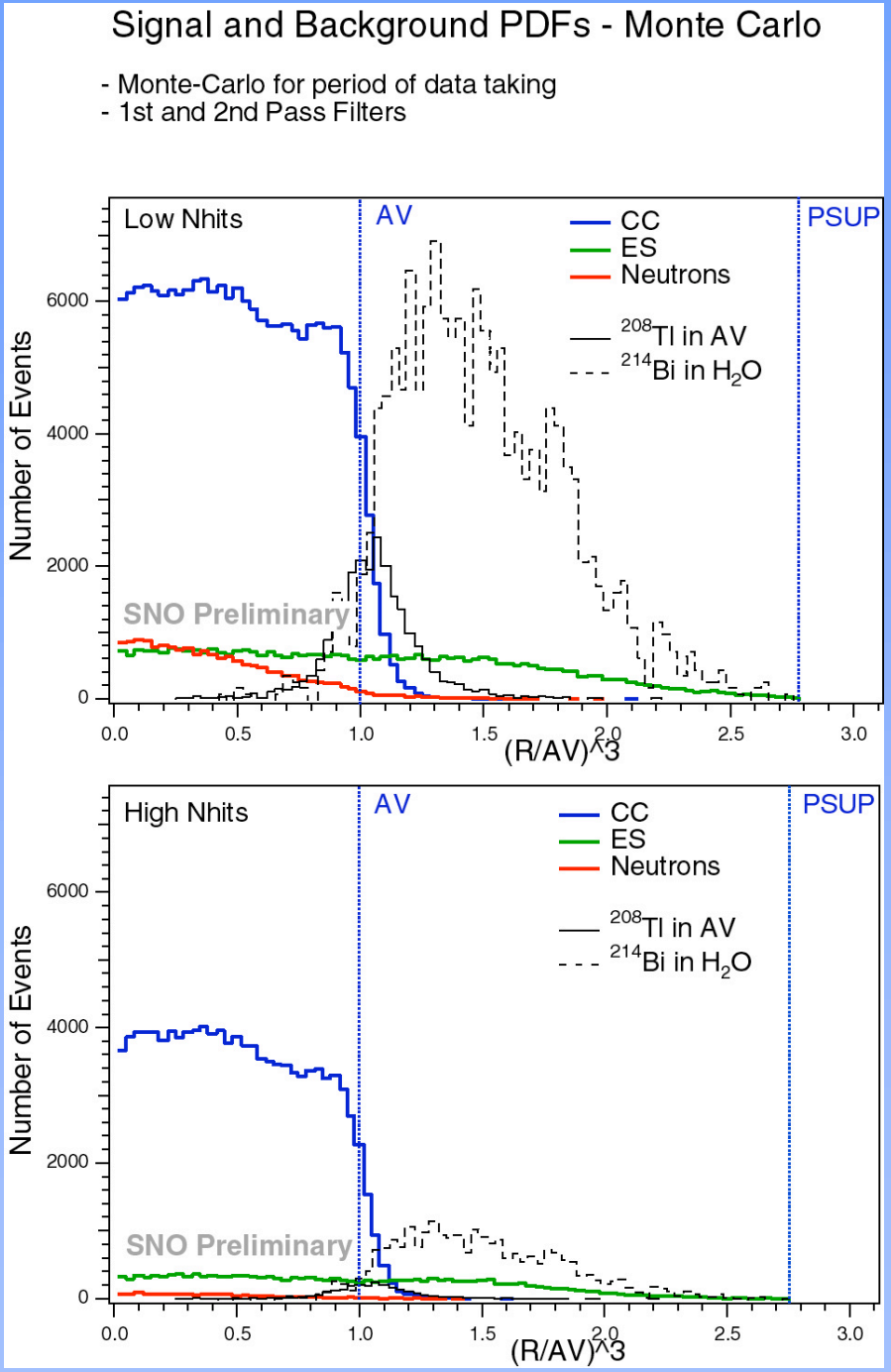
- **Variable Fiducial Volume (6.5 m) and Energy Thresholds**

  Fit CC, ES, Neutrons, Bckgrds PDFs

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

  Extended Maximum Likelihood

Consistent Results



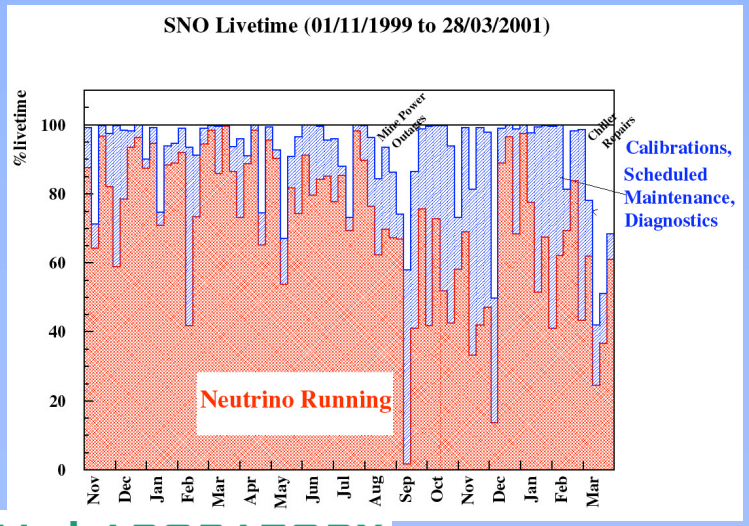
Signal Extraction Results

Data resolved into CC, ES, neutron components with Monte Carlo pdfs of T_{eff}, $\cos\theta_{sun}$, $(R/R_{AV})^3$
With the hypothesis of no neutrino oscillations

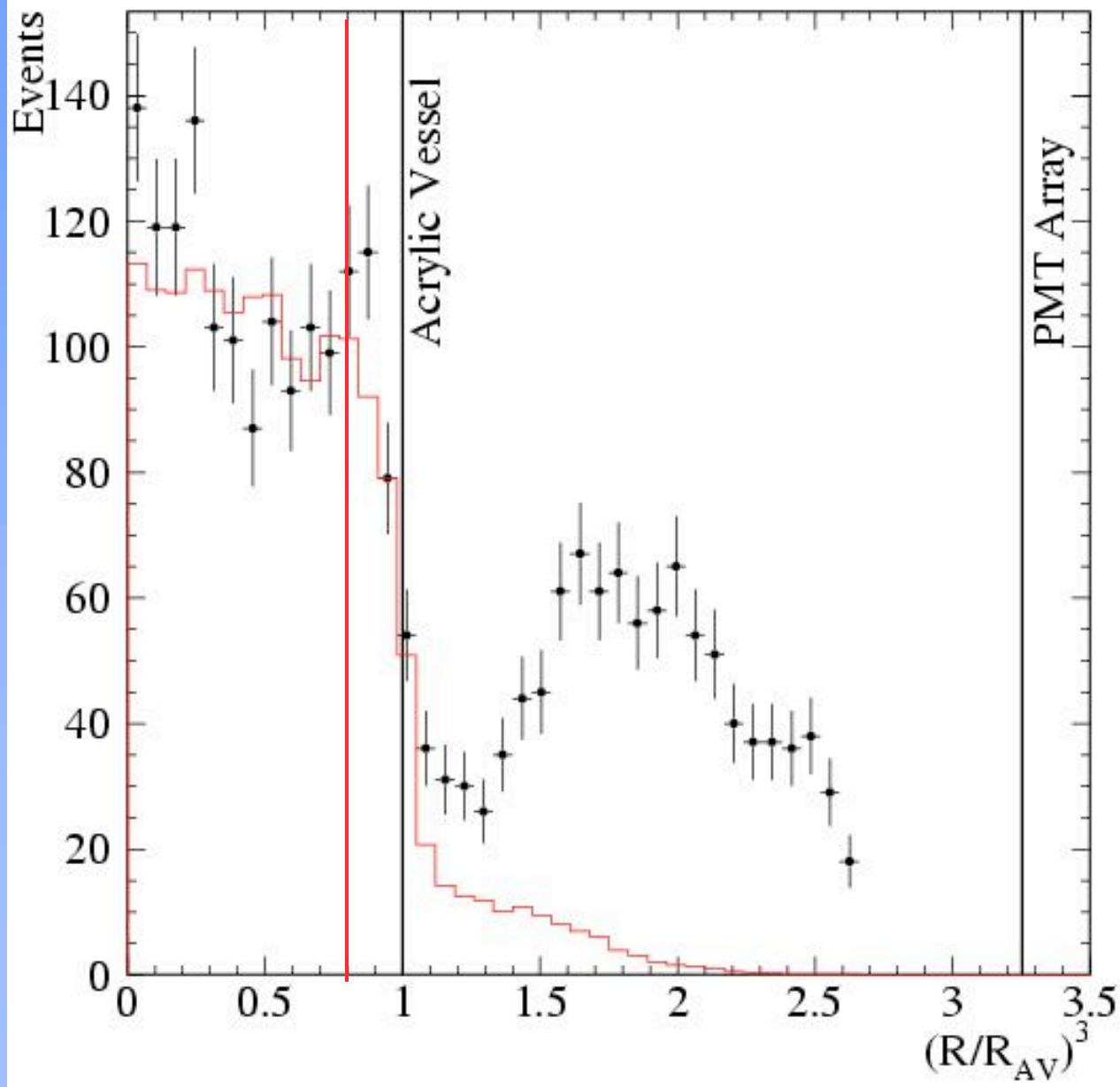
CC	975.4 ± 39.7 events
ES	106.1 ± 15.2 events
Tail of Neutrons	87.5 ± 24.7 events

240.9 live-days
between 11/99-1/01

No statistically significant differences between Blind and Open data sets (75 days/166 days)



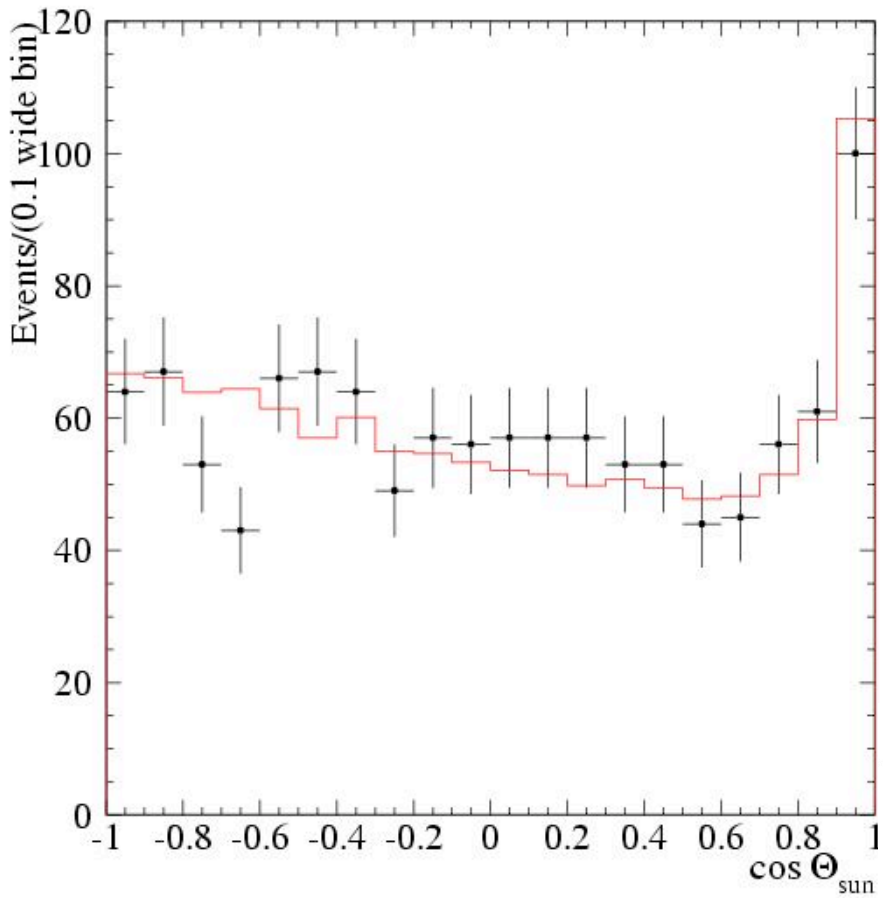
Results



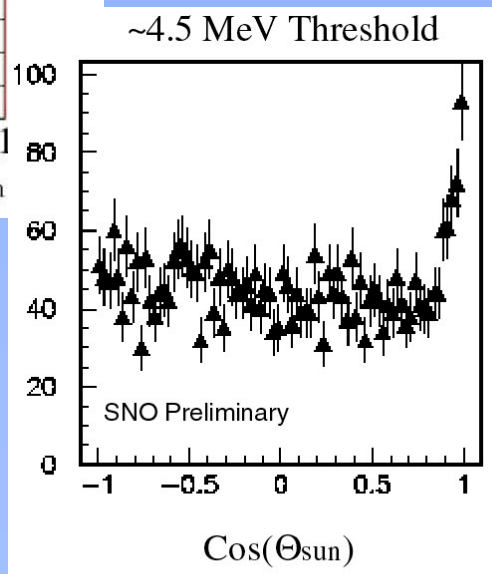
Radial Distribution of Neutrinos

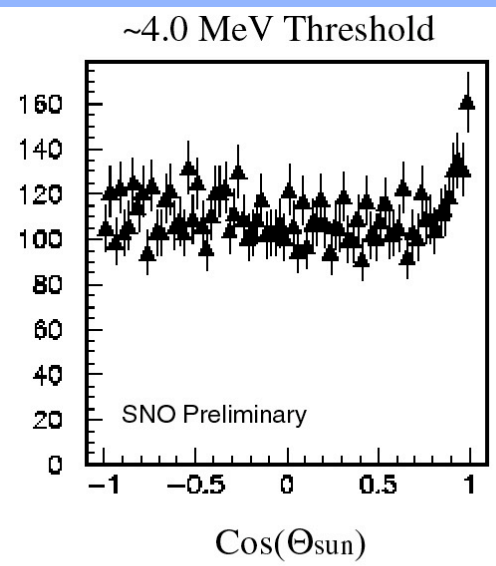
Results

Direction of Events with respect to the SUN



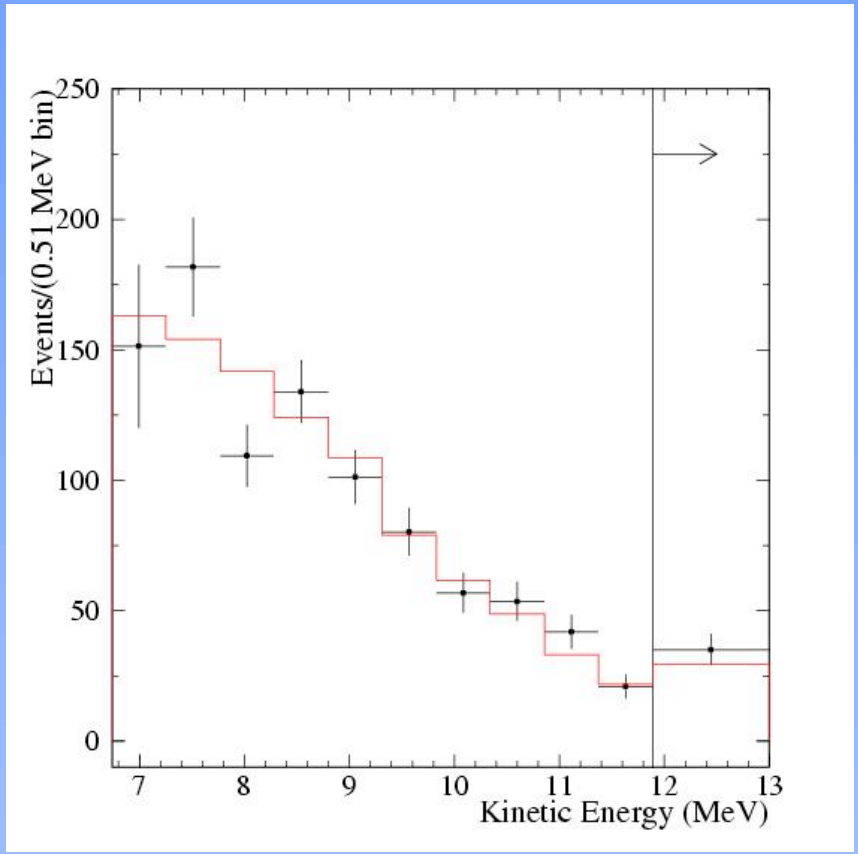
6.75 MeV threshold

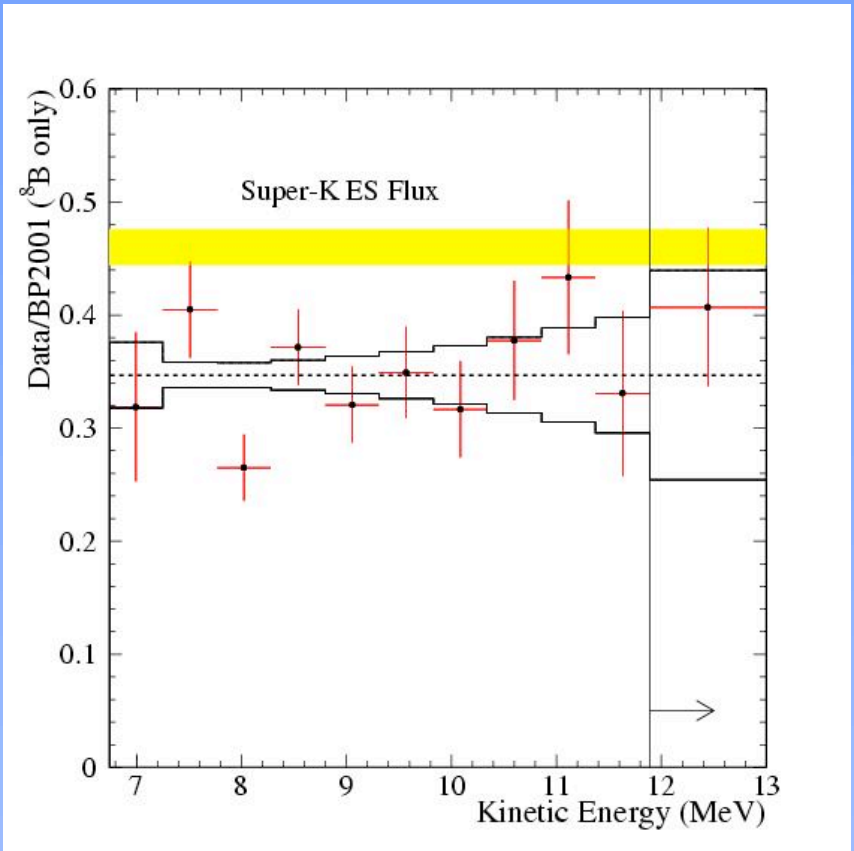




Charged Current Energy Spectrum

Results



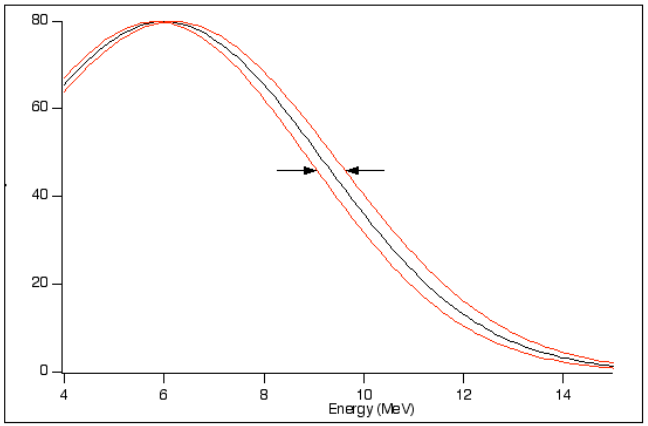


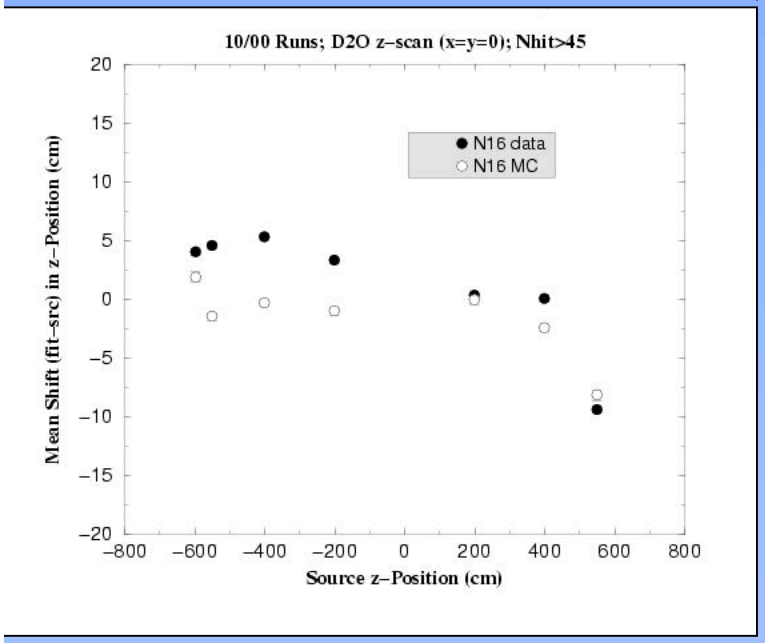
CC spectrum derived from fit *without* constraint on shape of ^{8}B spectrum

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

➥ no evidence for shape distortion.

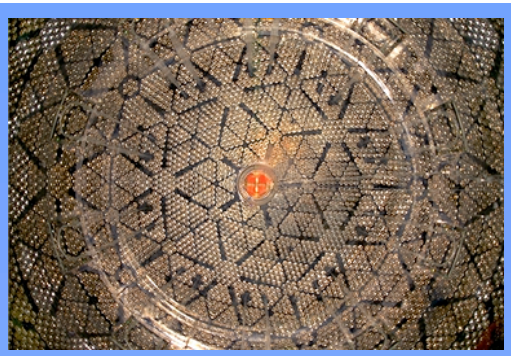
Systematic Uncertainties





Source	*CC (%)*	*ES (%)*
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 accuracy	±3.1	±3.3
Vertex resolution	±0.7	±0.4
Angular resolution	±0.5	±2.2
High energy	+0, -0.8	+0, -1.9
Low energy background	0.0 –0.2	0.0 –0.2
Instrumental background	+0.0, -0.2	+0.0, -0.5
Trigger efficiency	0.0	0.0
Live Time	±0.1	±0.1
Cut acceptance	+0.7, -0.6	+0.7, -0.6
Earth orbit eccentricity	±0.2	±0.2
^{17}O, ^{18}O	0.0	0.0
Experimental uncertainty	**+7.0, -6.2**	**+6.8, -5.7**
Cross section	**3.0**	**3.0**
Solar model	**+20, -16**	**+20, -16**

N(HE events): <10 events (68% CL)



Results from SNO

(Fluxes in $10^6/cm^2/s$)

$$\phi^{CC}_{SNO}(\nu_e) = 1.75^{+0.07}_{-0.07}(stat.)^{+0.12}_{-0.11}(sys.)^{+0.05}_{-0.05}(theor.)$$

$$\phi^{ES}_{SNO}(\nu_x) = 2.39^{+0.34}_{-0.34}(stat.)^{+0.16}_{-0.14}(sys.)$$

$$R^{CC}_{SNO}(\nu_e) = 0.347^{+0.029}_{-0.029}$$

CC is low compared to **ES**

$$\phi^{ES}_{SK}(\nu_x) = 2.32^{+0.03}_{-0.03}(stat.)^{+0.08}_{-0.07}(sys.)$$

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

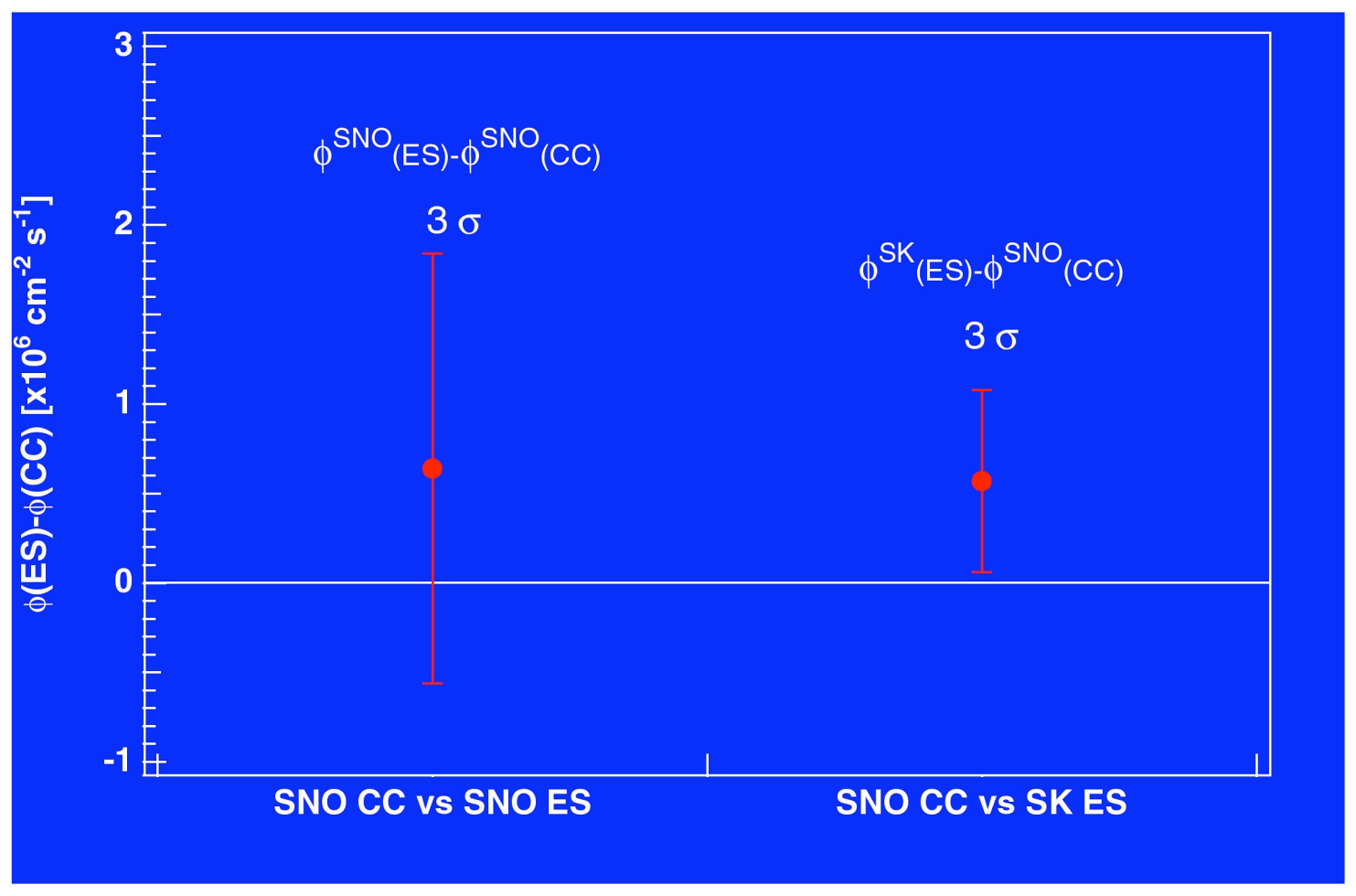
CC and ES Results

CC at SNO vs ES at SK

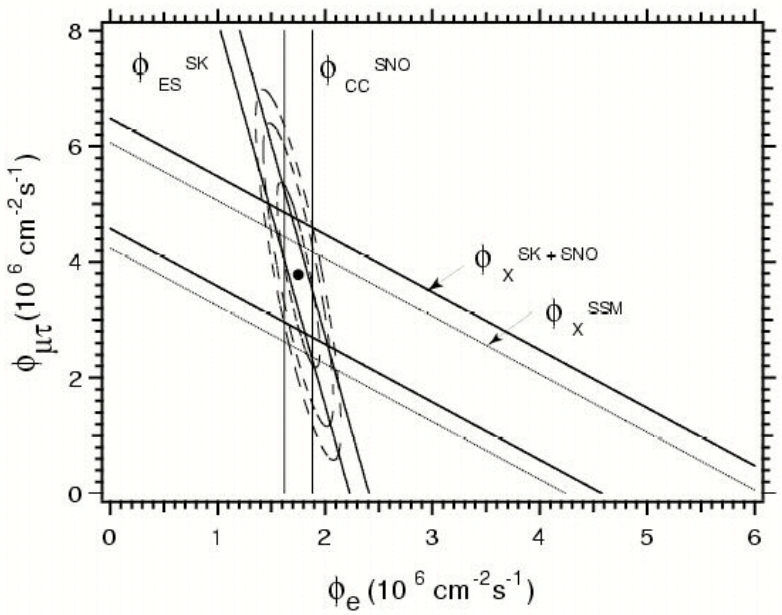
$$\phi^{ES}_{SK} - \phi^{CC}_{SNO} = 0.57 \pm 0.17 \quad \Rightarrow \quad \underline{3.3\sigma \text{ effect !!}}$$

> 99.9% cl

CC and ES Results



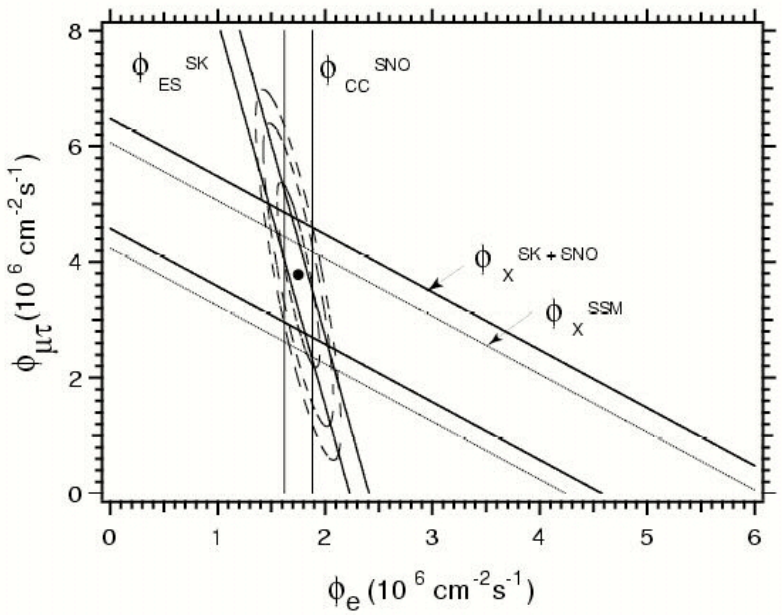
SNO + Super-K Results



These data are evidence with >99.96% confidence that ν_e produced in the sun are transformed into ν_μ and or ν_τ by neutrino oscillations

Flavor Changing Appearance!

Solar Flux Results



$\phi(\phi_{\mu,\tau}) = 3.69 \pm 1.13 \times 10^6$ cm^{-2}s^{-1}

$\phi(\phi_e) = 5.44 \pm 0.99 \times 10^6$ cm^{-2}s^{-1}

$\phi(\phi_e) = 5.05 +1.01/-0.81 \times 10^6$ cm^{-2}s^{-1}

Standard Models

SNO + Super-K

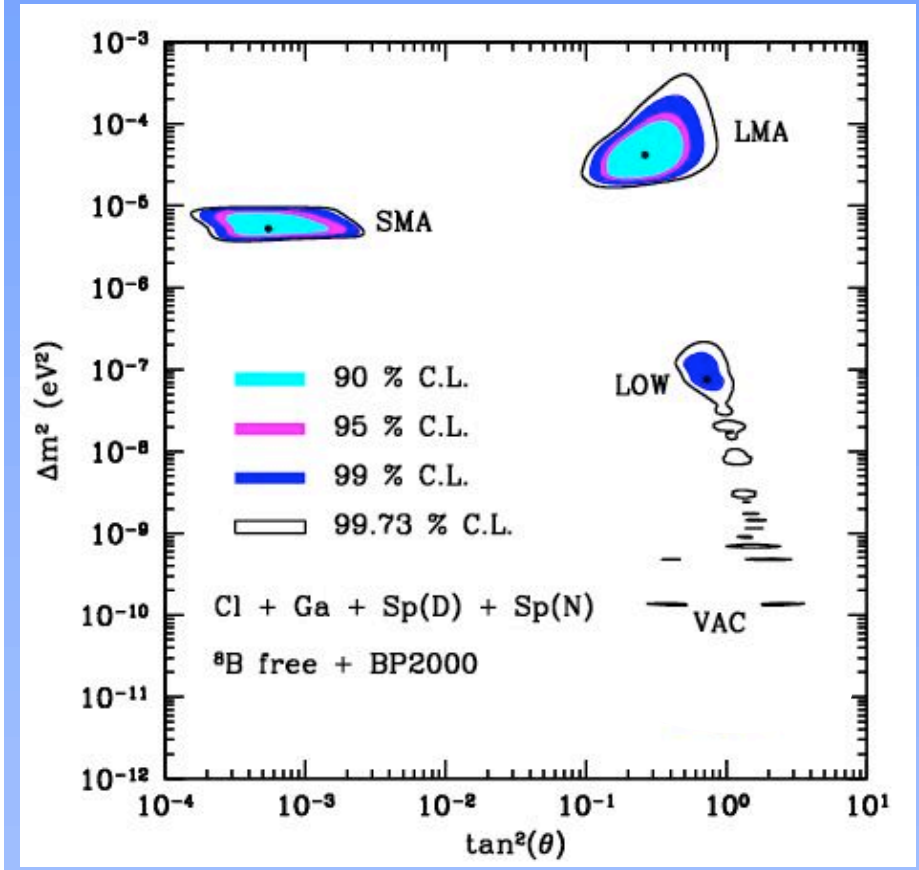
- "Just-So^2" ($\Delta m^2 = 6 \times 10^{-12}$ eV^2) excluded 3.3 σ
- "SMA sterile" excluded to a similar level of confidence
- "Vacuum Sterile" requires more effort:

If oscillation with maximal mixing to a sterile neutrino is occurring the SNO CC-derived ^{8}B flux above a threshold of 6.75 MeV will be essentially identical with the integrated Super-Kamiokande ES-derived ^{8}B flux above a threshold of 8.5 MeV .

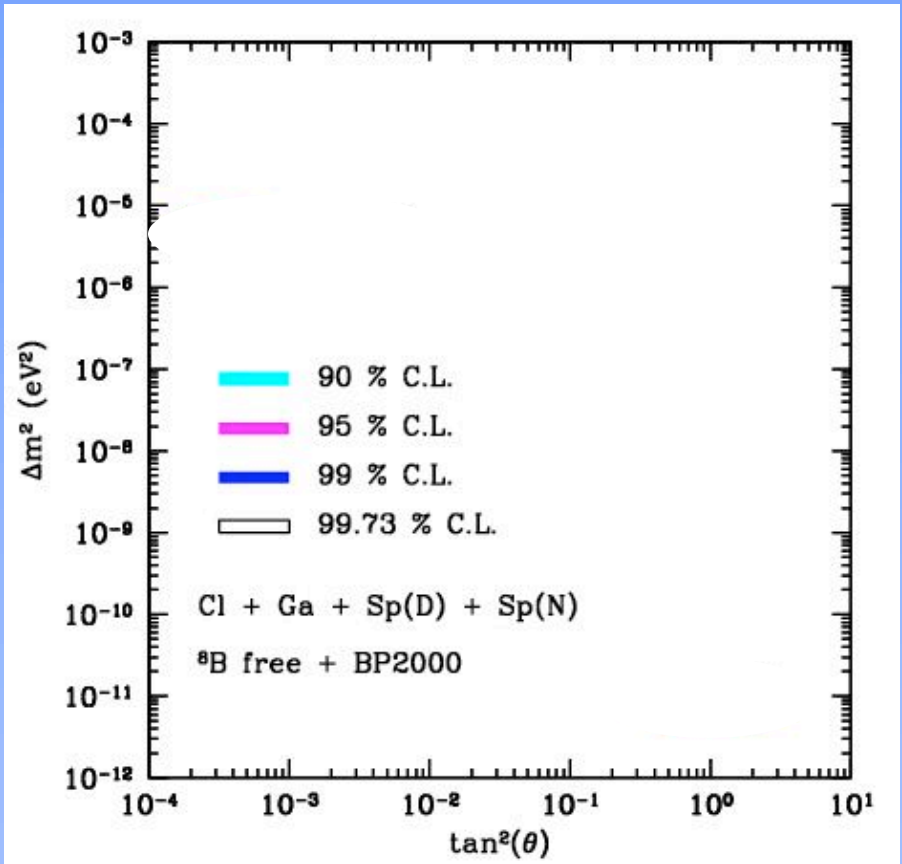
➥ Correcting the ES threshold the flux difference yields a flux difference of 0.53 ± 0.17 or

3.1 σ exclusion of maximal mixing to sterile neutrinos

SNO + Ga + Cl + SuperK



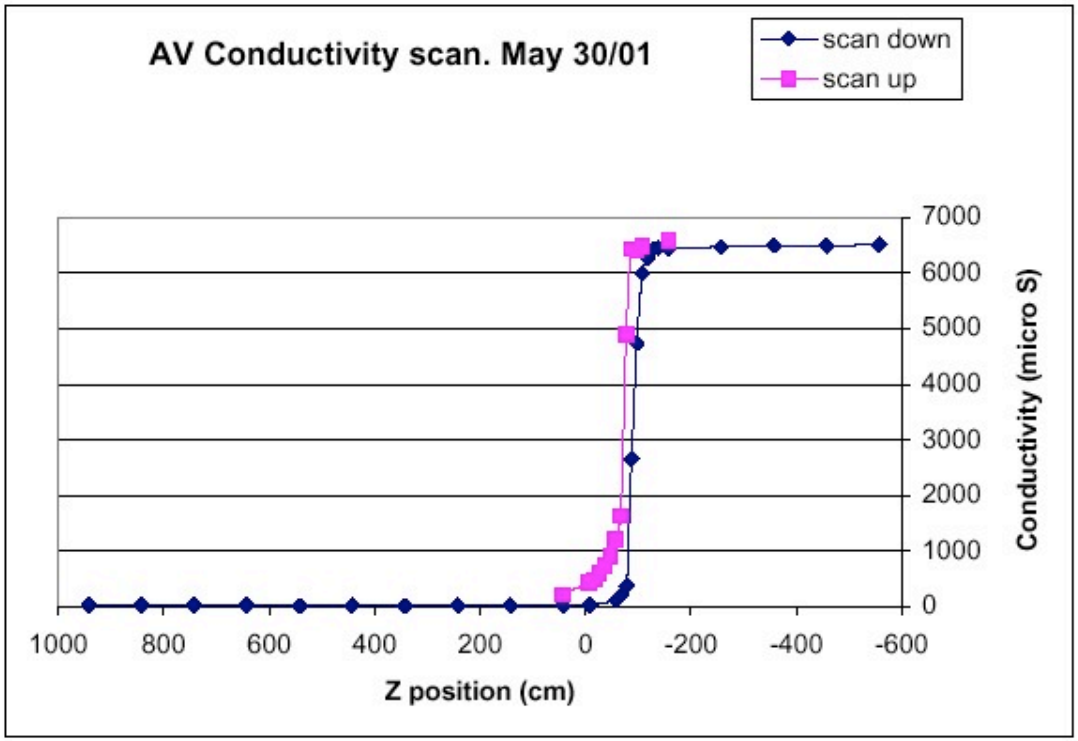
To Active Neutrinos

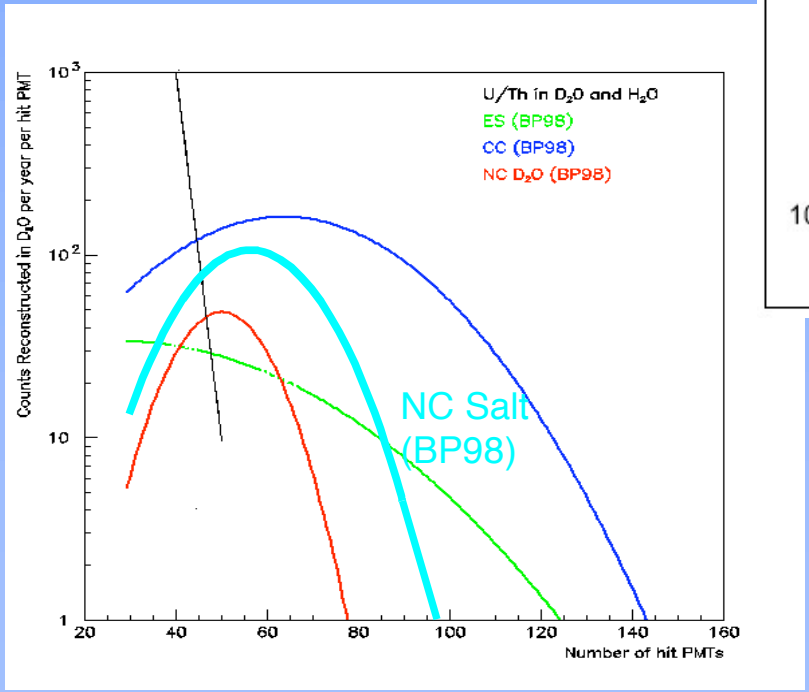


To Sterile Neutrinos

SNO's Immediate Future

Salt Injected 28 May 2001





Conductivity Measurements Taken During Salt Addition

SNO's Immediate Analysis Future

Muons

Lower analysis threshold for NC and Shape

Analysis from pure D_2O data

Day/Night analysis

hep-neutrino analysis

Seasonal and other Exotica

Calibration of D_2O + NaCl data

Don't touch that dial...

The Bigger Picture

1) First direct evidence that solar neutrinos oscillate into active species:

$\nu_e \rightarrow \nu_\mu$ or ν_τ at >99.96% confidence

2) Total solar flux agrees with standard models

3) Excellent evidence for atmospheric neutrino oscillations: $\nu_\mu \rightarrow \nu_\tau$

4) Mass differences are small

5) Maximal mixing to sterile is ruled out with better than 99.87% confidence

+

1) What is the absolute ν mass scale?

2) Determine solar oscillation parameters: SNO, KamLAND, Borexino

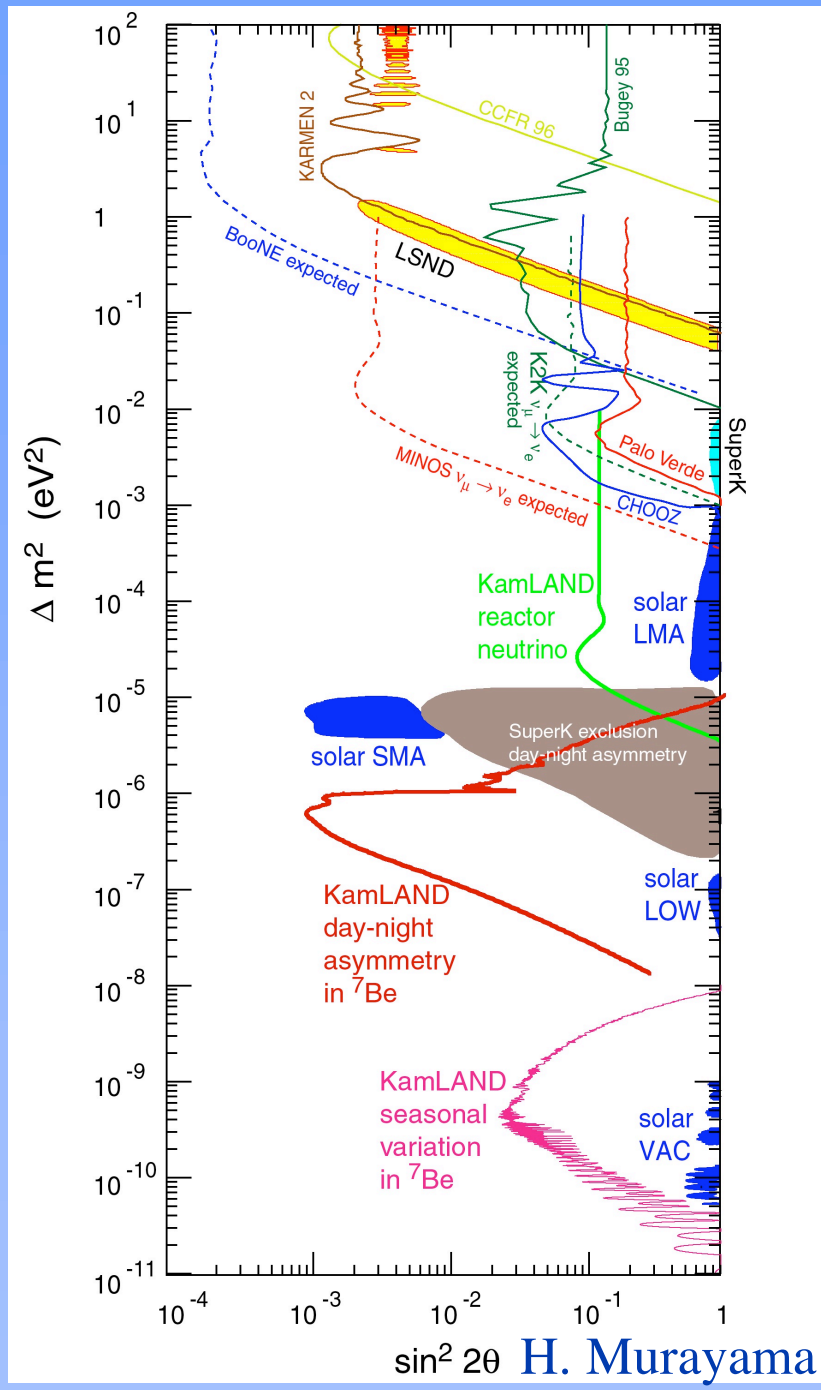
3) What are the mixing parameters, especially θ_{13}?

4) Is the neutrino its own antiparticle?

5) What is the nature of CP violation in the neutrino sector?

6) Extended Standard Model to embrace neutrino mass

Therefore,



H. Murayama

Implications for Cosmology

$M(\nu_e) < 2.8$ eV (Bonn *et al.* - Mainz)

Δm (atmospheric ν) ~ 50 meV (Toshito *et al.* Super-K)

$\sim 10^{-5} \leq \Delta m$ (solar ν) $\leq \sim 30$ meV (SNO + Apollonio *et al.*)

$$.05 \leq \Omega_\nu h^2 \leq 8.4\text{ev}$$

$$0.001 \leq \Omega_\nu \leq 0.18$$

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For Details, Preprint, Links, Pictures, and Releases and References:

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