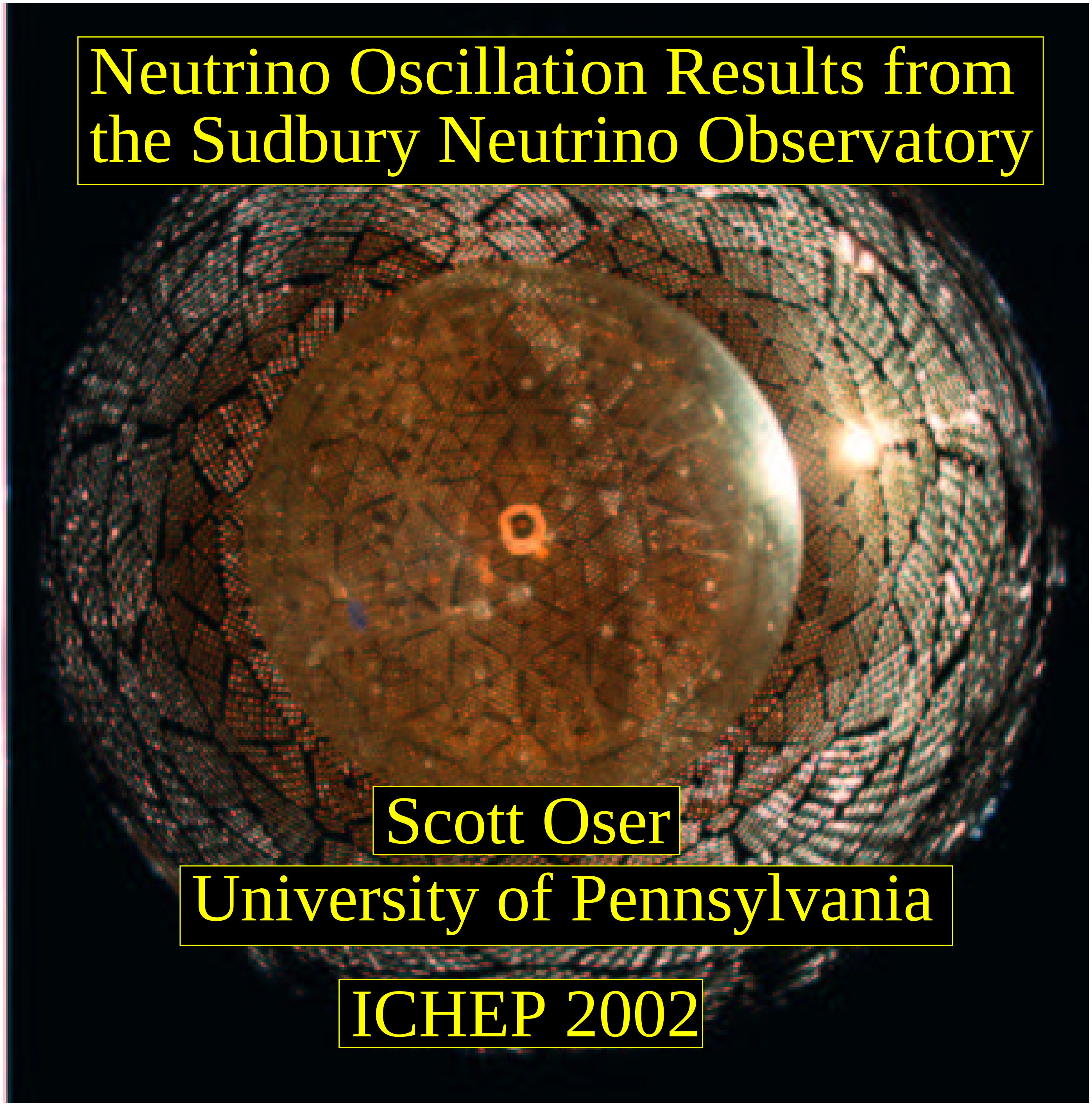
Neutrino Oscillation Results from the Sudbury Neutrino Observatory



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ICHEP 2002

GOALS OF SNO

- Provide direct evidence for neutrino flavor transformation of solar ν's
- Look for day-night effects, spectral distortions, other signatures of non-standard neutrino physics
- Constrain neutrino mixing parameters

The SNO Collaboration

Canada

University of British Columbia

Carleton University

University of Guelph

Laurentian University

Queen’s University

TRIUMF

United States

Brookhaven National Lab.

Lawrence Berkeley National Lab.

Los Alamos National Lab.

University of Pennsylvania

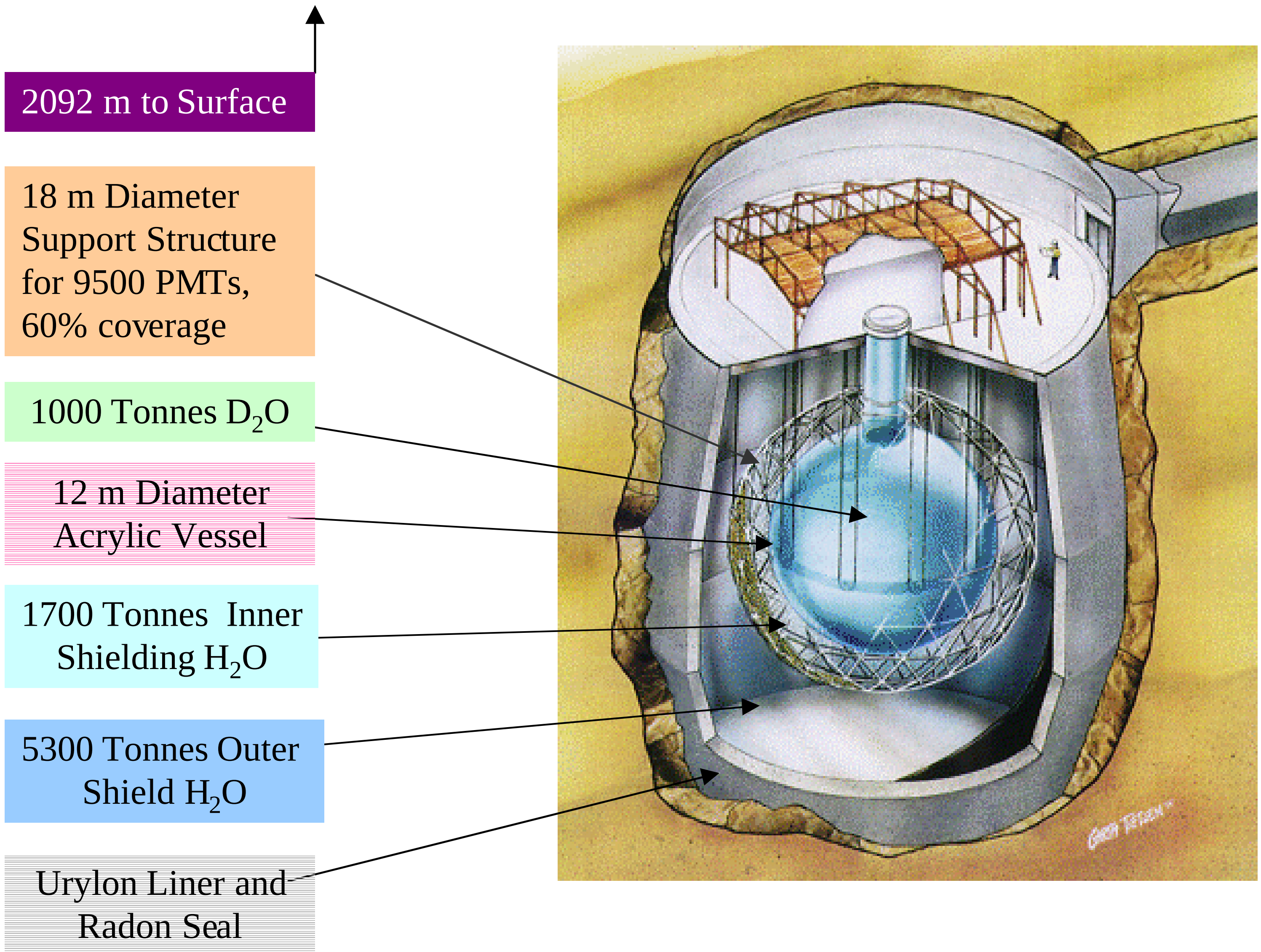
University of Washington

U.K.

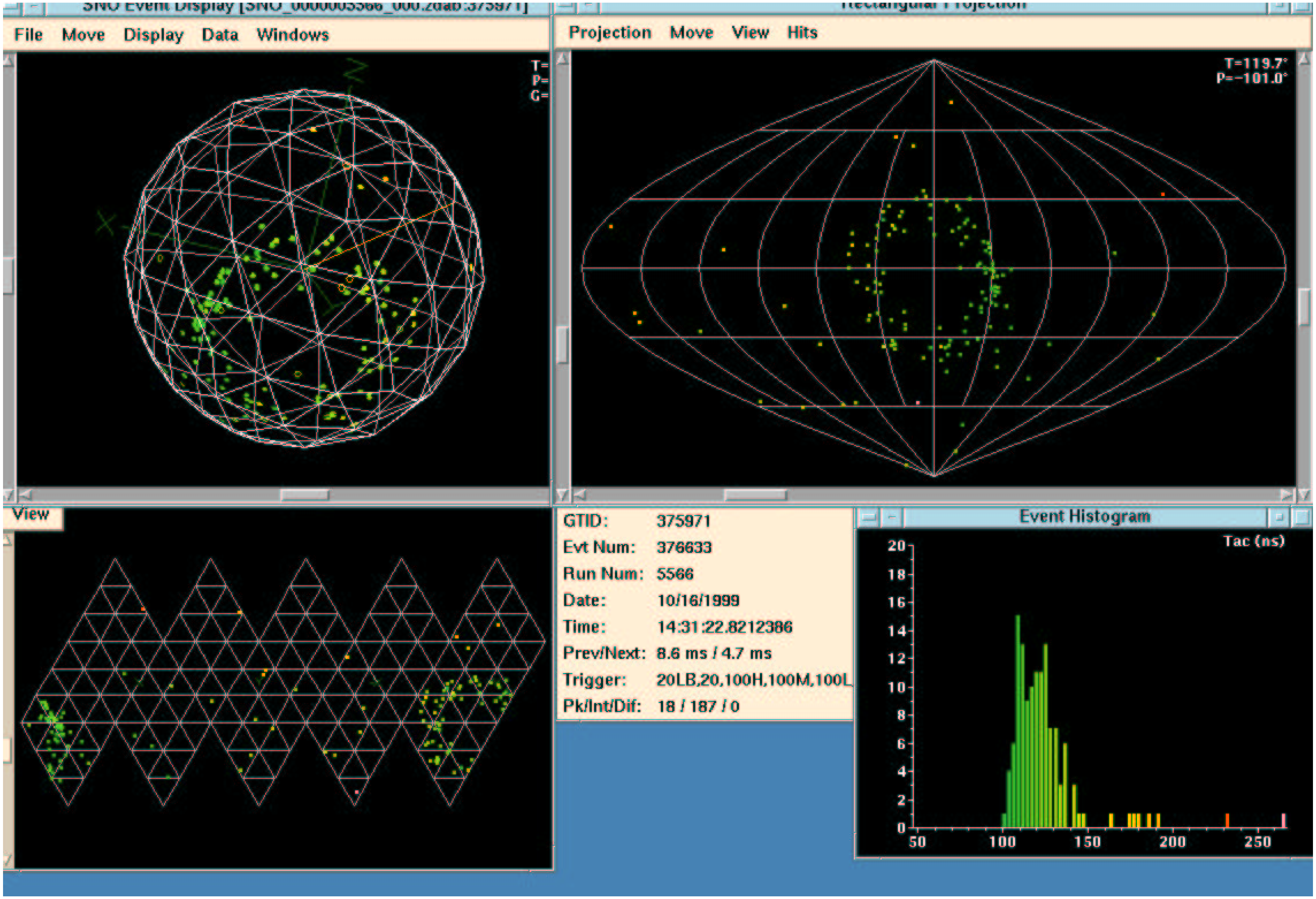
University of Oxford

RAL/Sussex

Sudbury Neutrino Observatory



Event Display–Neutrino Event



Solar ν Interactions in SNO

Elastic Scattering (ES) $\boldsymbol{\nu_x + e^- \longrightarrow \nu_x + e^-}$

- Directional sensitivity (e^- forward peaked)
- Cross-section for ν_e is $6.5\times$ larger than for $\nu_{\mu\tau}$

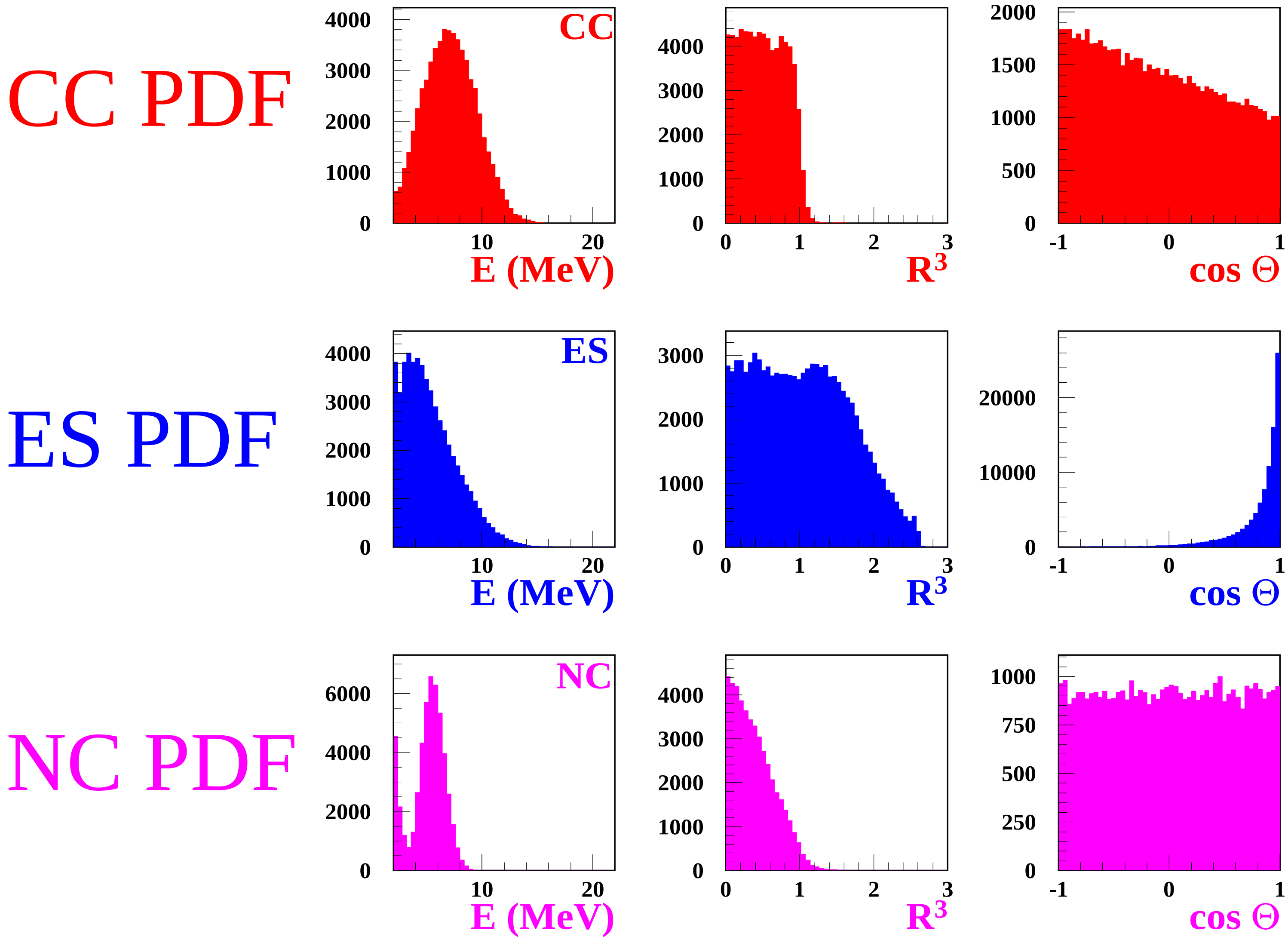
Charged Current (CC) $\boldsymbol{\nu_e + d \longrightarrow p + p + e^-}$

- Some directional information $(1 - \frac{1}{3}\cos\theta_{e\nu})$
- good E_ν sensitivity (ν_e spectrum)

Neutral Current (NC) $\boldsymbol{\nu_x + d \longrightarrow n + p + \nu_x}$

- Total flux of active neutrinos above 2.2 MeV
- Detect neutrons by $n + d \longrightarrow t + 6.25$ MeV γ

Signal Probability Distributions



Each signal has characteristic energy, radial, and angular distributions.

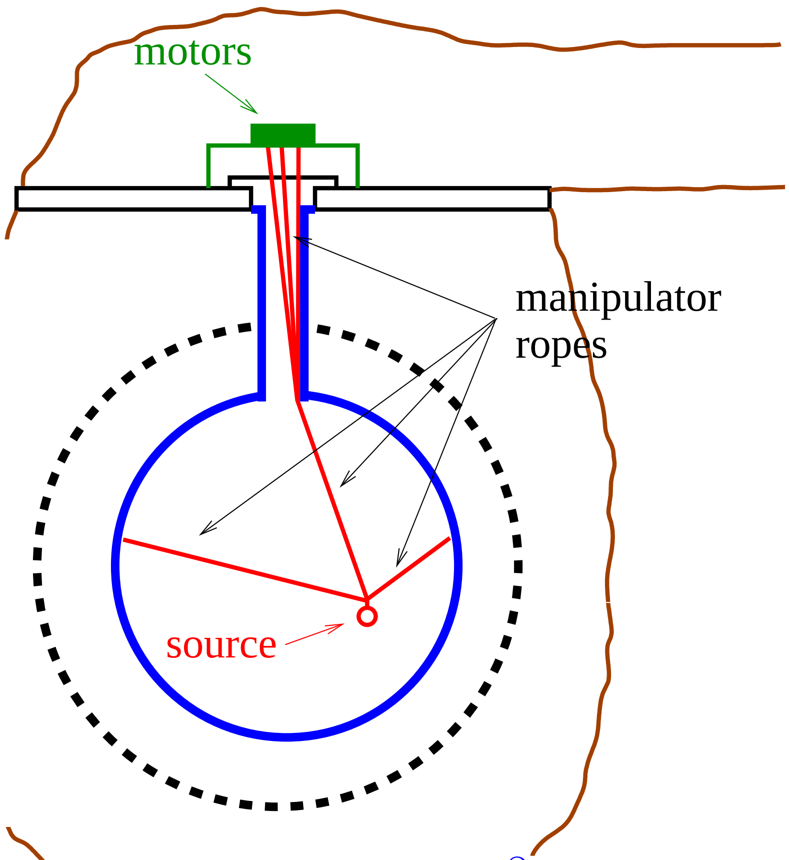
Deriving Flavor Content from Reaction Rates

$$
\begin{aligned}
\boldsymbol{CC} &= \boldsymbol{\nu_e} \\
\boldsymbol{ES} &= \boldsymbol{\nu_e + 0.154\,\nu_{\mu\tau}} \\
\boldsymbol{NC} &= \boldsymbol{\nu_e + \nu_{\mu\tau}}
\end{aligned}
$$

Measuring 2 out of 3 determines flavor content.

Measuring all three gives consistency check.

Detector Calibrations



- pulser
- Laser source
- $^{16}\mathrm{N}$ source: 6.1 MeV γ's
- pT source: 19.8 MeV γ's
- $^{8}\mathrm{Li}$ source: 0-13 MeV β's
- Acrylic U, Th sources
- $^{252}\mathrm{Cf}$ source

Low Energy Backgrounds

U and Th decay products have two effects ...

Photo-disintegration $d(\gamma, n)$

Cause:

- Intrinsic D_2O radioactivity
- H_2O, AV radioactivity

Techniques:

- Radiochemical assays
- In-situ Cherenkov monitoring

Cherenkov Tail Events

Cause:

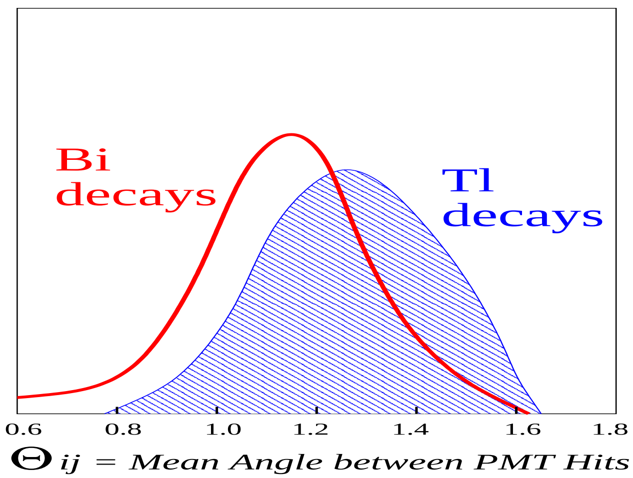
- Misreconstructed events
- Energy resolution tail

Techniques:

- Source studies
- Monte Carlo

Measuring U/Th Content

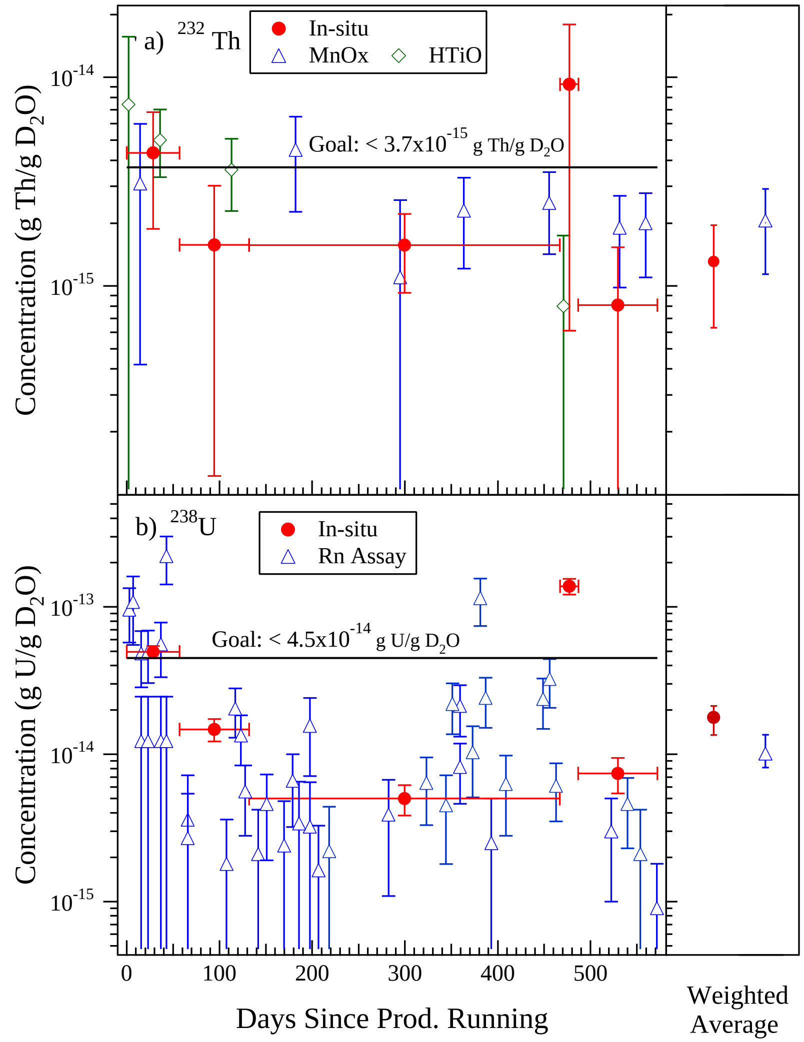
In-situ Cherenkov Monitoring



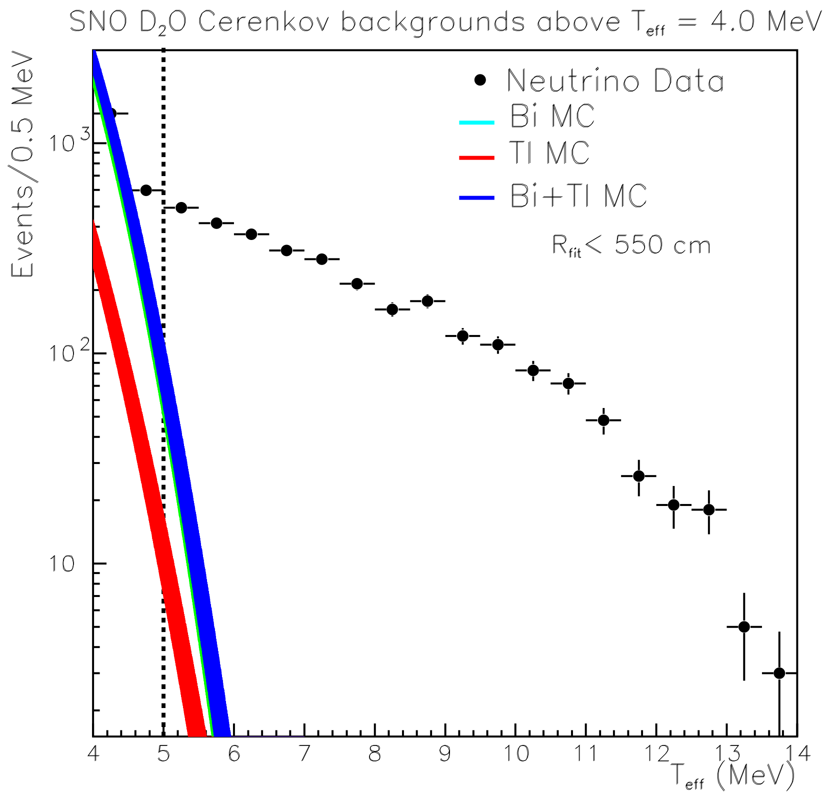
- Count low energy events
- Separate U, Th with event isotropy

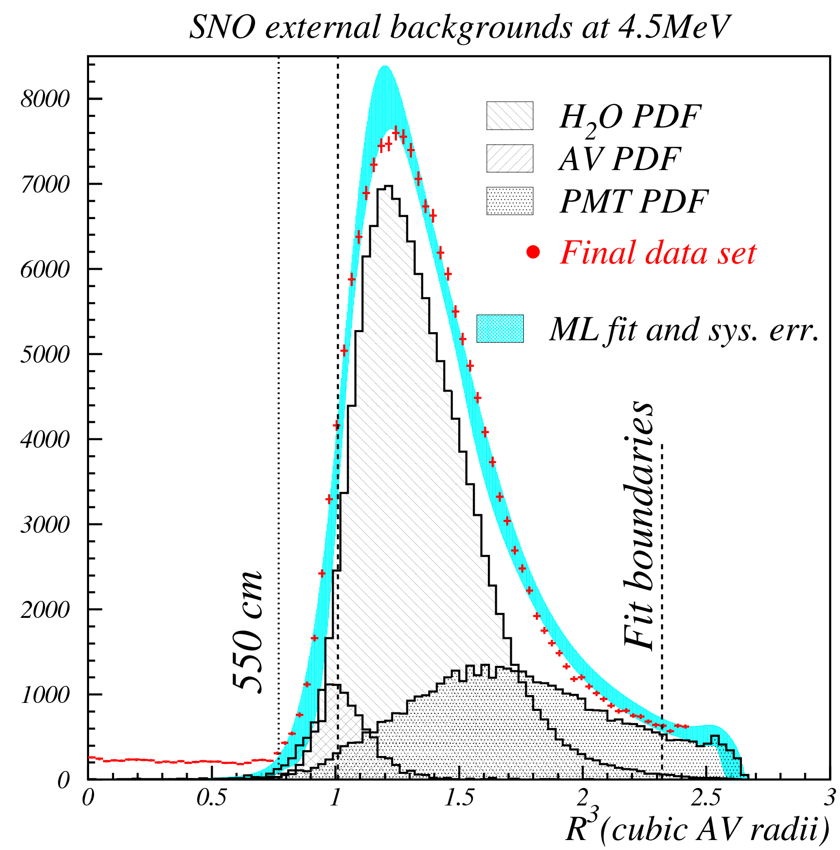
Radiochemical Assays

- Ion exchange media (Ra)
- Membrane degassing (Rn)



Cherenkov Tail Backgrounds





- Use calibration sources, Monte Carlo to model detector's response to U, Th

- Fit background PDFs to data at large radius
- Use PDF shapes to determine leakage of events inside D_2O

Extracted Event Totals

Extract signal with maximum likelihood fit of PDFs to data

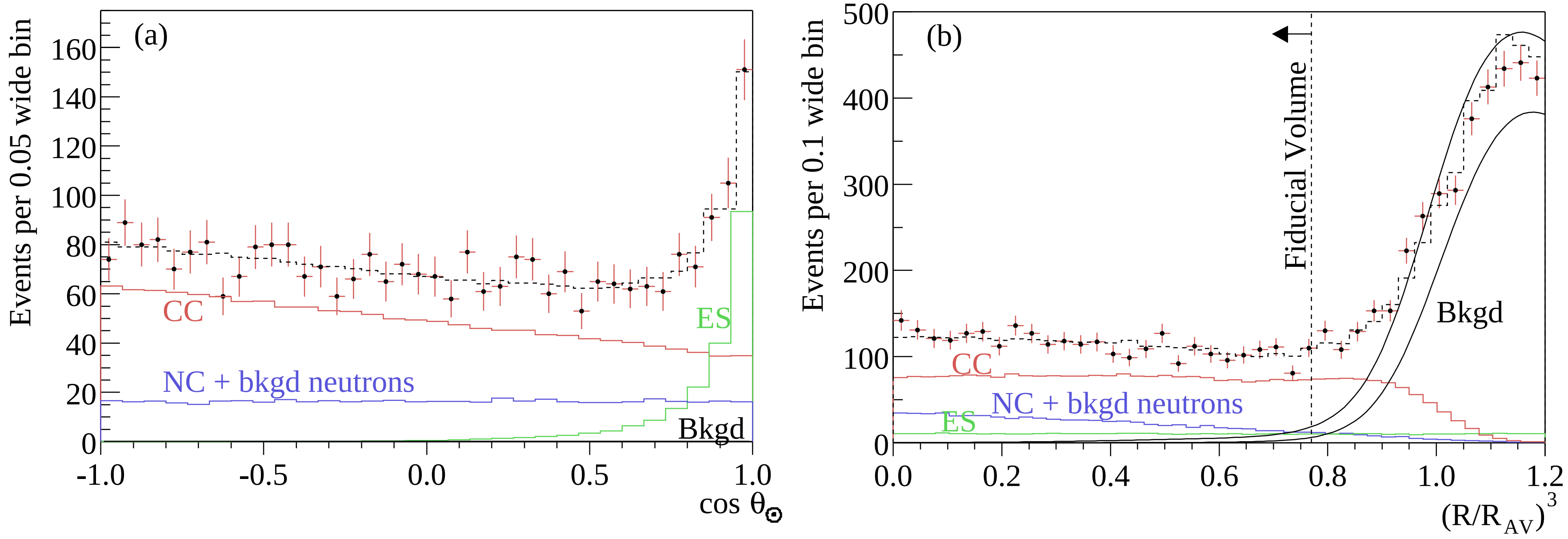
(306.4 livedays of data, 1999/11/2 - 2001/5/28)

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

Subtracted Backgrounds:

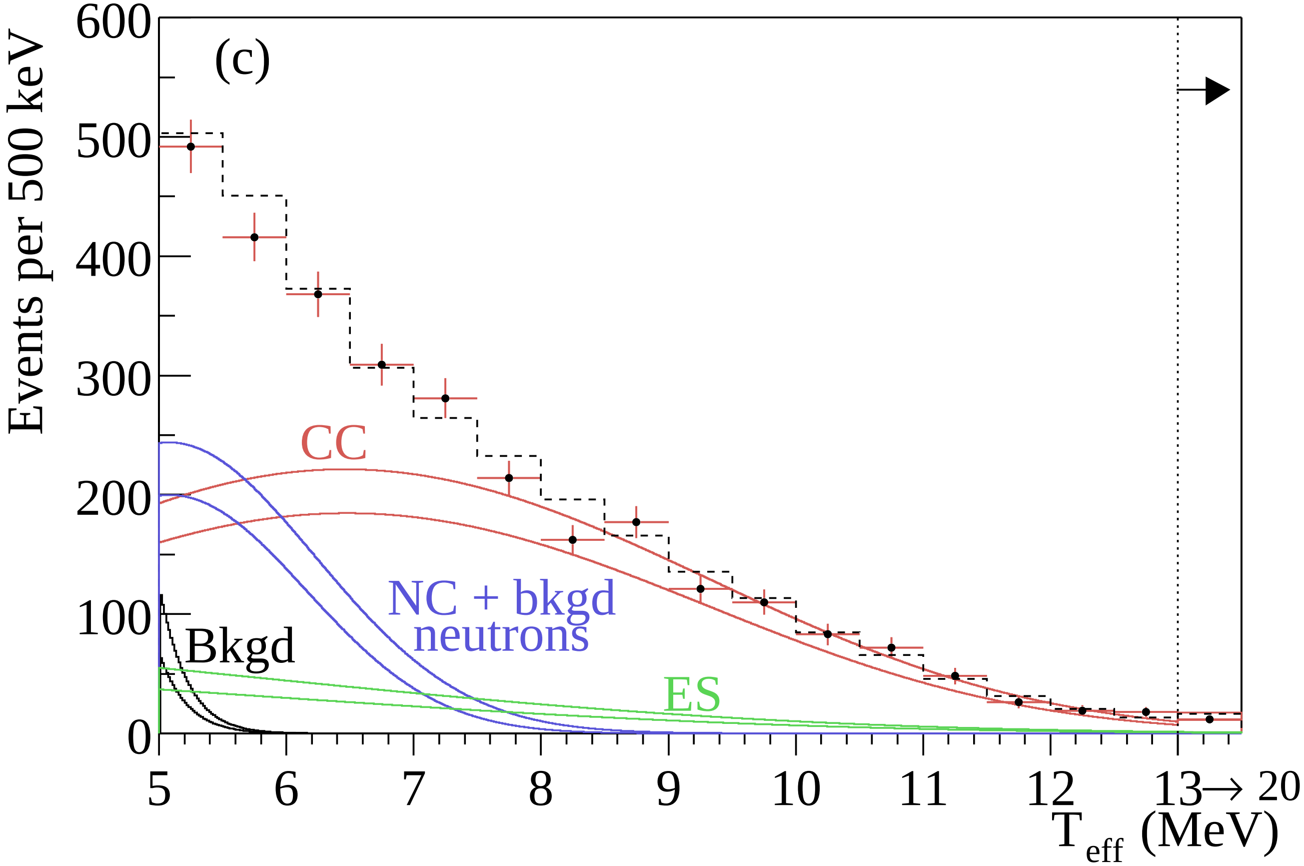
Photodisintegration	$\mathbf{78 \pm 12}$
Cherenkov Tail	$\mathbf{45^{+18}_{-12}}$

Radial And Angular Distributions

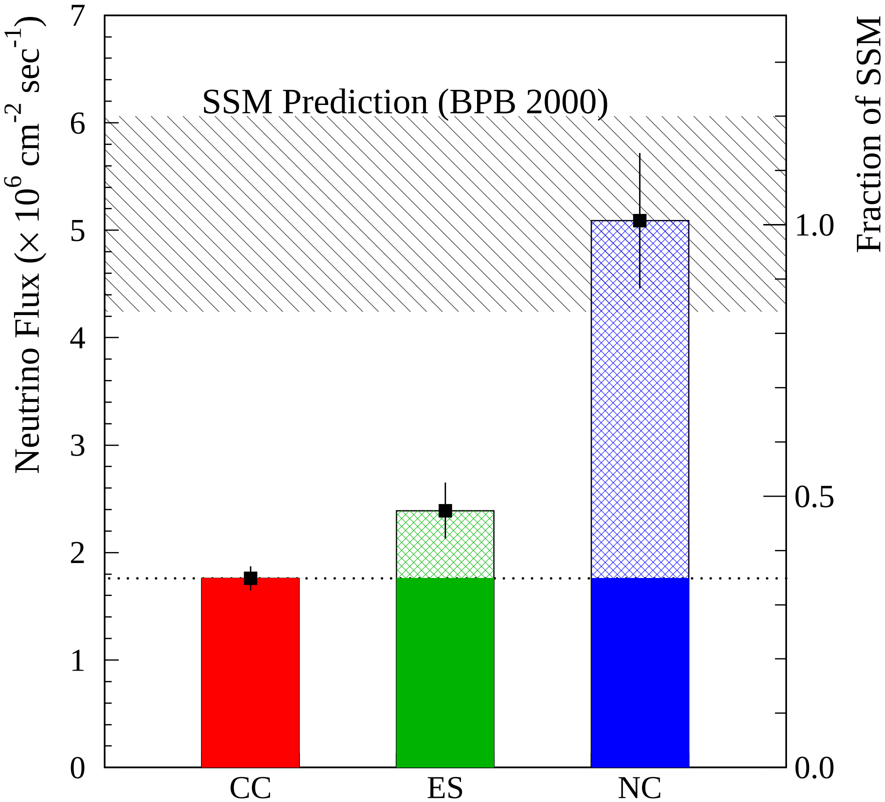


Signal region: $R < 550$ cm, $T > 5$ MeV

Total Energy Spectrum



Measured SNO Fluxes



Assuming ^{8}B energy spectrum ...

Fluxes ($\times 10^6$ cm^{-2} sec^{-1})

$$\phi_{CC} = 1.76^{+0.06}_{-0.05}\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{sys.})$$

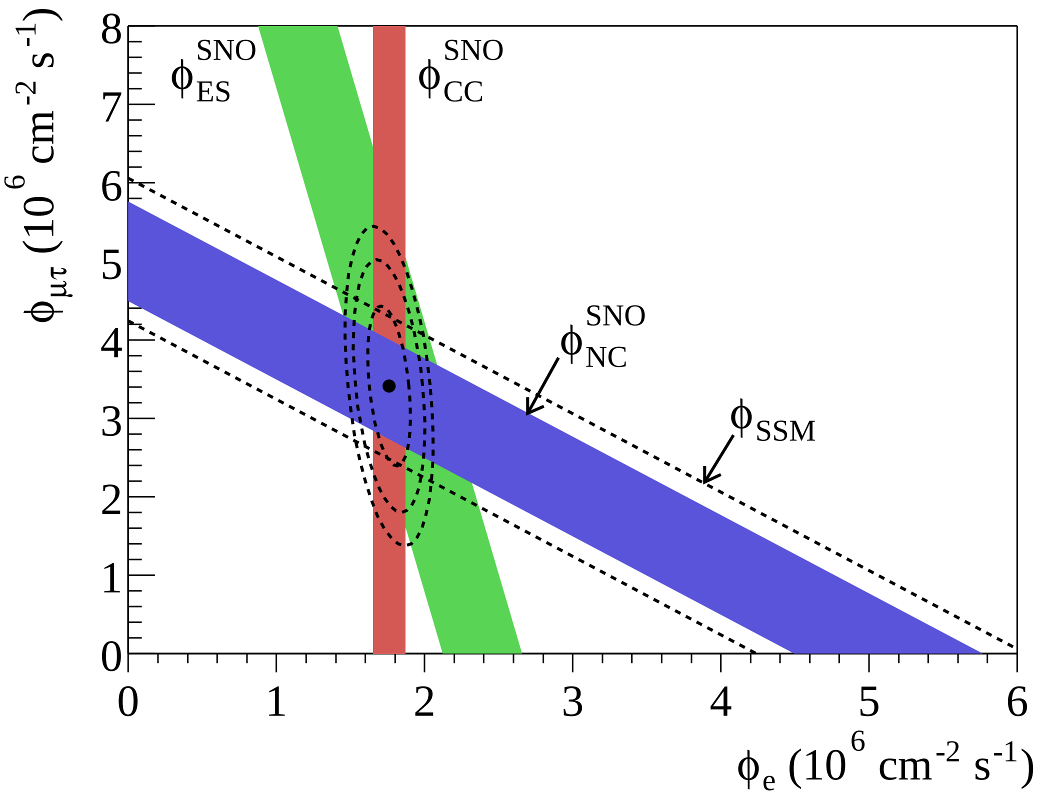
$$\phi_{ES} = 2.39^{+0.24}_{-0.23}\,(\mathrm{stat.}) \pm 0.12\,(\mathrm{sys.})$$

$$\phi_{NC} = 5.09^{+0.44}_{-0.43}\,(\mathrm{stat.})^{+0.46}_{-0.43}\,(\mathrm{sys.})$$

$$\phi_{CC} < \phi_{ES} < \phi_{NC}$$

NC flux in agreement with SSM prediction!

Flavor Content



$$\phi_e = 1.76 \pm 0.06 \pm 0.09 \quad \times 10^6\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$$

$$\phi_{\mu\tau} = 3.41 \pm 0.45^{+0.48}_{-0.45} \quad \times 10^6\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$$

$\phi_{\mu\tau} > 0$ at 5.3σ level!

Day-Night Asymmetries

Day-night rate asymmetry is signature of matter effects:

$$A = \frac{N - D}{\frac{1}{2}(N + D)}$$

Measure both A_e and A_{tot}:

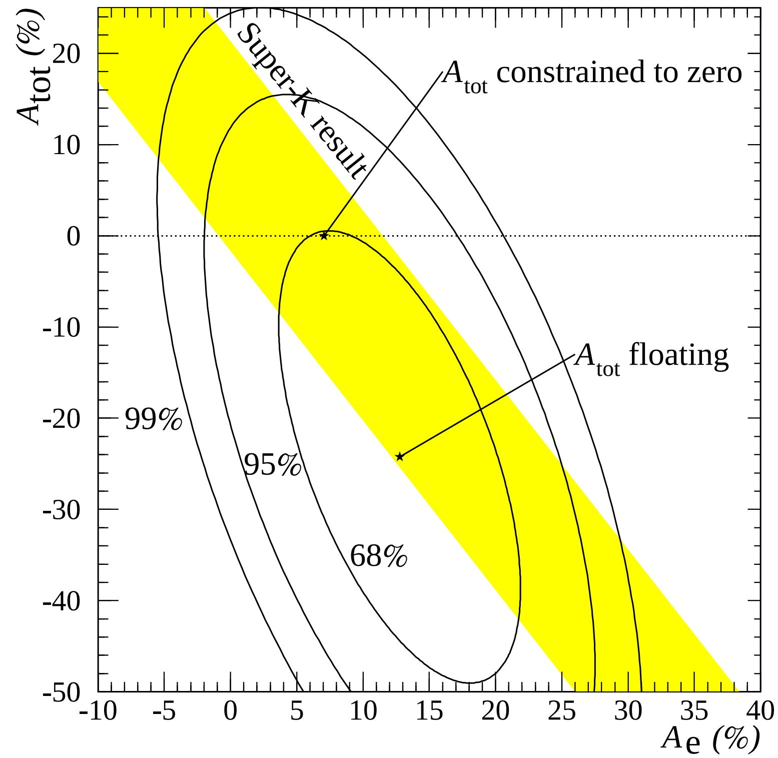
- MSW matter effect: $0 < A_e < 20\%$
- If only active ν's, $A_{tot} = 0$

Letting A_{tot} float:

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

Demanding $A_{tot} \equiv 0$:

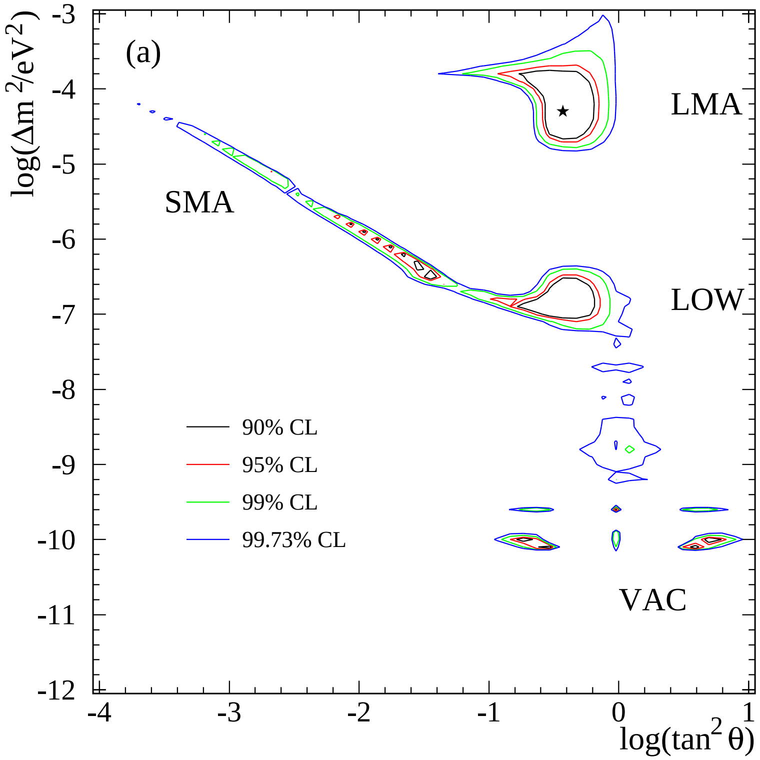
$$A_e = +7.0\% \pm 4.9\%^{+1.3}_{-1.2}\%$$



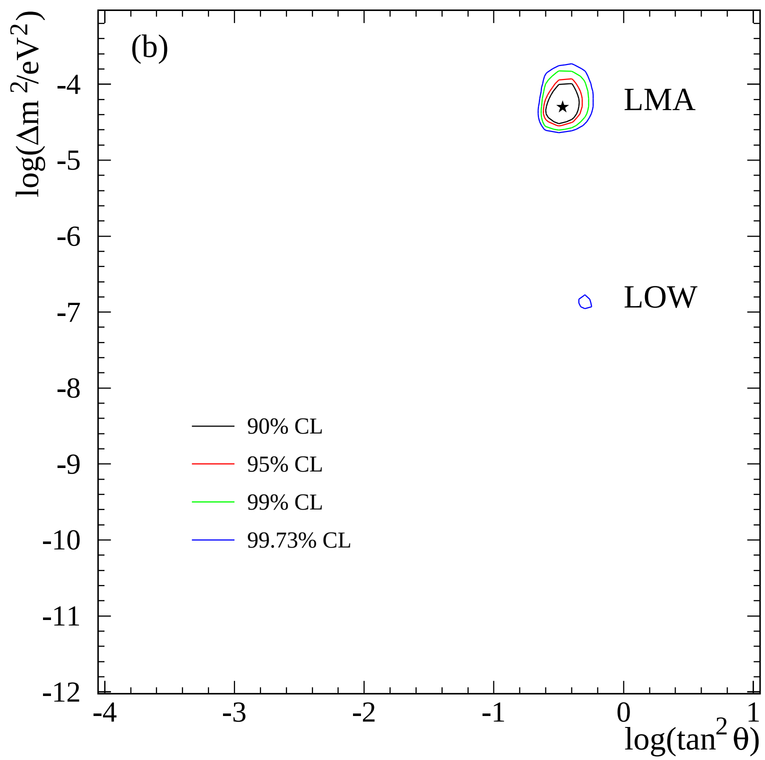
All results assume undistorted ^{8}B spectrum.

Constraints on ν Mixing Parameters

Only SNO Data



Global Analysis

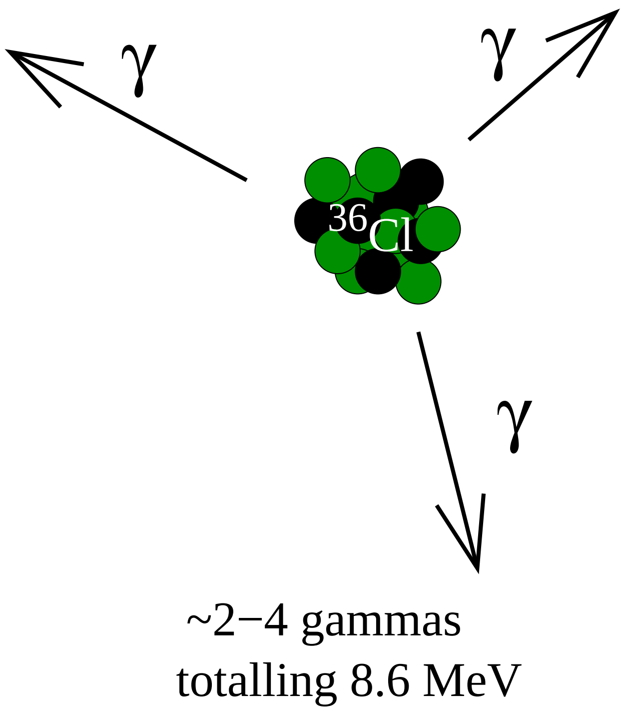


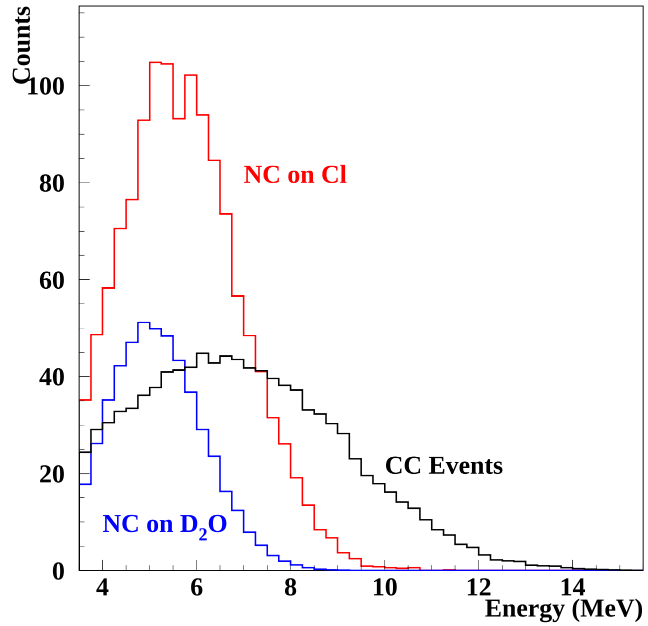
LMA solution with $\tan^2\theta < 1$ is strongly favored.

Next Phase: Salt

In June 2001 added 0.2% NaCl to D_2O to increase neutron capture (on ^{35}Cl)

Capture efficiency increased by $\times 2.6$





Emitted radiation increases from 6.25 MeV to 8.6 MeV

Multiple γ's emitted—separate CC, NC events using event topology, isotropy

Conclusions

- First neutral current results from SNO!
- Direct evidence for neutrino flavor transformation at the 5.3σ level.
- Measurement of total ^{8}B flux from the Sun in excellent agreement with SSMs
- Limits on day-night asymmetries of electron neutrino flux and total neutrino flux
- Global fit including SNO day-night energy spectra strongly favors LMA solution.

Limits on Sterile ν's

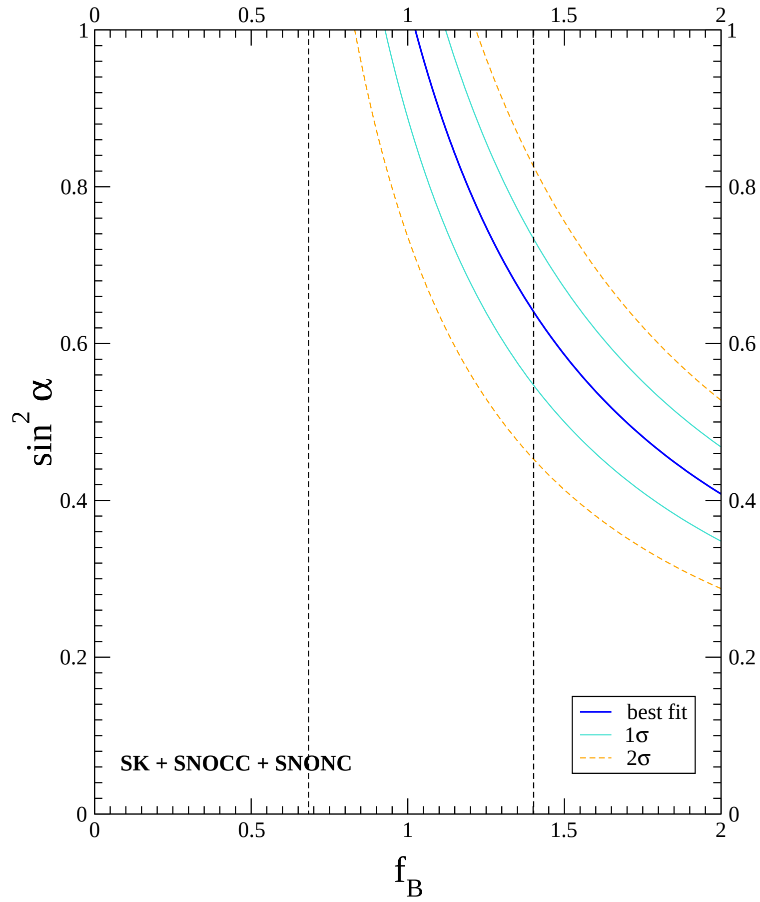
SNO results establish that some ν_e's turn into ν_μ or ν_τ.

But a substantial admixture of sterile ν's still allowed.

To constrain this, one must compare SSM flux prediction to measured SNO flux.

Improvements in SSM predictions (ex. better S_{17} cross-section measurements) translate directly into better limits on sterile neutrinos!

Plot at right based on rate comparison. A more complete treatment will require consideration of spectral effects.



Bandyopadhyay et al. (hep-ph/0204286)

Dominant Systematic Errors

Source	CC Uncert. (percent)	NC Uncert. (percent)	$\phi_{\mu\tau}$ Uncert. (percent)
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
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 pd †	± 0.0	-1.5,+1.6	-2.0,+2.2
External source pd	± 0.1	-1.0,+1.0	± 1.4
D_2O Cherenkov †	-0.1,+0.2	-2.6,+1.2	-3.7,+1.7
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
Experimental uncertainty	-5.2,+5.2	-8.5,+9.1	-13.2,+14.1
Cross section	± 1.8	± 1.3	± 1.4

Proton Decay Background

Protons decaying inside deuterons leave behind free neutrons.

SNO detected $576.5^{+49.5}_{-48.9}$ free neutrons above known backgrounds.

Assuming that all these neutrons came from proton decay, we get a lower limit on the proton lifetime for "invisible" modes[a]:

$$\tau > \ \sim 10^{28}\text{years}$$

This is approximately 3 orders of magnitude better than previous limit.[b]

For the remainder of this talk, we shall ignore the proton decay background to the neutral current signal ...

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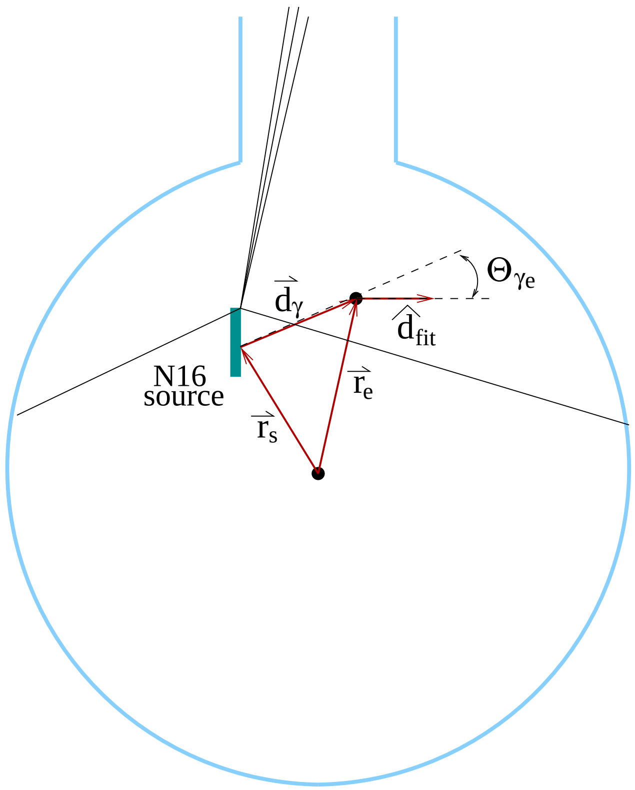
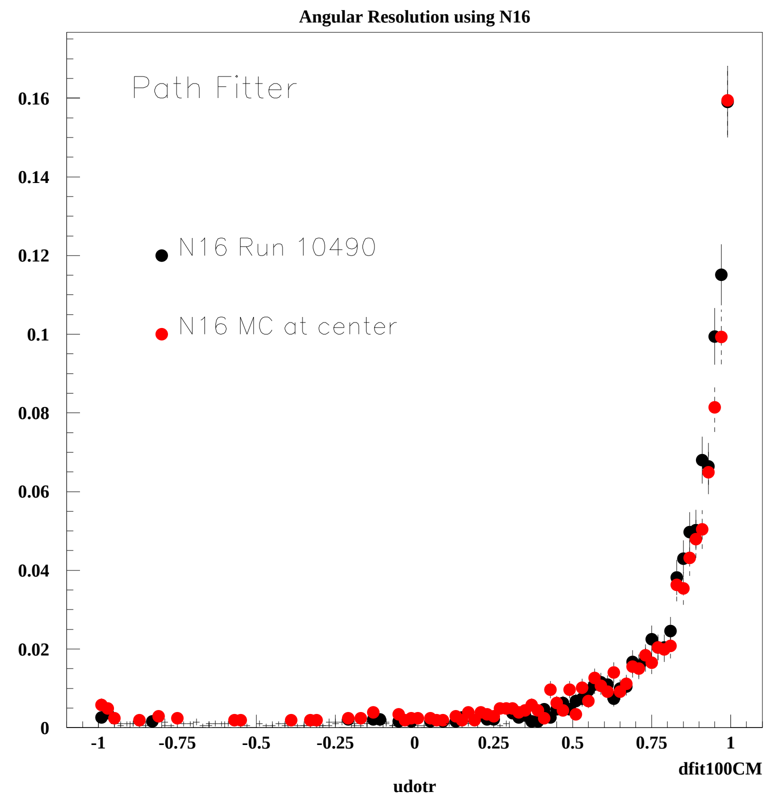
[a] V. I. Tretyak and Yu. G. Zdesenko, Phys. Lett. B505, 59 (2001)

[b] J. Evans and R. Steinberg, Science, 197, 989 (1977)

Angular Resolution with ^{16}N Source

$^{16}\mathrm{N}$ at the center of detector, $d_{fit} > 100$ cm





Use $\vec{r}_{fit}$ as estimator for $\vec{r}_e$

$$\cos\theta = \frac{\vec{r}_{fit} - \vec{r}_s}{|\vec{r}_{fit} - \vec{r}_s|} \cdot \hat{d}_{fit}$$

Angular resolution: 26.7 degrees at 5 MeV

Estimating Vertex Resolution and Shift from $^{16}\mathrm{N}$ Source

Motivated by Monte Carlo, assume Gaussian vertex distribution for reconstructed e^-'s

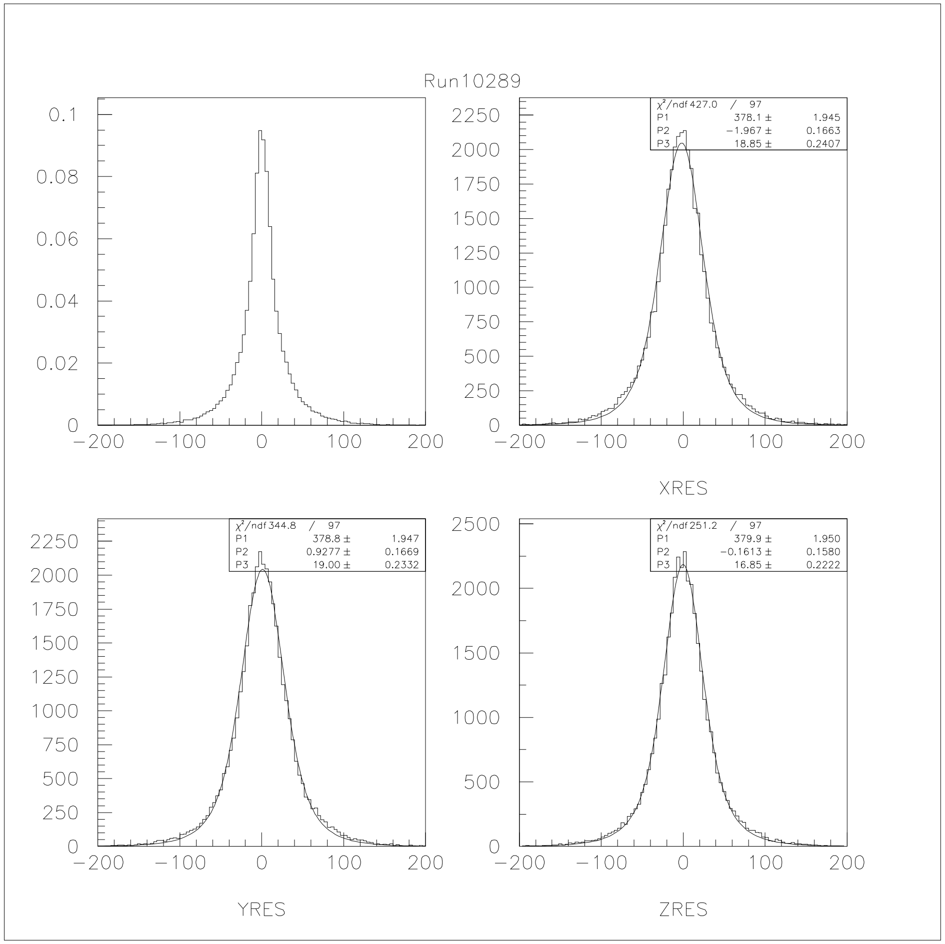
$$F(x_{res}, \sigma, \mu; x_{src}) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x_{xres} - \mu)^2}{2\sigma^2}}$$

Convolve F with 1-D Compton scattering distribution S

$$\xi(x_{res}; \sigma, \mu) = \int_{-\infty}^{\infty} F(x_{res}, \sigma, \mu; x_{src}) S(x_{src}) dx_{src}$$

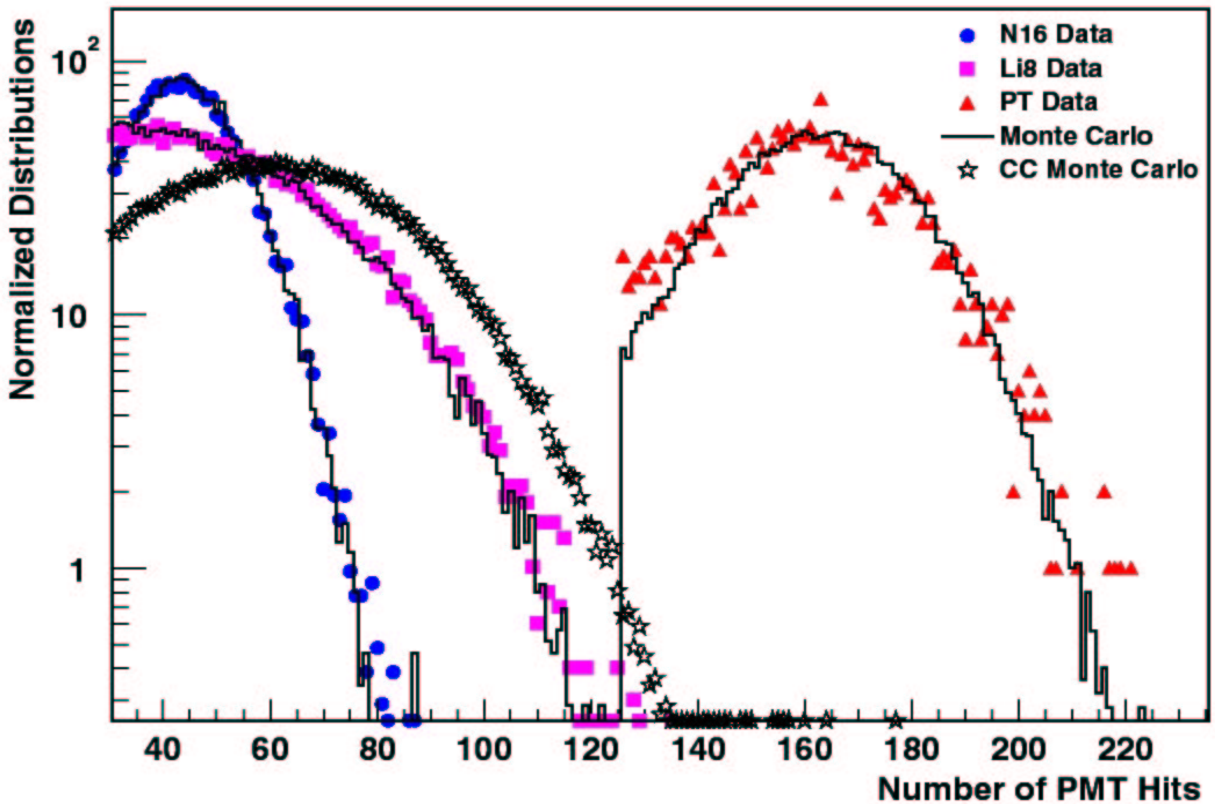
Fit ξ to $^{16}\mathrm{N}$ x,y,z fit residual distributions

$\longrightarrow \mu, \sigma$ for each axis



Vertex resolution ~ 16 cm at 5 MeV

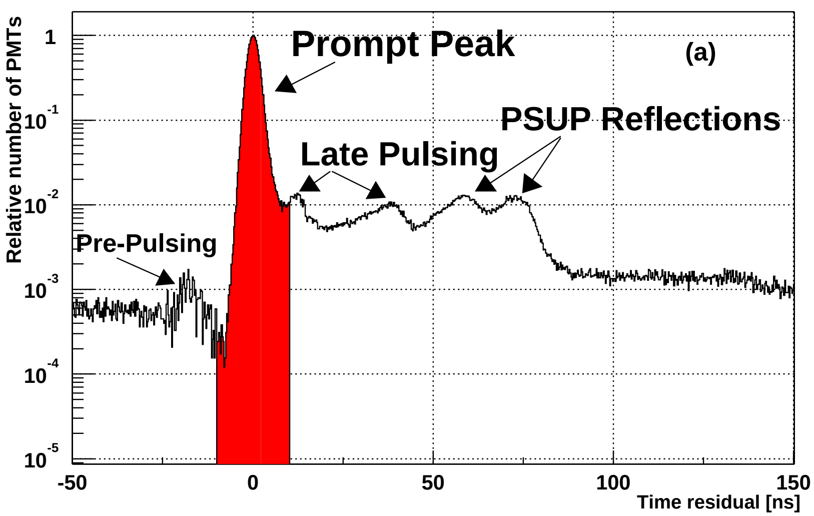
SNO's Energy Response

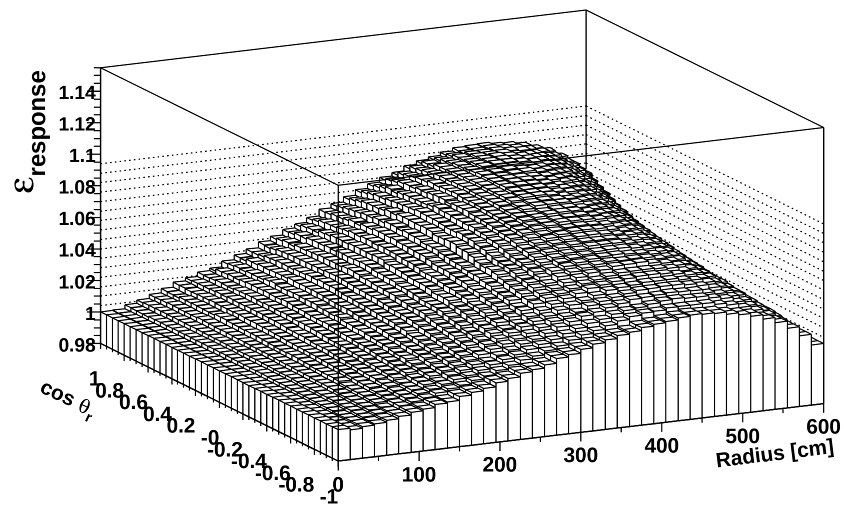


Energy Calibration

Identify “direct light” (no scatters) through prompt time window cut.

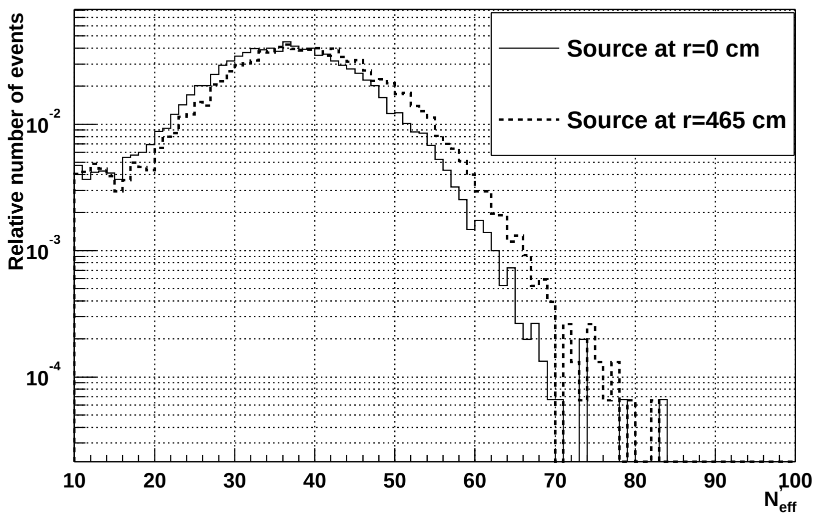
Total number of “prompt hits” maps to energy.

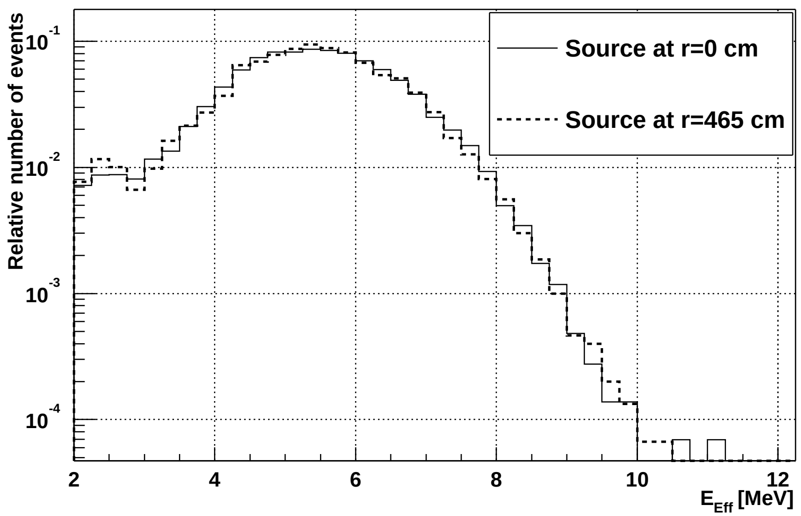




Use detailed optical model, measured attenuations to correct for position and angular dependence of energy response.

Energy Calibration 2





Energy response from ^{16}N source before optical corrections.

Energy response from ^{16}N source after optical corrections.

Calibrating Neutron Response

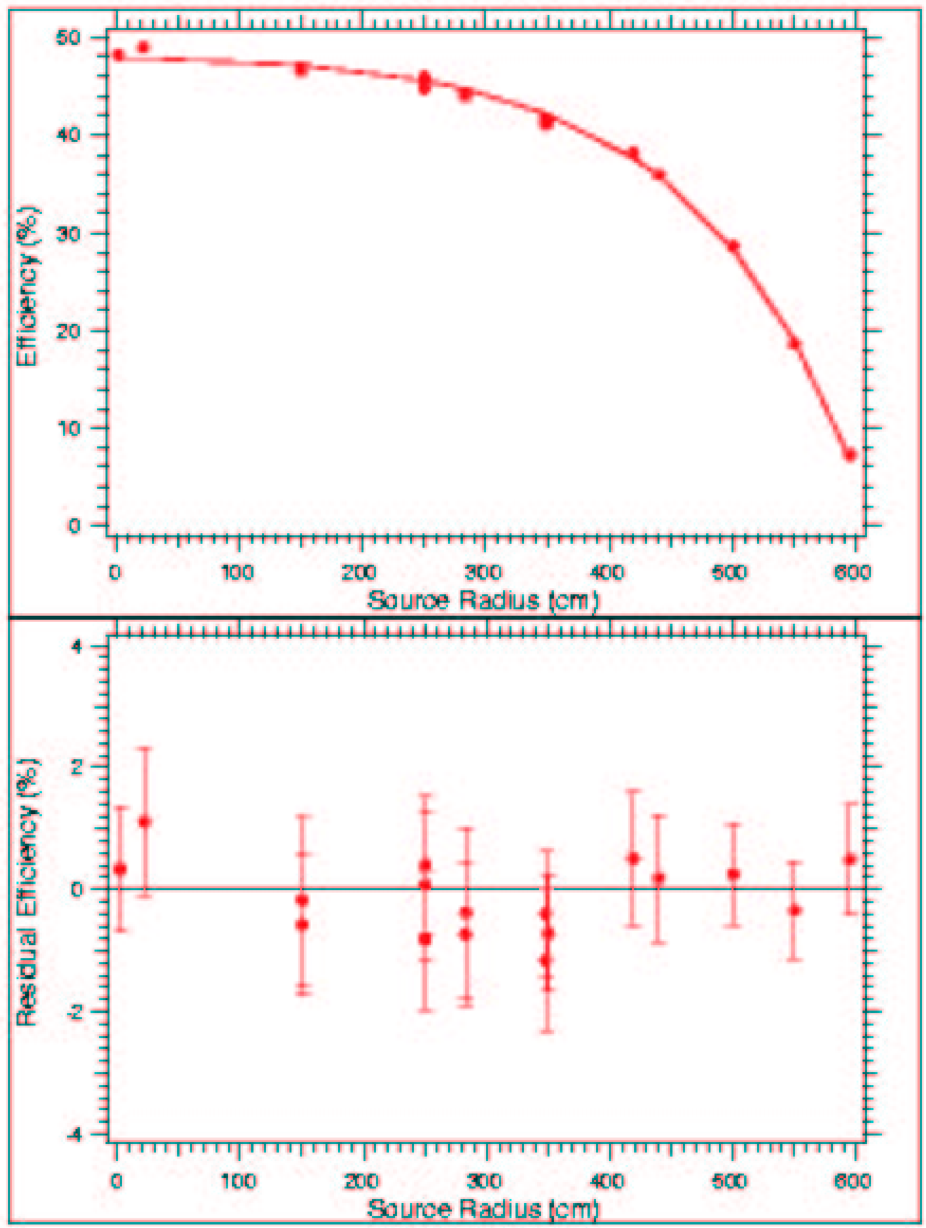
Use fission neutrons from ^{252}Cf source to measure neutron capture efficiency.

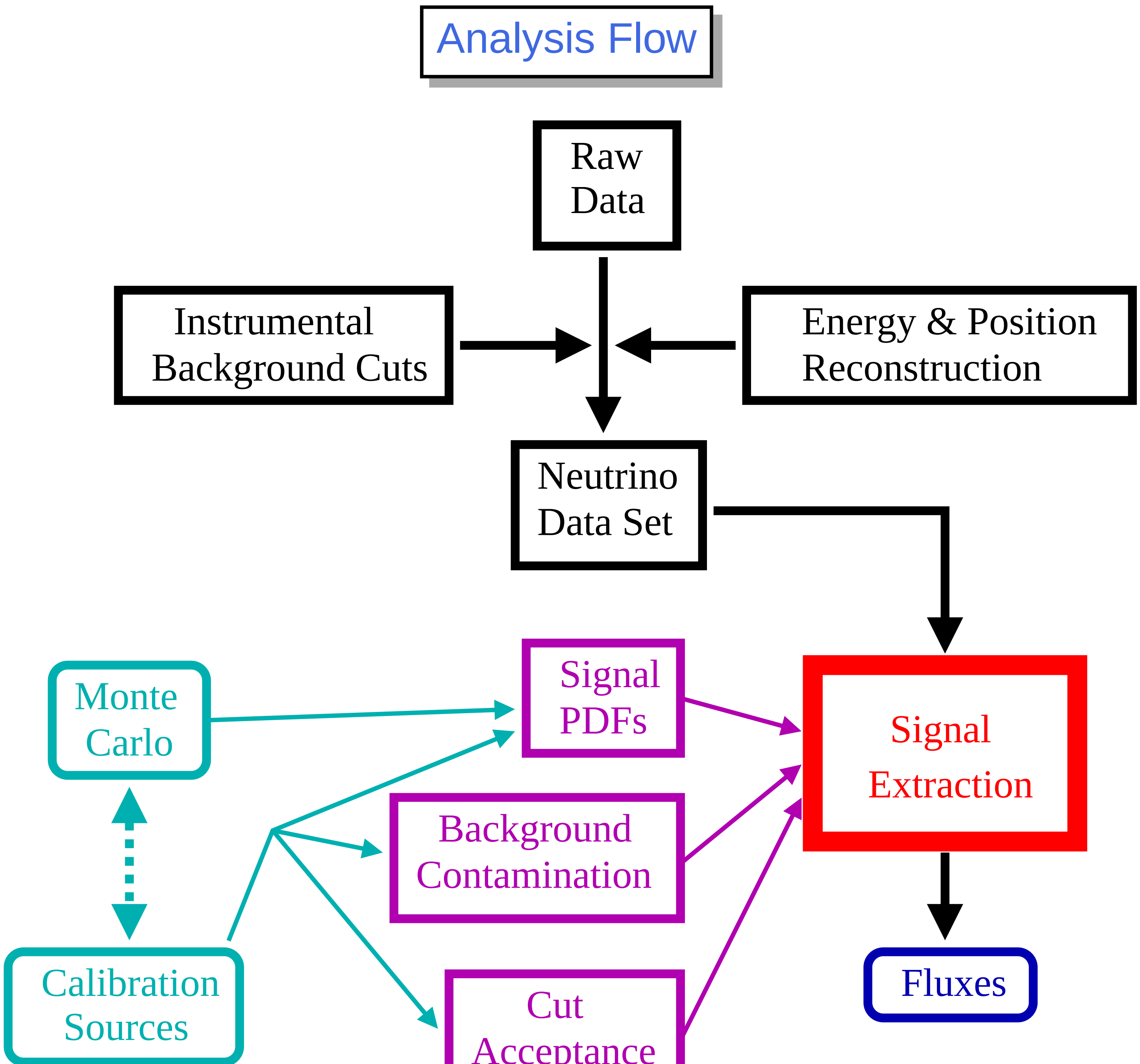
Average capture efficiency for NC events:

$$29.9\% \pm 1.1\%$$

Fraction inside 550 cm, above $T > 5$ MeV:

$$14.4\% \pm 0.5\%$$





Analysis Flow
Raw Data
Instrumental Background Cuts
Energy & Position Reconstruction
Neutrino Data Set
Monte Carlo
Signal PDFs
Signal Extraction
Background Contamination
Calibration Sources
Cut Acceptance
Fluxes

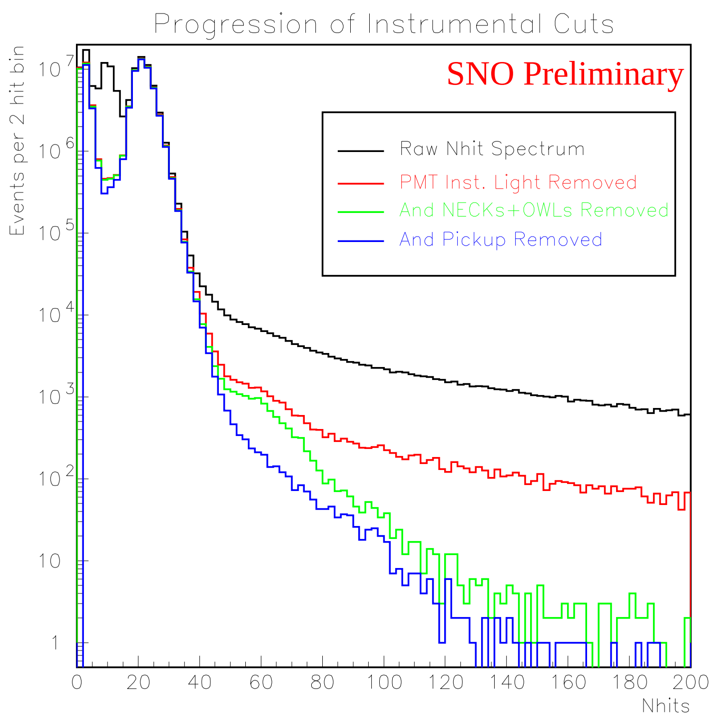
Instrumental Backgrounds 1

Instrumental backgrounds due to:

- electrical pickup
- static discharge
- "Flasher" PMTs

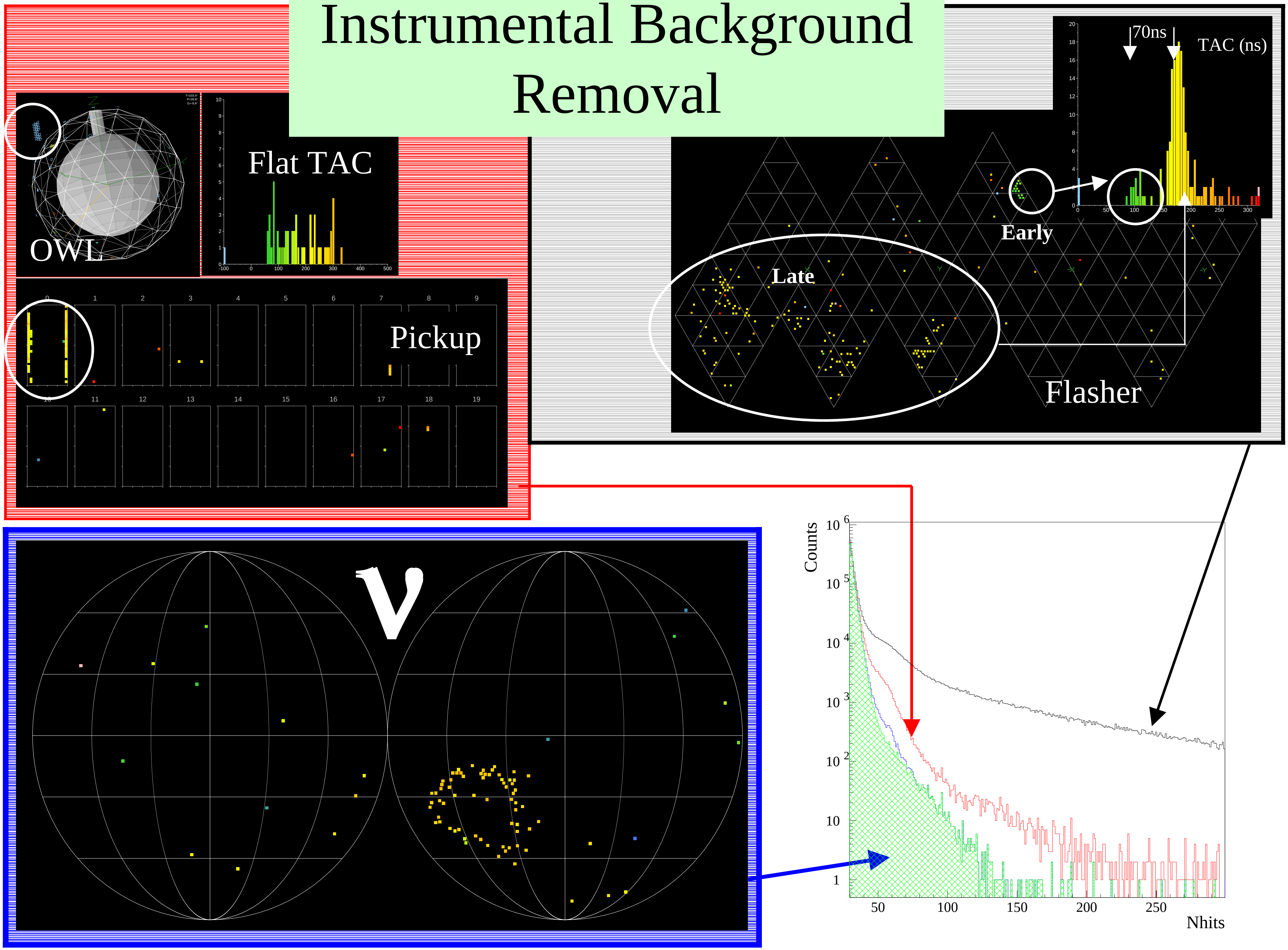
Remove with cuts based on:

- Time correlations
- Charge distributions, means
- Veto PMTs
- Raw time distributions



Cuts applied before reconstruction of data

Instrumental Background Removal



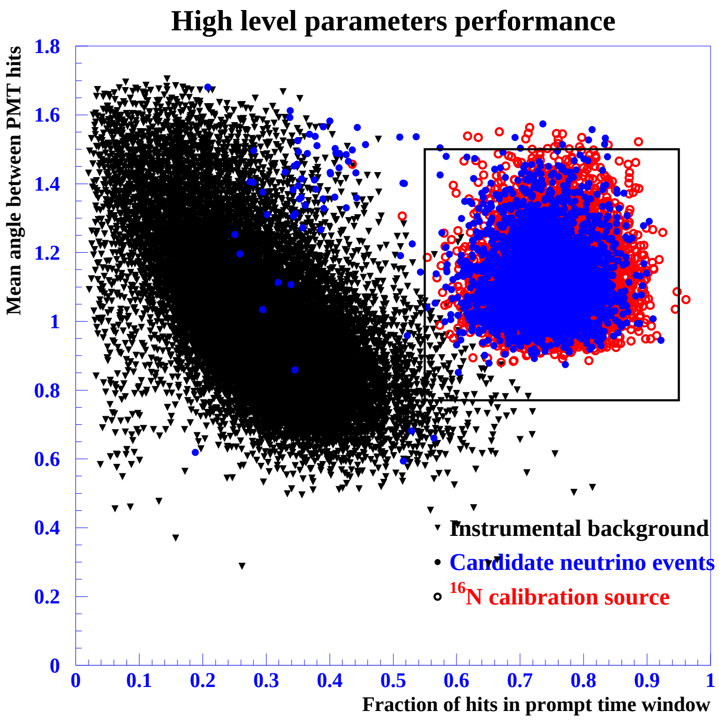
Instrumental Backgrounds 2

Apply high level cuts after reconstruction to remove residual instrumental backgrounds, measure contamination.

- ITR – fraction of in-time PMT hits
- Θ_{ij} - average angle between hit PMTs relative to vertex

These cuts define a "Cherenkov box"

Use ratio of events inside/outside box to calculate contamination

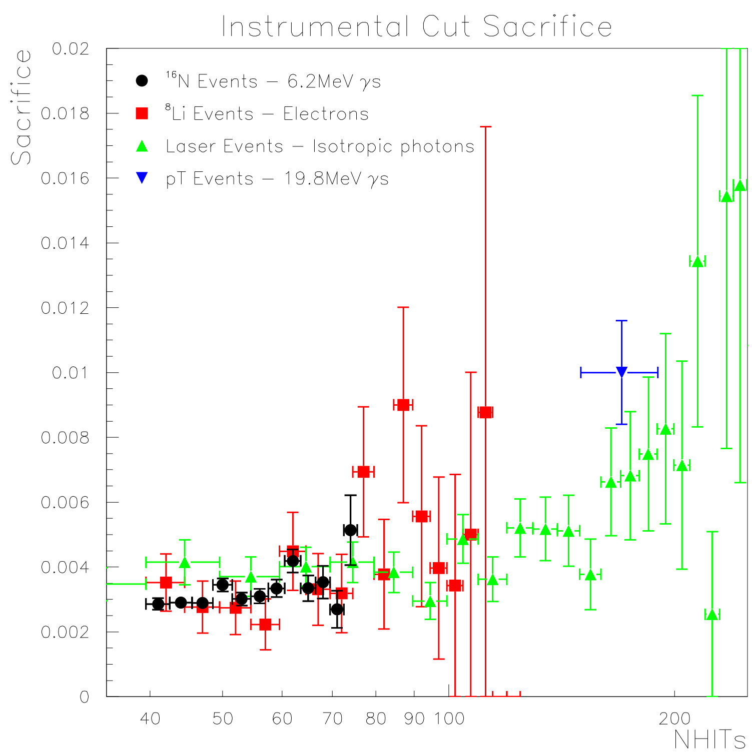


Residual contamination 0.03 ± 0.04 events—95% upper limit is 3 events.

Finding A Needle In A Haystack

Analysis step	Number of events
Total event triggers	450 188 649
Neutrino data triggers	191 312 560
$N_{\rm hit} \geq$30	10 088 842
Instrumental background cuts	7 805 238
High level cuts	3 418 439
Fiducial volume cut	67 343
Energy threshold cut	3 440
Muon follower cut	2 981
Cosmogenic cut	2 928
Total events	2 928

Signal Loss From Cuts



Neutrino signal loss due to cuts measured with calibration sources.

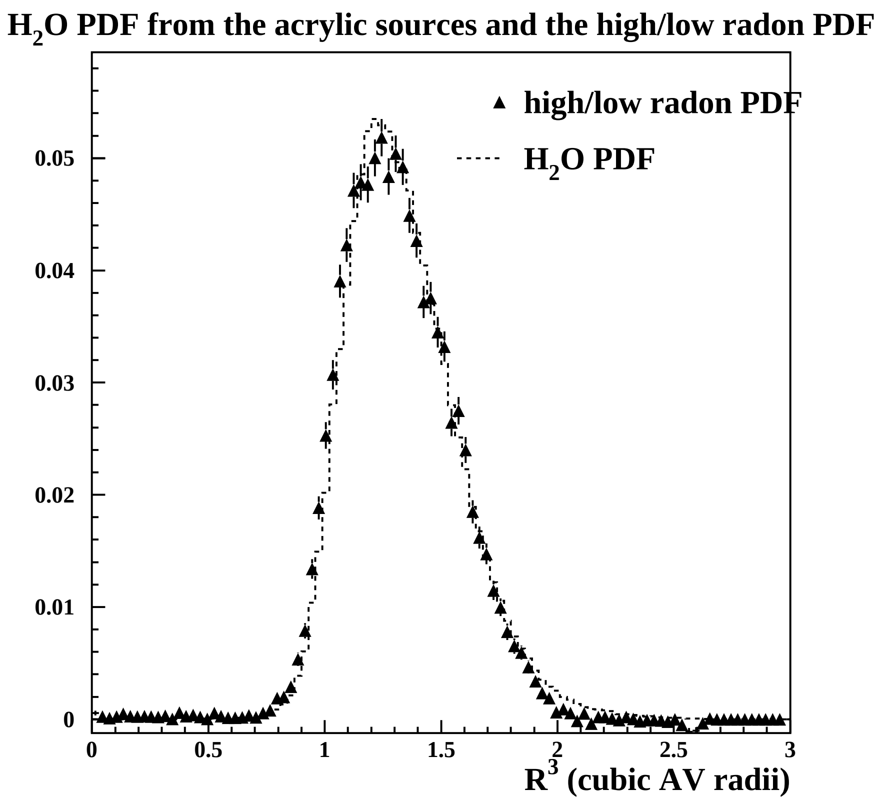
Signal loss from instrumental cuts: $< 1\%$

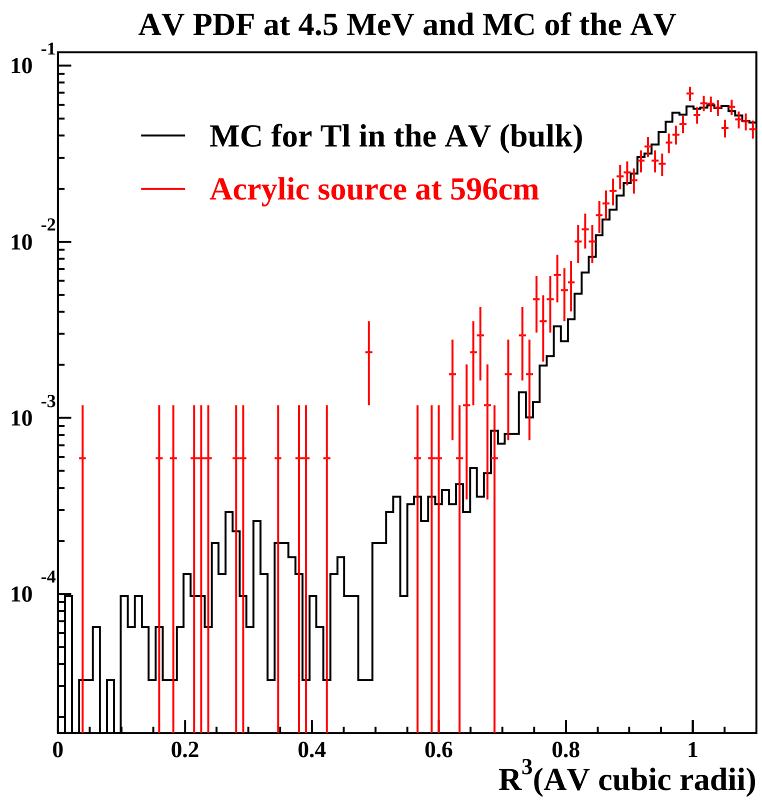
Total loss for CC events: $1.4^{+0.4}_{-0.2}\%$

Total loss for ES events: $1.5^{+0.4}_{-0.2}\%$

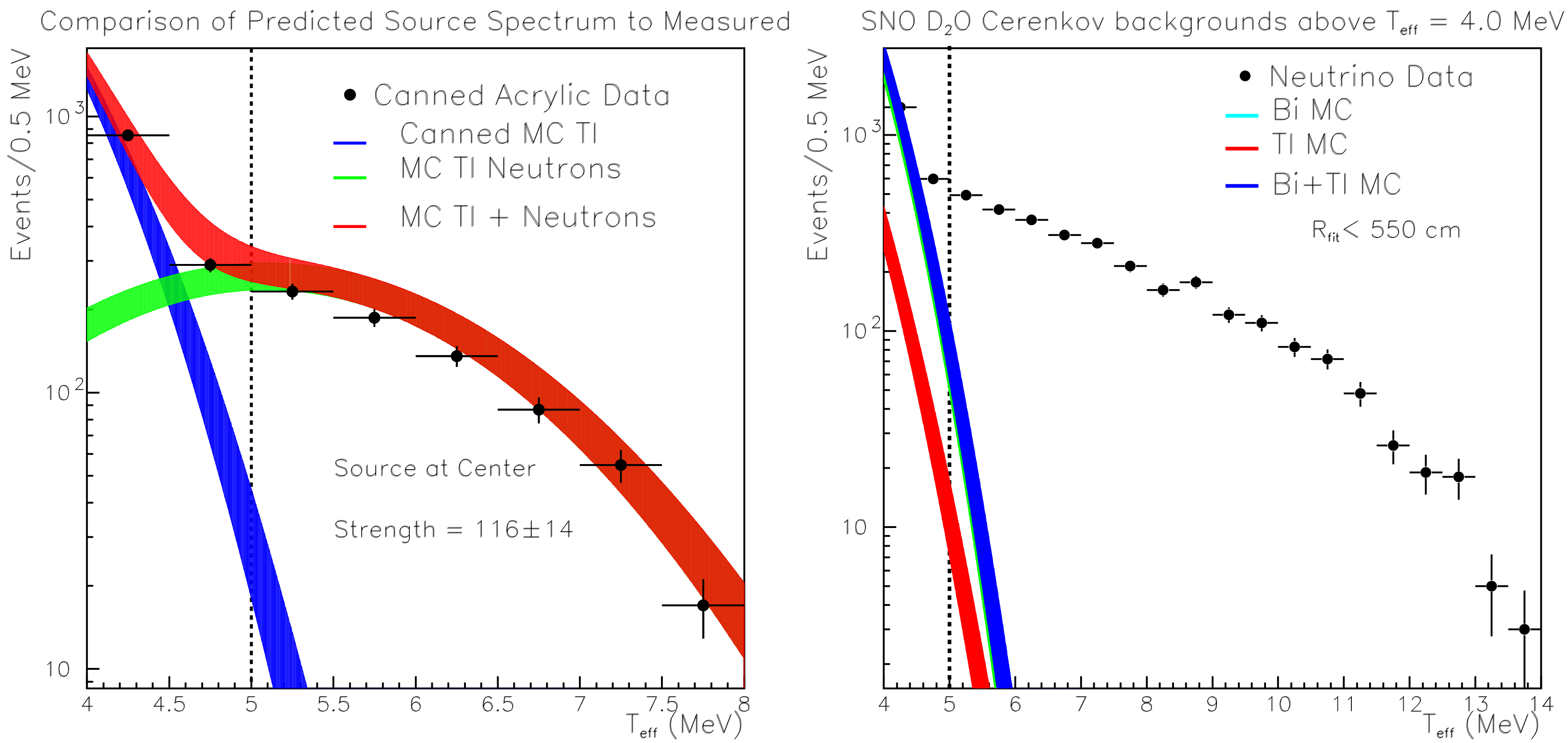
Total loss for NC events: $2.3^{+0.4}_{-0.2}\%$

External Cherenkov Consistency Checks





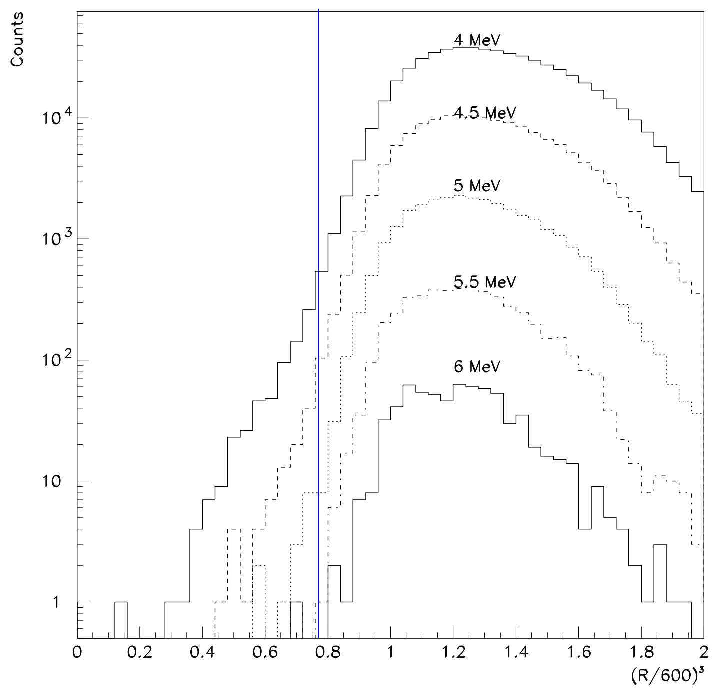
D_2O Cherenkov Tail Backgrounds

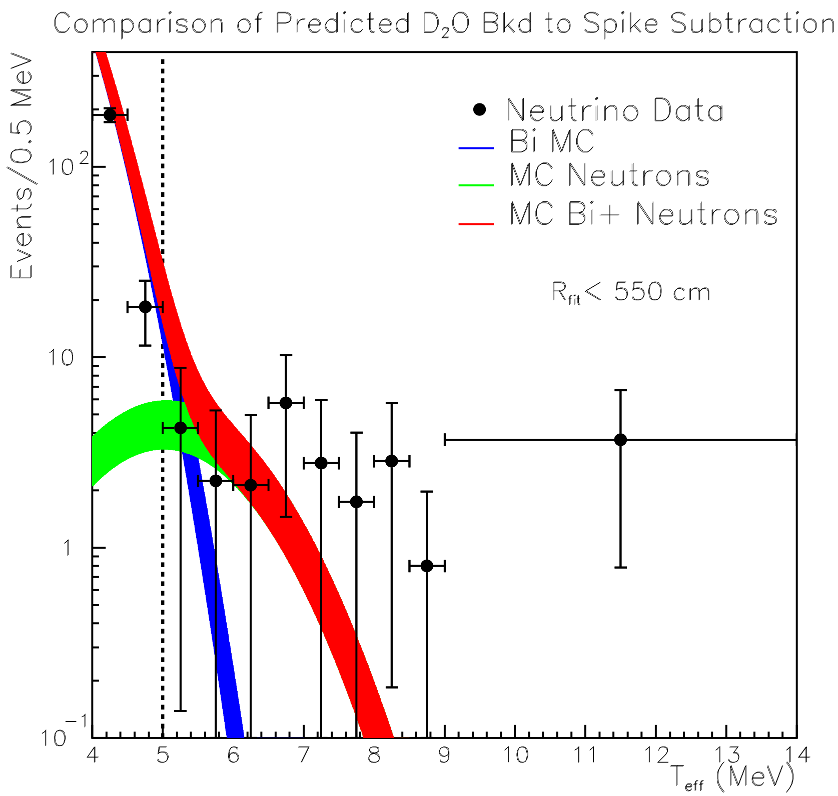


Monte Carlo models energy tails well, but verify against acrylic source data and neutrino data.

D_2O β-γ background matches the background wall when normalized to in-situ/ex-situ radioactivity measurements.

More Cherenkov Tail Consistency Checks





Left: Energy dependence of H_2O PDF, from Monte Carlo

Right: Comparison of D_2O β-γ prediction to D_2O radon spike, normalized by in-situ/ex-situ radioactivities

Cosmogenic Backgrounds

Various cosmogenic sources of neutrons exist:

1. Through-going muons
2. Muons produced in detector by atmospheric ν's
3. Deuteron breakup by atmospheric ν NC interactions
4. Terrestrial and reactor $\bar{\nu}$'s
5. External neutrons produced in rock that enter detector

Veto whatever events you can ...

- Outer detector vetoes through-going muons
- Remove any event that occurs within 250 ms after an event with > 60 hit tubes

Calculate and subtract off the rest ...

- Atmospheric ν NC interactions: 4 ± 1 events
- Anti-neutrinos: 1^{+3}_{-1} events
- External neutrons: negligible

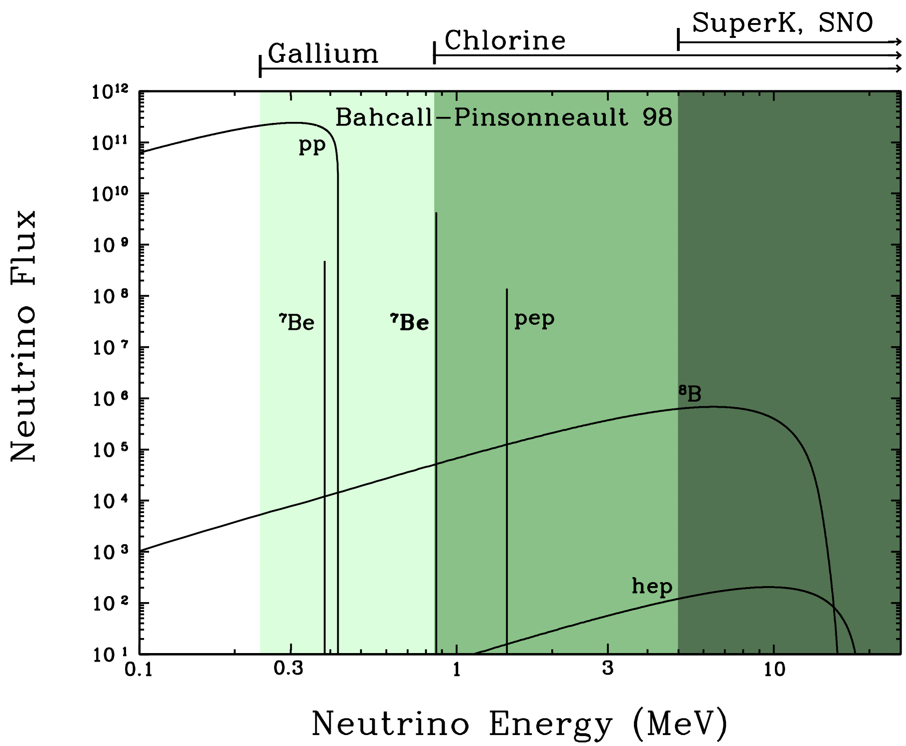
Summary of Backgrounds

Neutron Source	Events	Cherenkov Tail Source	Events
D_2O photodisintegration	44^{+8}_{-9}	D_2O Cherenkov	20^{+13}_{-6}
H_2O + AV photodisintegration	27^{+8}_{-8}	H_2O Cherenkov	3^{+4}_{-3}
Atmospheric ν's and sub-Cherenkov threshold μ's	4 ± 1	AV Cherenkov	6^{+3}_{-6}
		PMT Cherenkov	16^{+11}_{-8}
Fission	$\ll 1$	Total Cherenkov background	45^{+18}_{-12}
^{2}H(α, α)pn	2 ± 0.4		
^{17}O(α,n)	$\ll 1$		
Terrestrial and reactor $\bar{\nu}$'s	1^{+3}_{-1}		
External neutrons	$\ll 1$		
Total neutron background	78 ± 12		

Backgrounds are subtracted during signal extraction by including background PDFs of fixed amplitude in the fit.

Solar Neutrinos

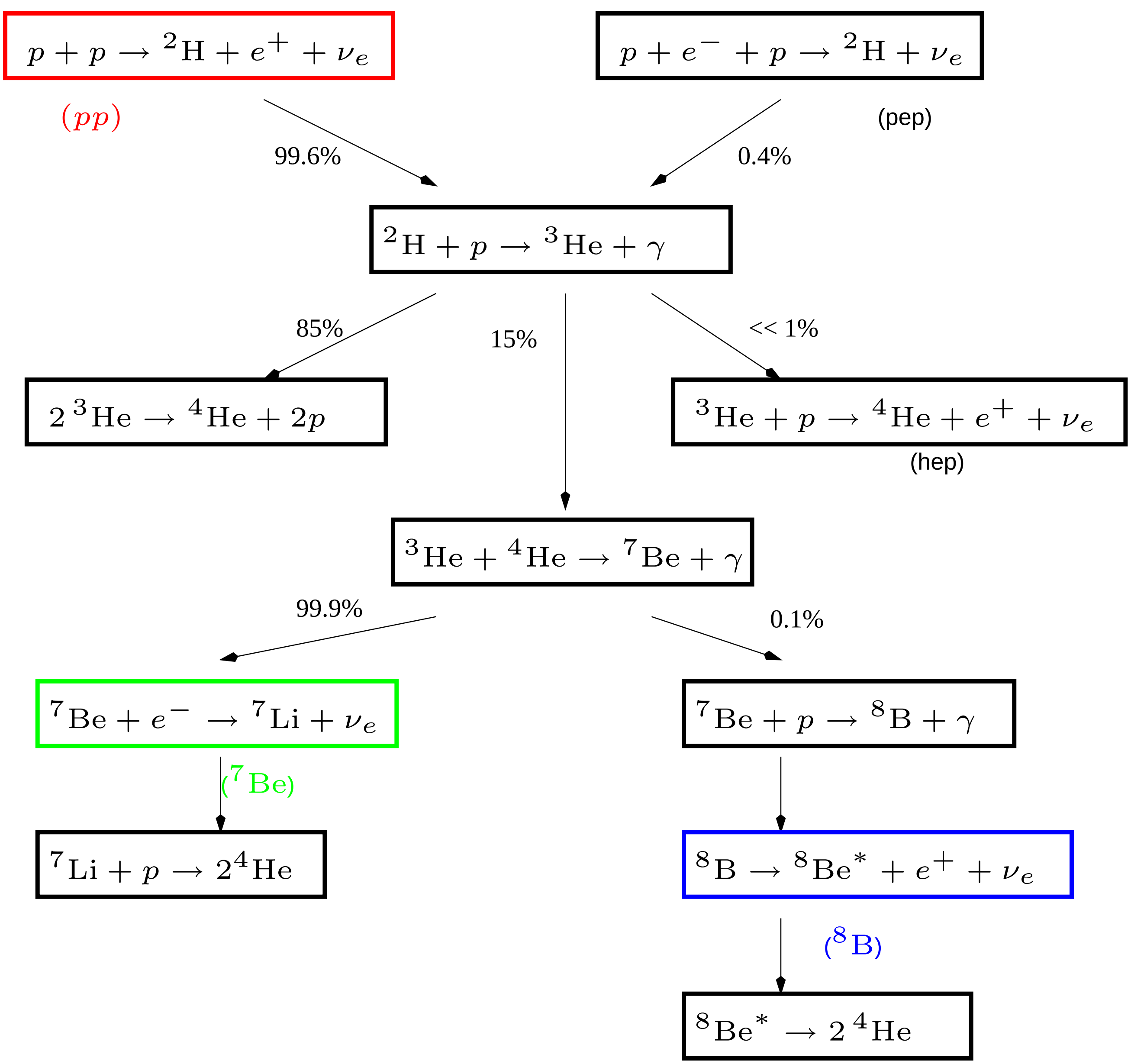
The Sun is an intense source of MeV neutrinos!



Shape of Spectra Determined By Nuclear Physics.

Solar Models Only Affect Normalization.

The pp Chain



$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$
(pp)
$p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_e$
(pep)
99.6%
0.4%
${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$
85%
15%
<< 1%
$2\,{}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$
${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$
(hep)
${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$
99.9%
0.1%
${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$
${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$
$({}^7\mathrm{Be})$
${}^7\mathrm{Li} + p \rightarrow 2\,{}^4\mathrm{He}$
${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e$
$({}^8\mathrm{B})$
${}^8\mathrm{Be}^* \rightarrow 2\,{}^4\mathrm{He}$

Previous SNO Results

CC and ES fluxes above $T > 6.75$ MeV, 241 livedays

Reaction	Flux as fraction of SSM
$\phi^{CC}_{SNO} =$	$0.347 \pm 0.014\,(\text{stat.})^{+0.024}_{-0.022}\,(\text{sys.}) \pm 0.010\,(\text{th.})$
$\phi^{ES}_{SNO} =$	$0.473 \pm 0.067\,(\text{stat.})^{+0.032}_{-0.028}\,(\text{sys.})$
$\phi^{ES}_{SK} =$	$0.459 \pm 0.006\,(\text{stat.})^{+0.016}_{-0.014}\,(\text{sys.})$

$$\phi^{ES}_{SK} - \phi^{CC}_{SNO} = 0.112 \pm 0.033$$

3.35σ deviation from Standard Model

$$\text{Derived } {}^{8}\text{B flux}: \quad 5.44 \pm 0.99 \times 10^{6}\ \text{cm}^{-2}\,\text{sec}^{-1}$$

$$1.08 \pm 0.20 \times \text{SSM}$$