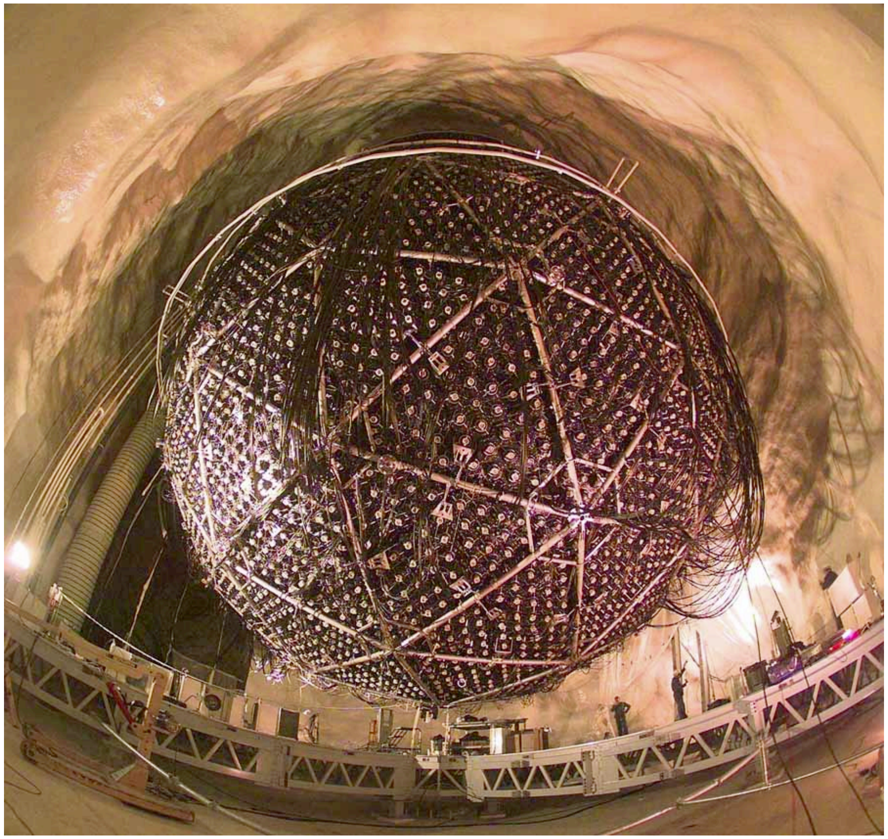
Solar Neutrino Observations at the Sudbury Neutrino Observatory (SNO)



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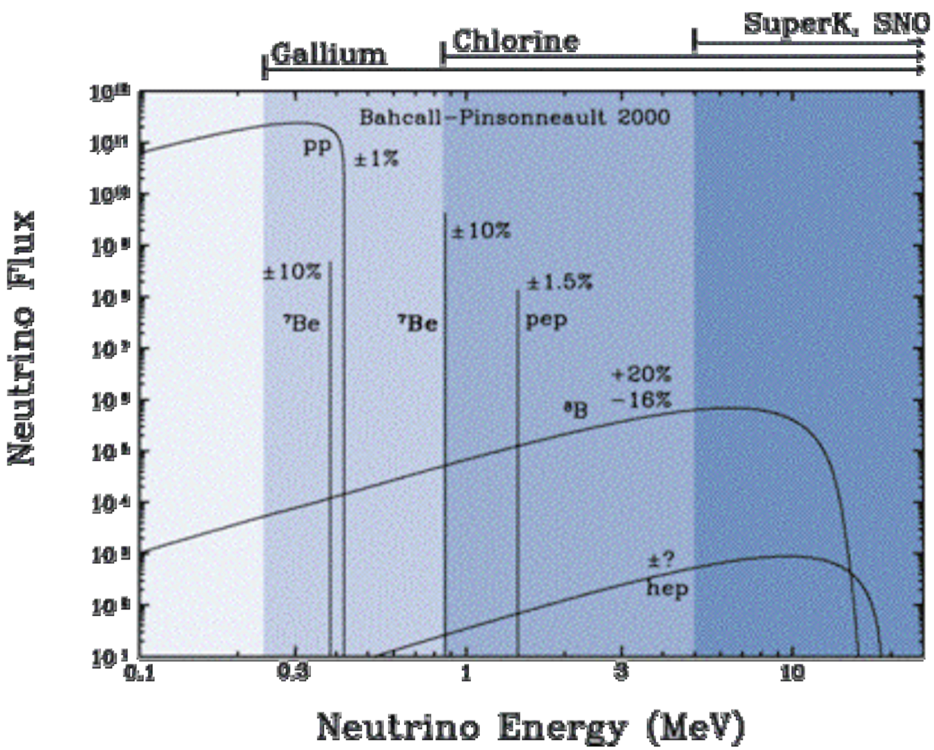
Outline

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

Solar Neutrino Problem

***pp* Chain:** $4p + 2e \rightarrow {}^4He + 2\nu_e + 26.7\,\text{MeV}$



Experiment	*Reaction*
Homestake	$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e$
SAGE	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e$
Gallex + GNO	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e$
Kamiokande + Super-Kamiokande	$\nu_x + e \rightarrow \nu_x + e$

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

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

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

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

Solar Neutrino Problem

either

Solar models are incomplete/incorrect

or

Neutrinos undergo flavor-changing oscillation

In this talk, we will demonstrate that:

Solar model prediction of the active ^{8}B ν flux is consistent with experiments

AND

Neutrinos change flavors while in transit to the Earth

Neutrino Oscillation

The lepton mixing matrix (Maki-Nakagawa-Sakata-Pontecorvo) is expressed as

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

and the ν_e flavor state evolves as

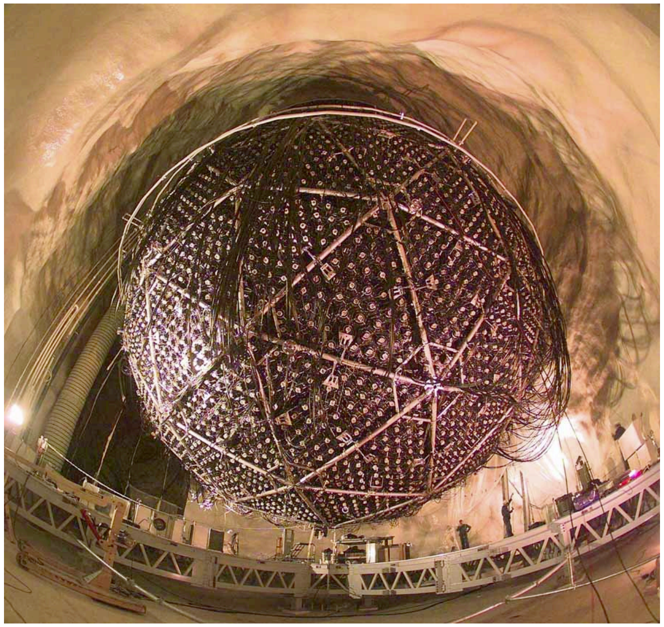
$$\nu_e = U_{e1} e^{-iE_1 t} \nu_1 + U_{e2} e^{-iE_2 t} \nu_2 + U_{e3} e^{-iE_3 t} \nu_3$$

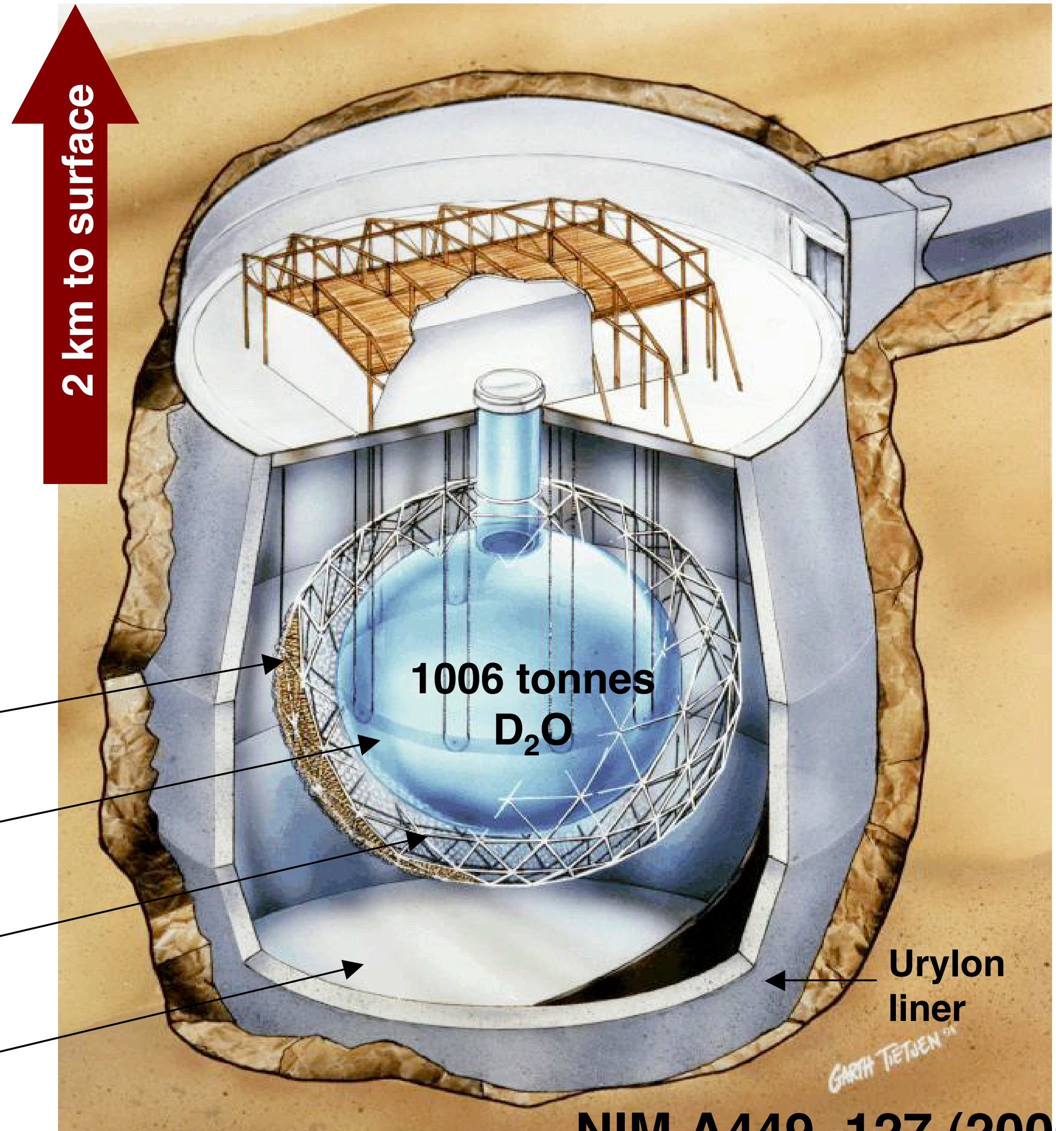
2 ν Survival : Prob.

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2 [\mathrm{eV}^2] \; L[\mathrm{m}]}{E[\mathrm{MeV}]} \right) \text{ where } \Delta m^2 = m_2^2 - m_1^2$$

Note: May also have resonant flavor conversion in matter — Mikheyev-Smirnov-Wolfenstein (MSW) effect

Sudbury Neutrino Observatory





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

12.01m dia. acrylic vessel

1700 tonnes of inner shielding H_2O

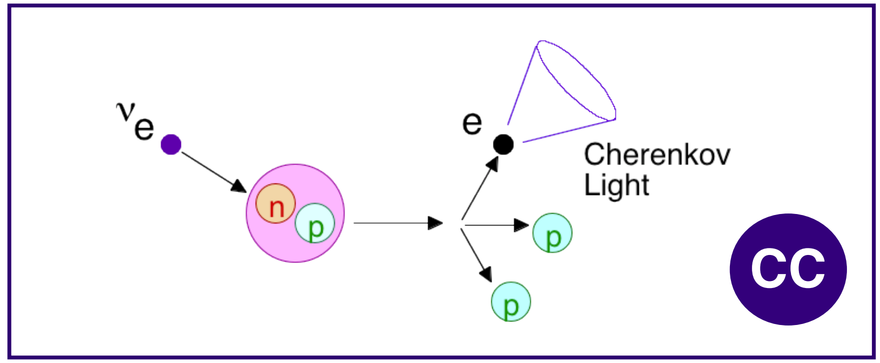
5300 tonnes of outer shielding H_2O

NIM A449, 127 (2000)

Detecting ν in SNO

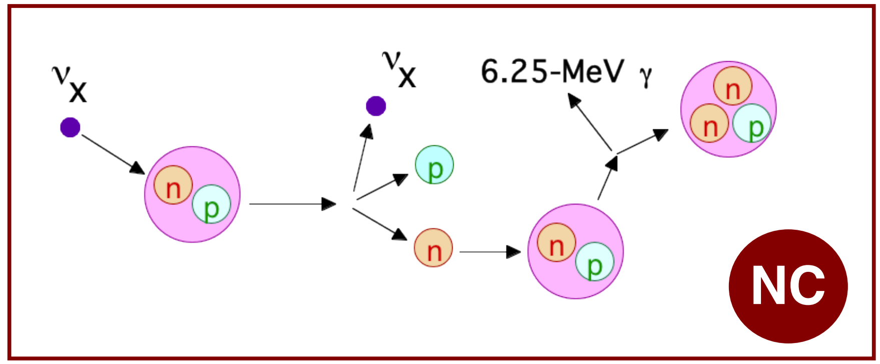
CC $\nu_e + d \rightarrow p + p + e^-$

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



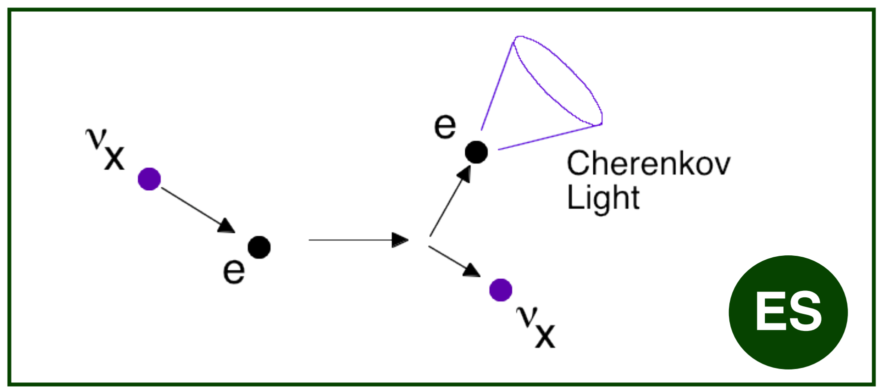
NC $\nu_x + d \rightarrow p + n + \nu_x$

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



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

- Low Statistics
- $\phi_{ES} = \phi(\nu_e) + 0.154\ \phi(\nu_\mu + \nu_\tau)$
- Strong directionality: $\theta_e \approx 18^o$ (T_e = 10 MeV)



Smoking Guns for Flavor Changing Oscillation

Measure:

$$\frac{\phi^{CC}}{\phi^{ES}} = \frac{\nu_e}{\nu_e + 0.15(\nu_\mu + \nu_\tau)}$$

Oscillation to active flavor if:

$$\phi^{CC}(\nu_e) < \phi^{ES}(\nu_x)$$

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

THIS TALK

$$\frac{\phi^{CC}}{\phi^{NC}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

$$\phi^{CC}(\nu_e) < \phi^{NC}(\nu_x)$$

April 2002 : $\phi^{CC}_{SNO}(\nu_e), \phi^{NC}_{SNO}(\nu_x), \phi^{ES}_{SNO}(\nu_x)$ [PRL 89, 011301 (2002)]

$$\phi^{CC(ES)}_{Night} \Box \phi^{CC(ES)}_{Day}$$

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

April 2002 : Day and Night fluxes [PRL 89, 011302 (2002)]

What else can NC tell us?

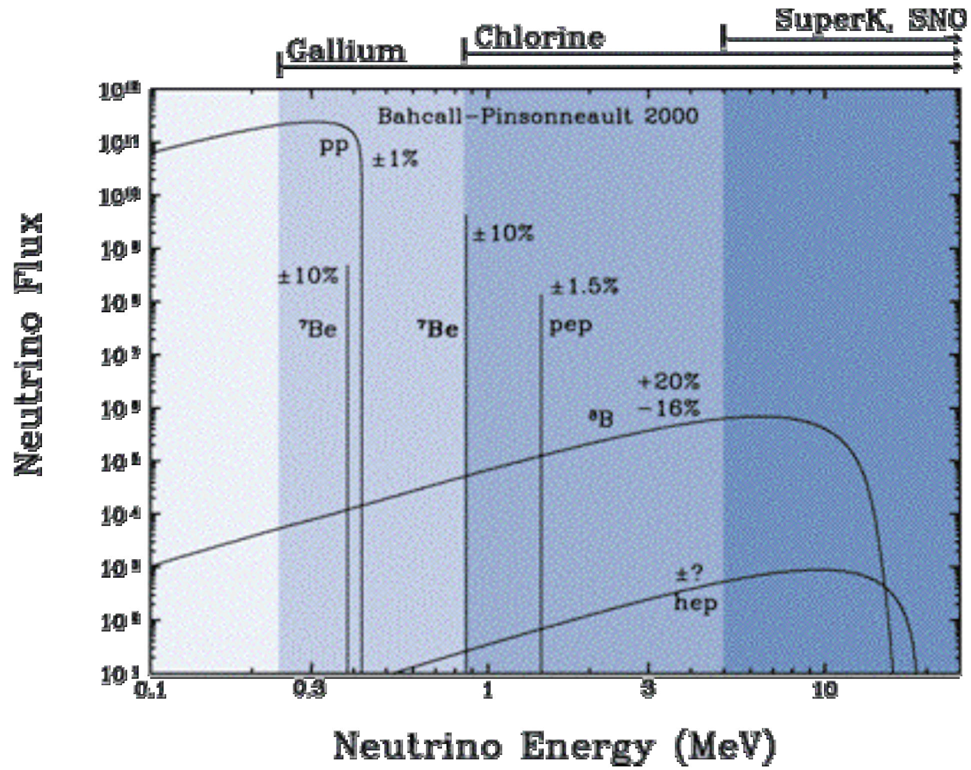
$\nu_x + d \rightarrow n + p + \nu_x$

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

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

→ SNO NC

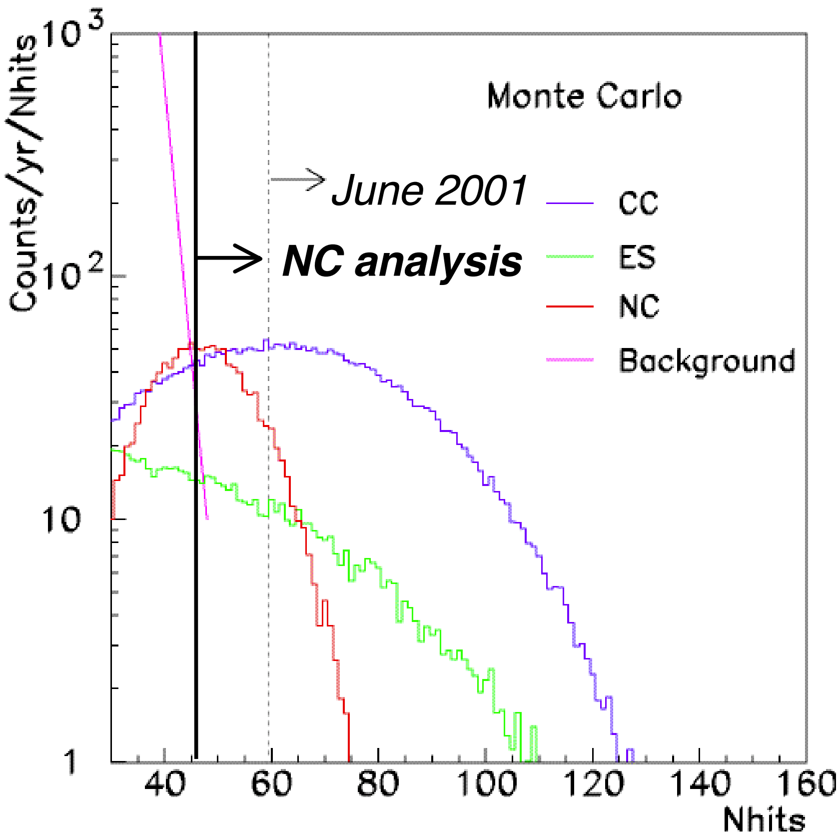
→ **SNO CC**

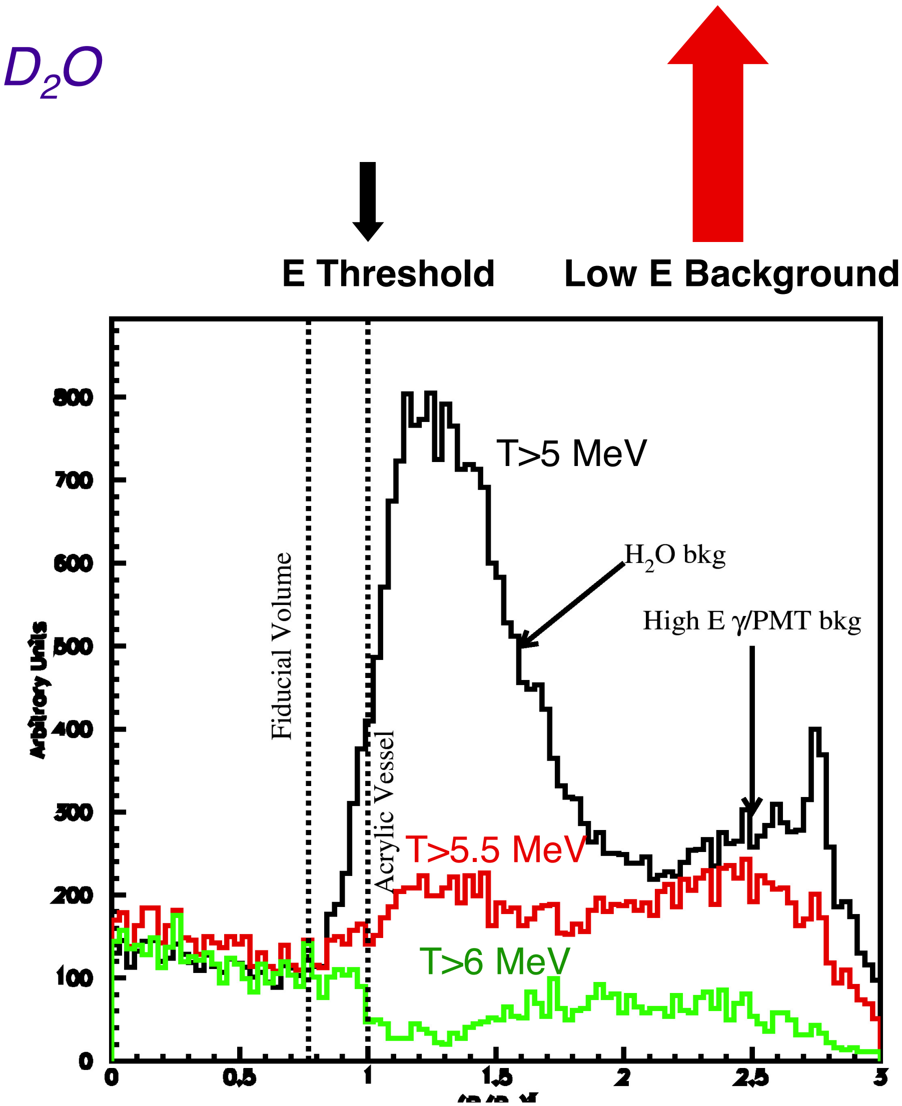


Solar Neutrino Analysis (NC+CC+ES)

NC and Day-Night Analysis in Pure D_2O

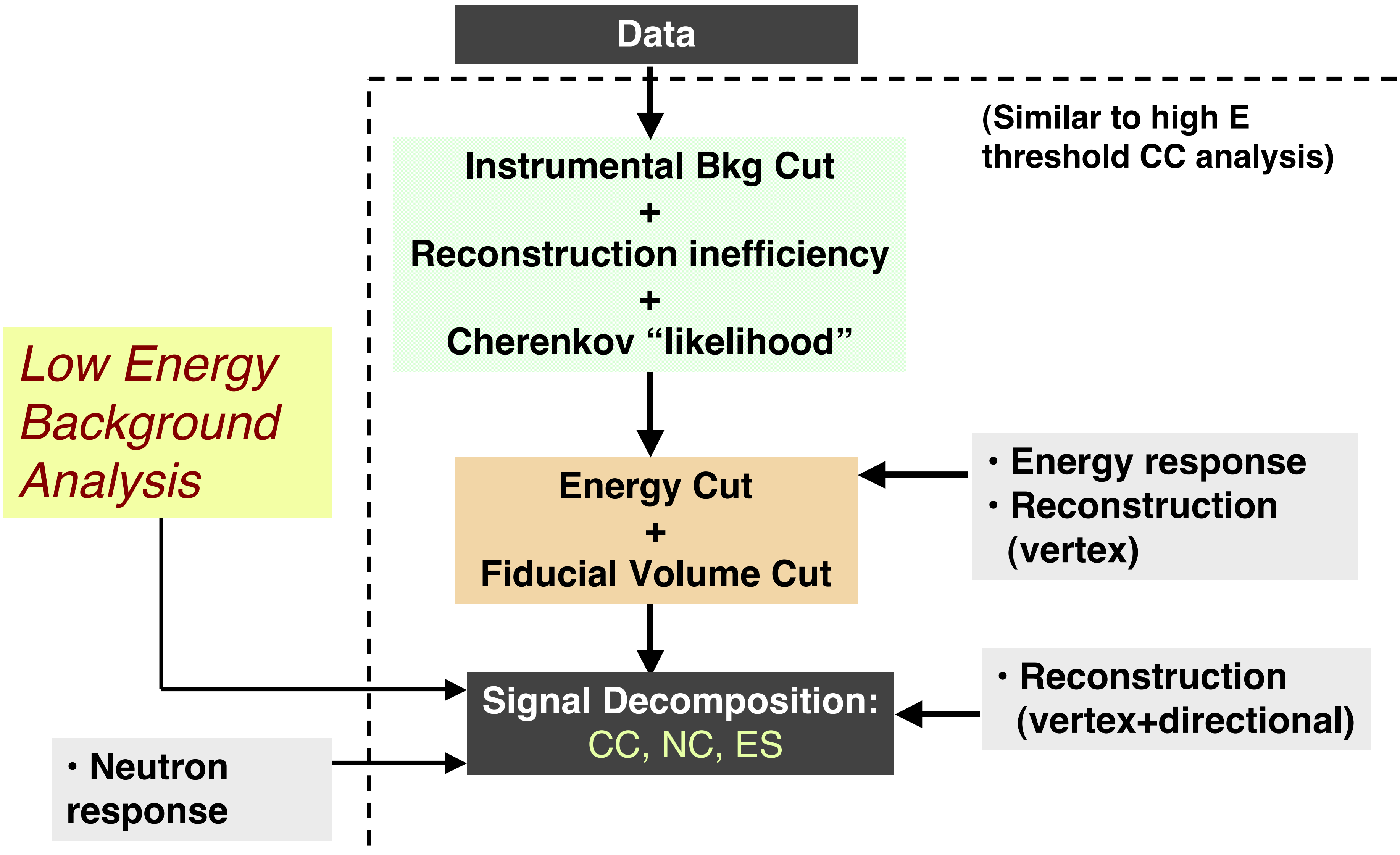
- Energy: $T_{eff} > 5$ MeV
- Fiducial vol.: R < 550 cm





Energy □　　~8 PMT hits / MeV　　*Radius*　　$(R/R_{AV})^3$

NC Data Analysis



Data Reduction

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

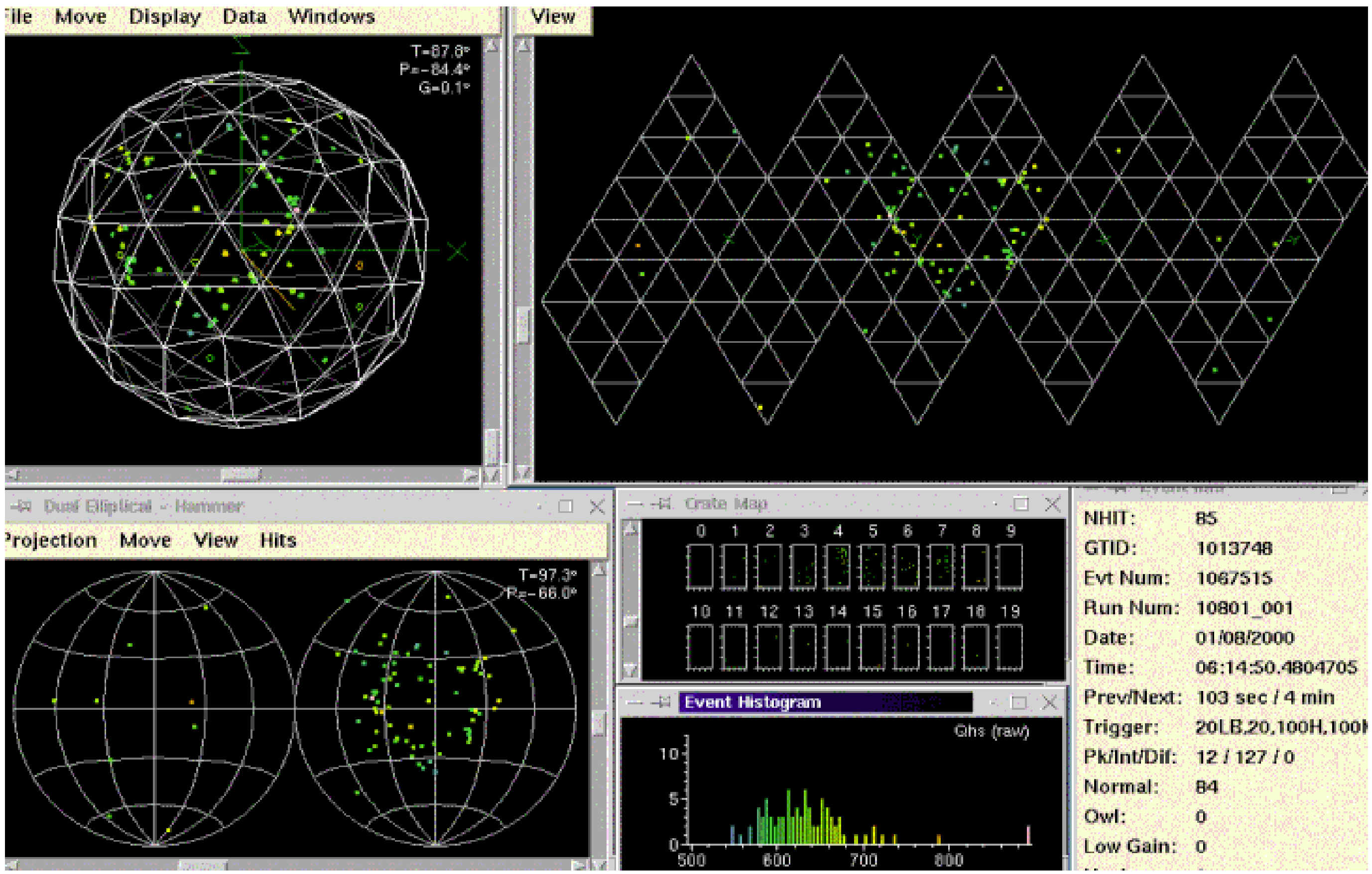
Analysis Step	*Events*
Total Event Triggers	450,188,649
Neutrino Data Trigger	191,312,560
NHIT ≥30	10,088,842
Instrumental Background	7,805,238
Cherenkov "likelihood"	3,418,439
Fiducial Volume (R<550cm)	67,343
Energy Threshold (T>5 MeV)	3440
Muon Follower	2981
Residual Cosmic Background	2928
Candidate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

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

A neutrino candidate event

PMT Information:
Positions,
Charges, Times

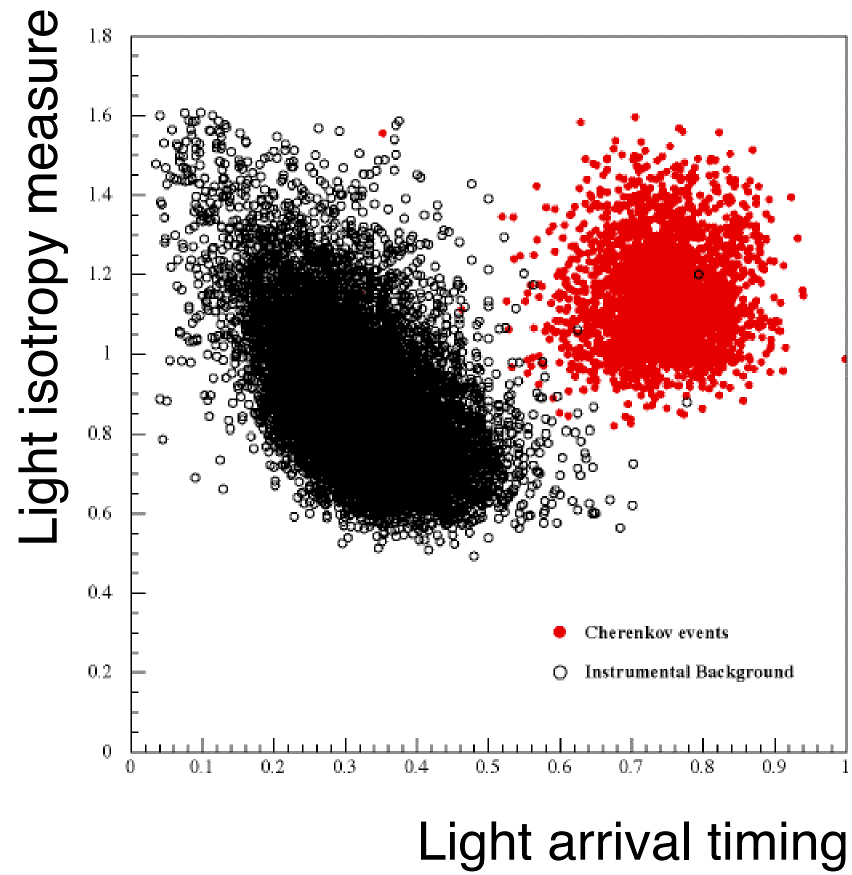
Event Reconstruction:
Vertex, Direction,
Energy, Light Isotropy



Data Reduction Cuts

Remove instrumental background using:

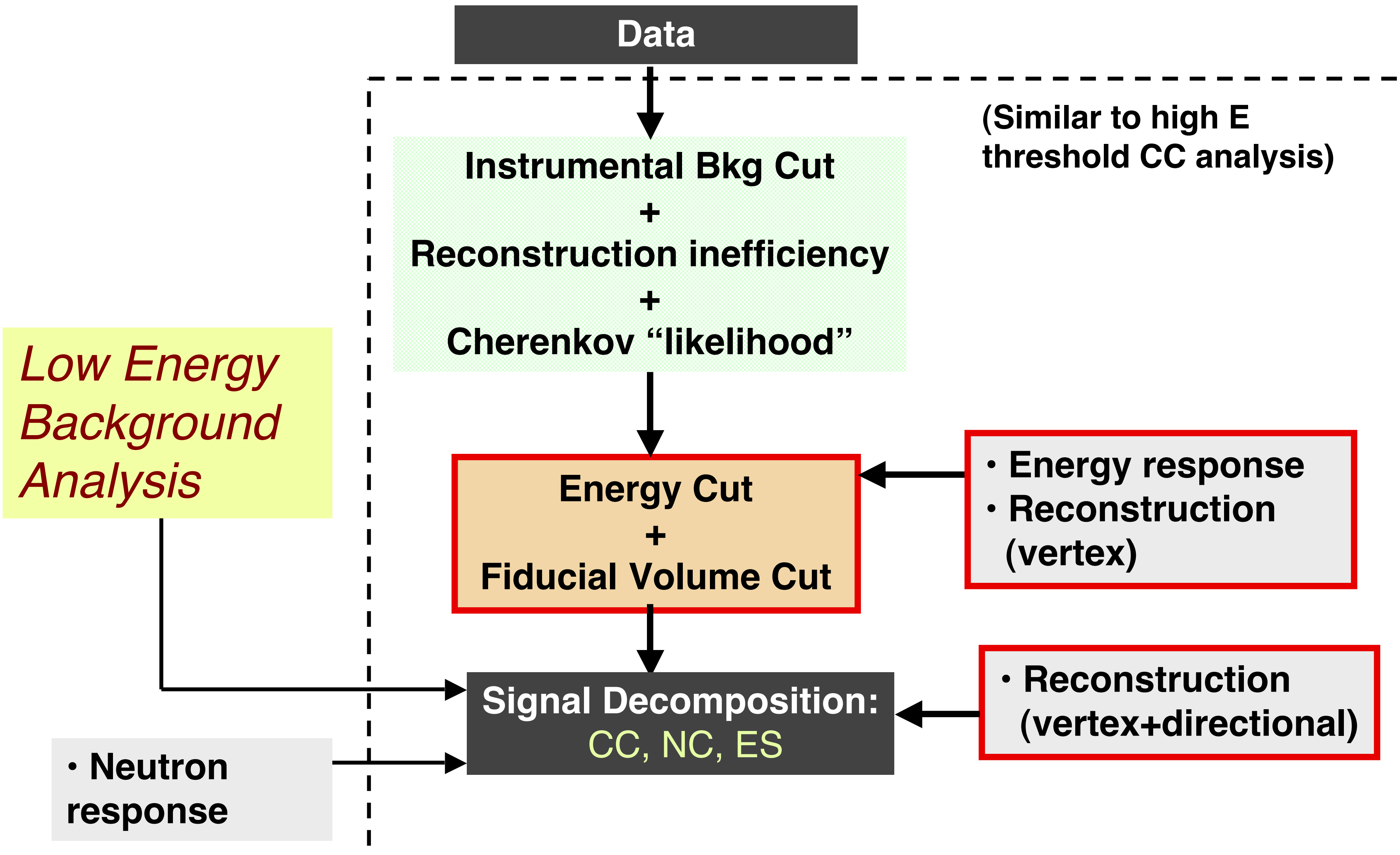
- **PMT time & charge distribution**
- **Event time correlation**
- **Veto PMT tag**
- **Reconstruction information**
- **Light isotropy & arrival timing**



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

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

NC Data Analysis



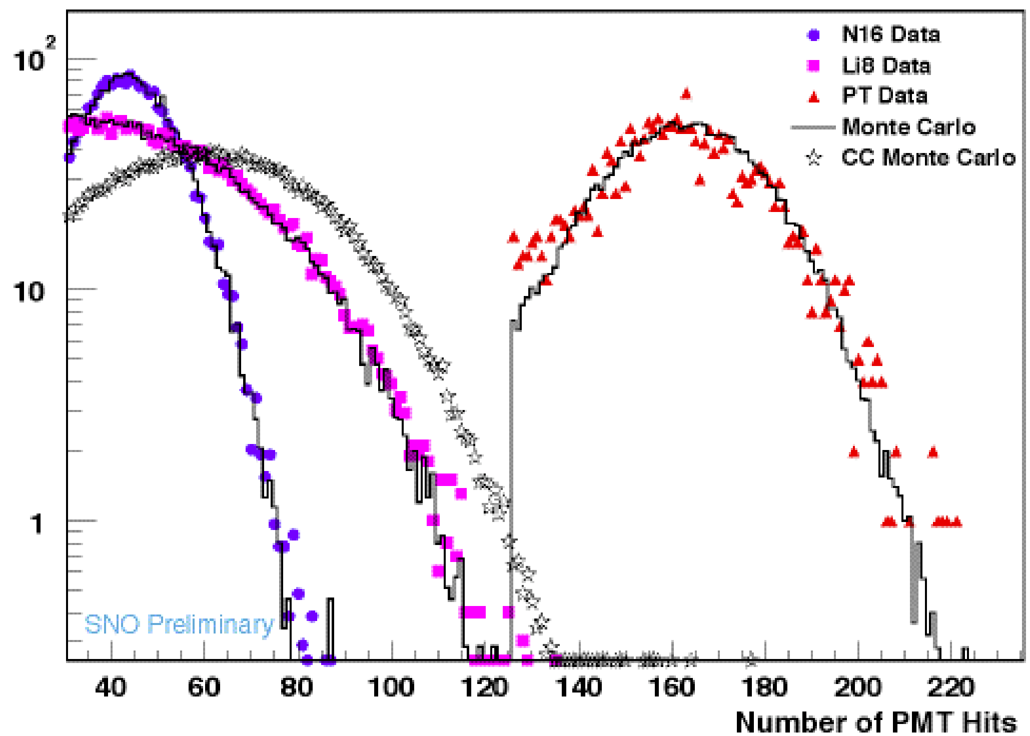
Energy Response

Calibration:

- PMT & Optics
- Normalized to ^{16}N [E_{γ}=6.13 MeV]
- Check with
  - ^{8}Li [13 MeV β]
  - ^{252}Cf [d(n,γ), E_{γ}=6.25 MeV]
  - ^{3}H(p,γ) [19.8 MeV γ]

$\delta E/E$ = ± 1.21%
$\delta\sigma/\sigma$ = + 4.5%
Linearity = ±0.23% @ E_e=19.1 MeV

	$\delta\Phi^{CC}/\Phi^{CC}$	$\delta\Phi^{NC}/\Phi^{NC}$
δE	$^{+4.3}_{-4.2}$ %	$^{+6.1}_{-6.2}$ %
$\delta\sigma$	$^{+0.0}_{-0.9}$ %	$^{+4.4}_{-0.0}$ %
Linearity	±0.1%	±0.4%
Total	$^{+4.3}_{-4.3}$ %	$^{+7.5}_{-6.2}$ %



Event Reconstruction

Given:
Hit PMTs' positions & timing

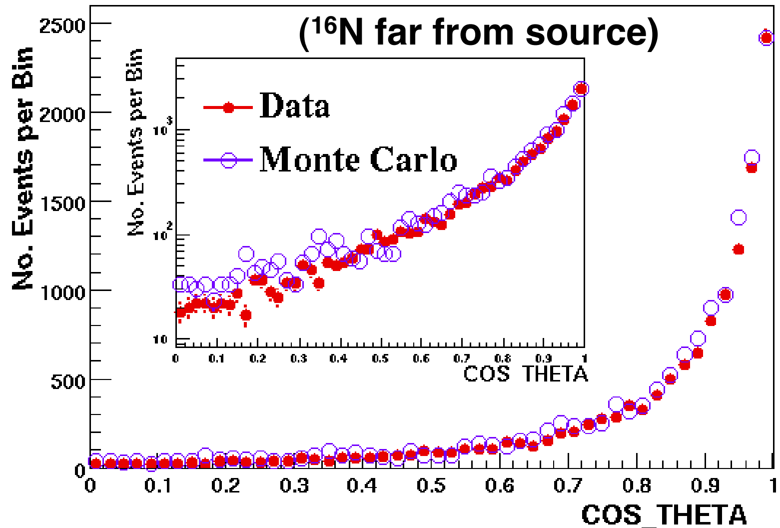
Determine event's: **(x,y,z)** & **(□,□)**

Fiducial volume determination (N_{target}=?)

Separation of □ signals from background

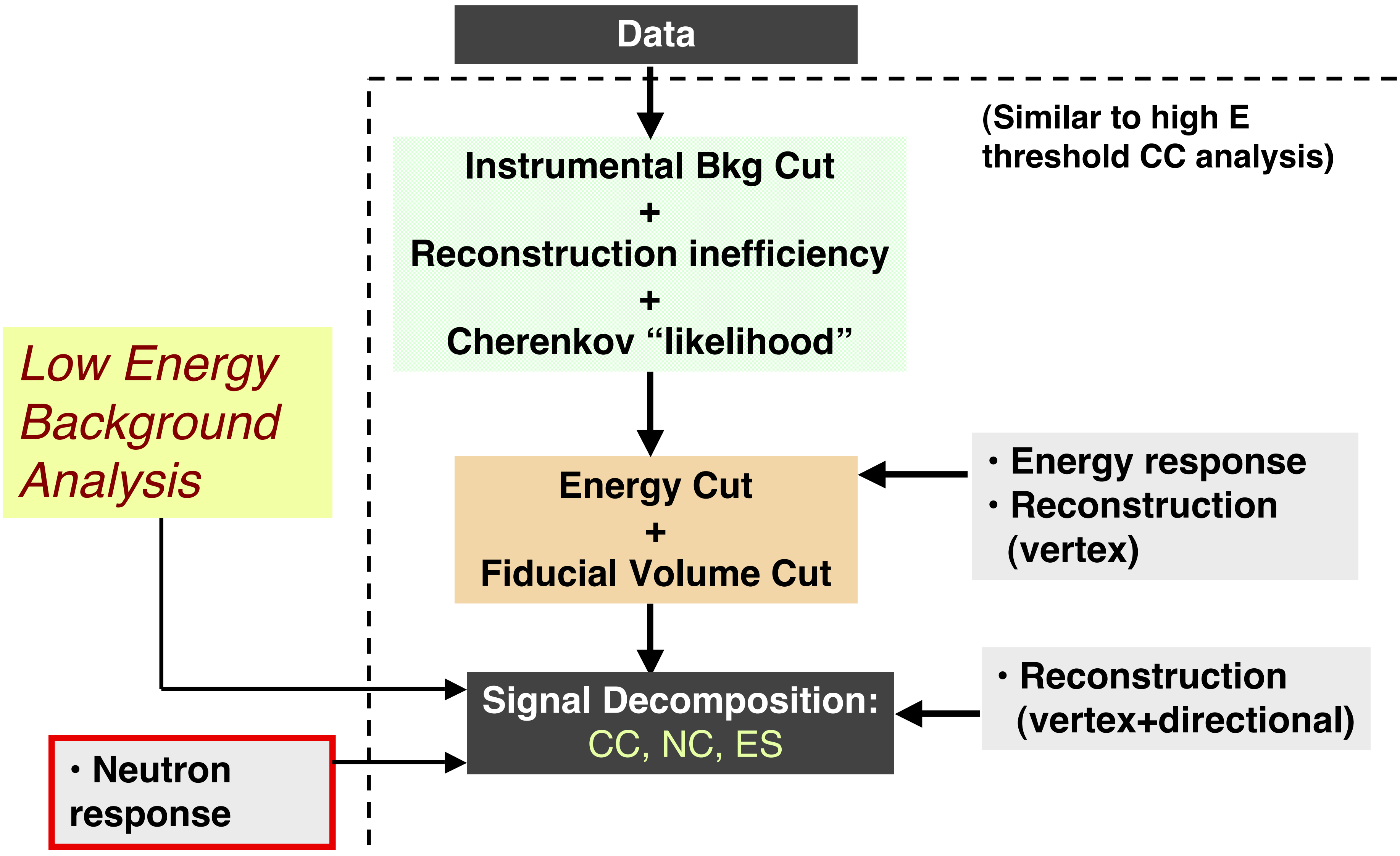
Tools: Triggered □and □ sources

Example: Angular Resolution



	□□^{CC}/□^{CC}	□□^{NC}/□^{NC}
Vertex Accuracy	+2.9 □2.8 %	+1.8 □1.8 %
Vertex Resolution	+0.0 □0.0 %	+0.1 □0.1 %
Angular Resolution	+0.2 □0.2 %	+0.3 □0.3 %
Total	+2.9 □2.8 %	+1.8 □1.8 %

NC Data Analysis



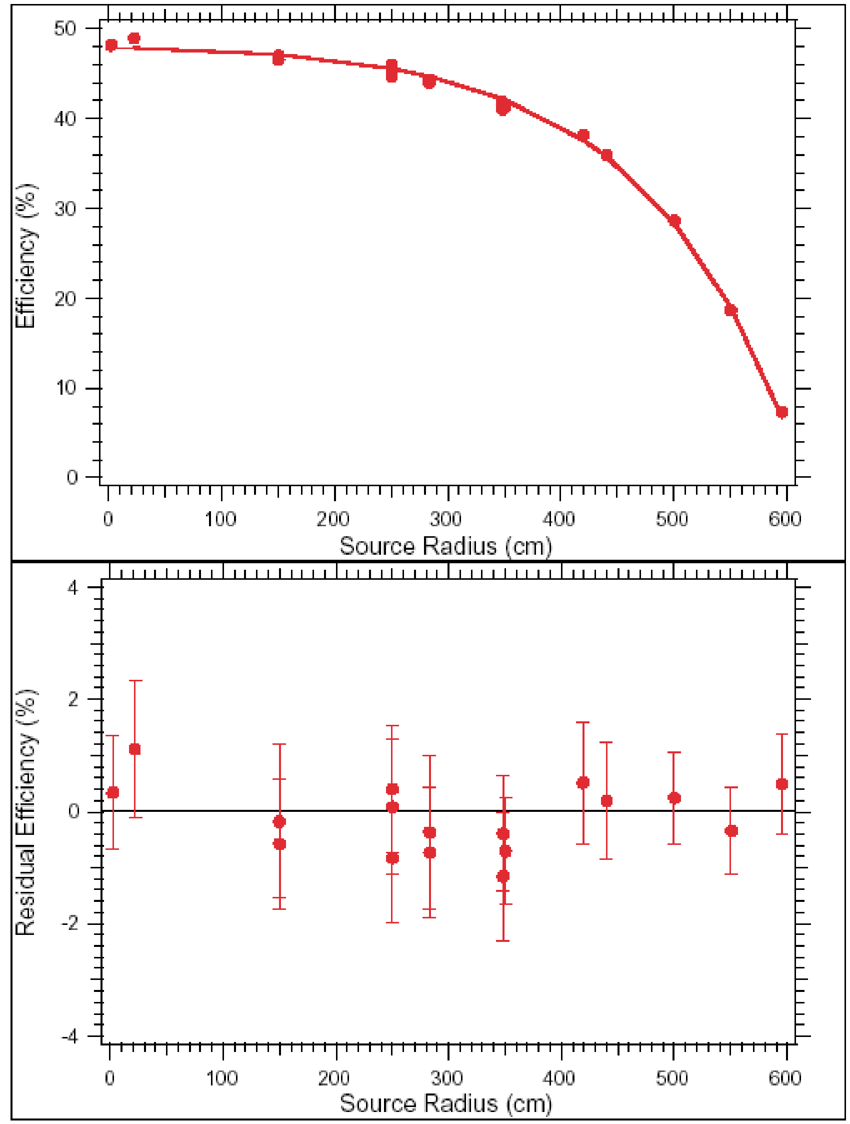
Neutron Detection Efficiency

- **Calibrate using ^{252}Cf fission source (~3.8 n per fission)**

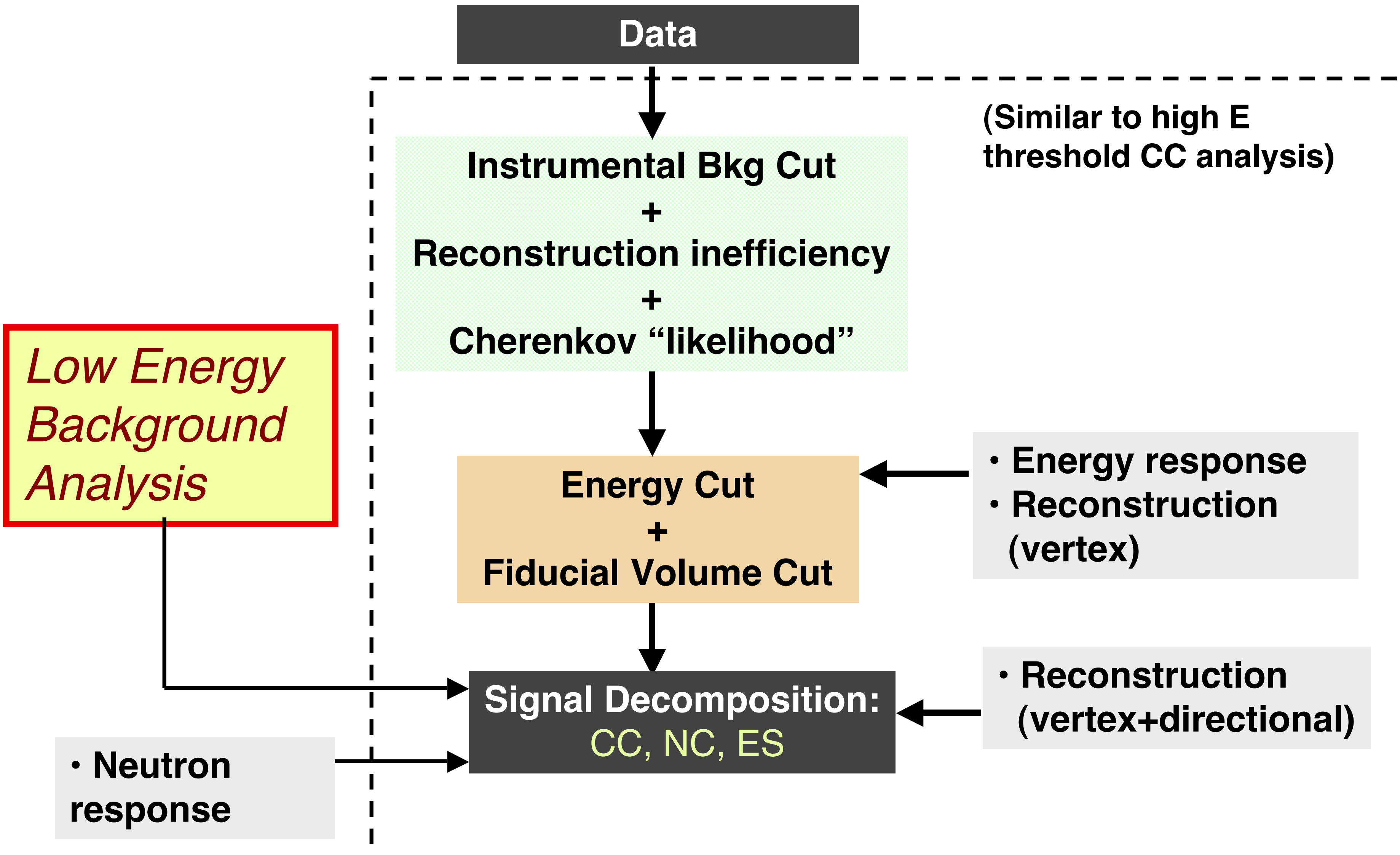
Capture Efficiency

Total:	**29.90 ± 1.10 %**
With energy threshold & fiducial volume selections (T>5 MeV, R<550 cm)	**14.38 ± 0.53 %**

Response vs ^{252}Cf source position



NC Data Analysis



Low Energy Background (Overview)

Daughters in U or Th chain

- decays
- decays

"Photodisintegration" *(pd)*

+ d n + p

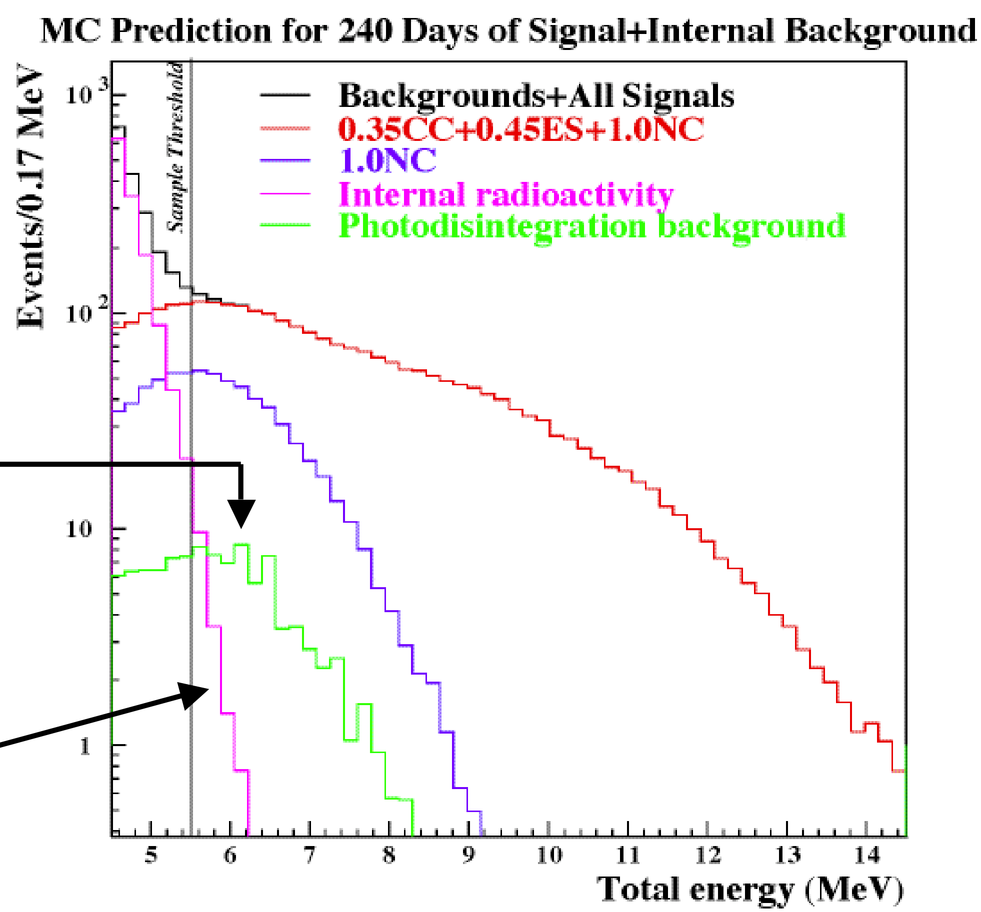
Indistinguishable from NC !

Technique: **Radiochemical assay**
 Light isotropy

"Cherenkov Tail"

Cause: Tail of resolution, or
 Mis-reconstruction

Technique: U/Th calib. source
 Monte Carlo



Must know U and Th concentration in D_2O

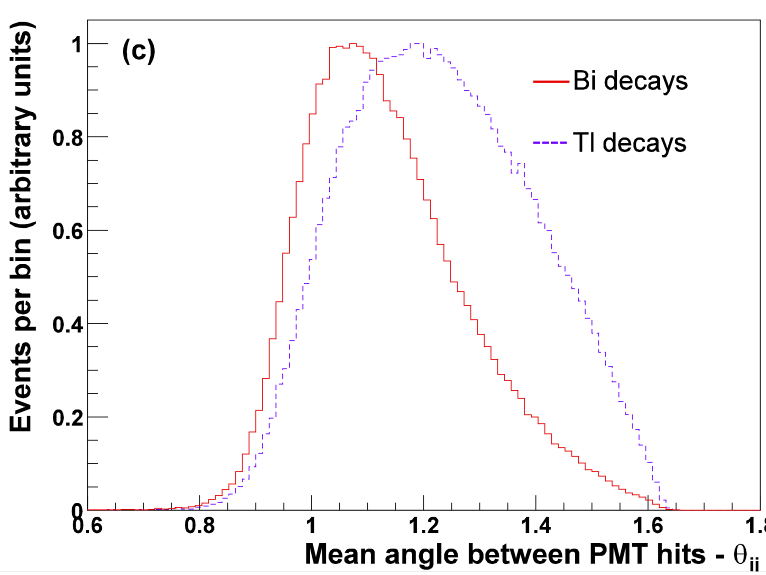
Measuring the U and Th Concentration in "Water"

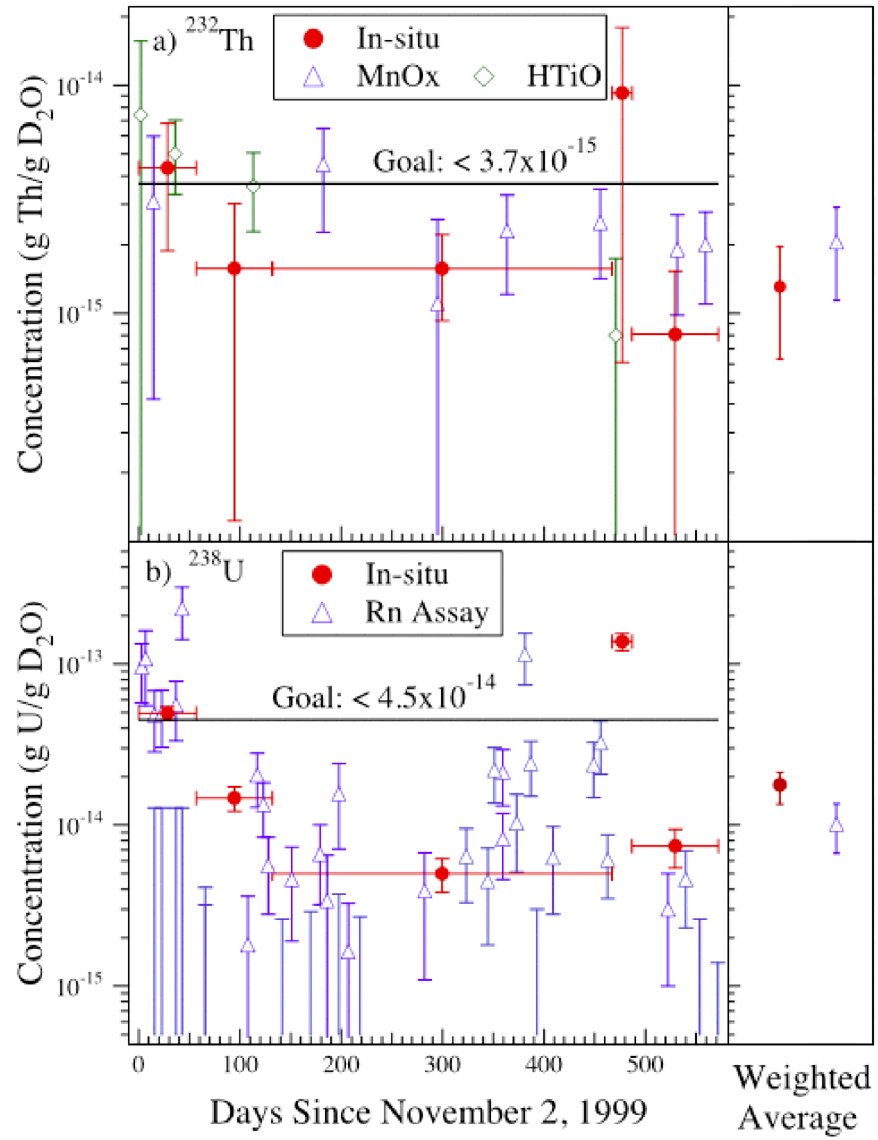
I. **Ex-situ (Radiochemical Assays)**

- **Count daughter product decays: ^{224}Ra, ^{226}Ra, ^{222}Rn**

II. **In-situ (Low energy physics data)**

- **Statistical separation of ^{208}Tl and ^{214}Bi using light isotropy**





LE Background Summary

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

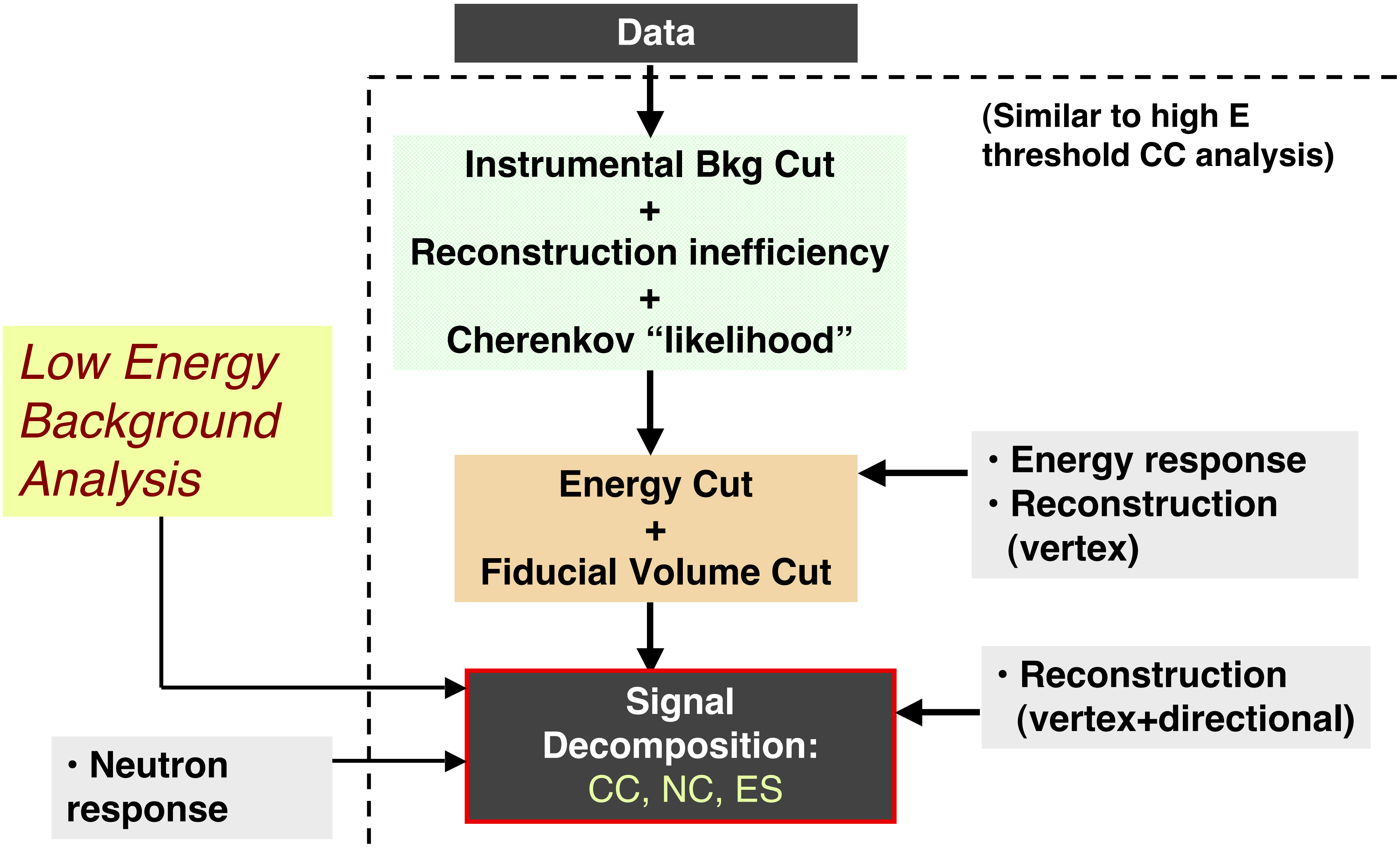
	pd neutron bkg. (counts)
D_2O	44^{+8}_{-9}
H_2O+AV	27^{+8}_{-8}
Atmospheric ν	4 ± 1
^{235}U spont. fission	<< 1
^{2}H(γ,γ)pn	2.0 ± 0.4
^{17}O(α,n)	<< 1
Terrestrial & reactor ν	1^{+3}_{-1}
External neutrons	<< 1
Total	**78 ± 12**

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

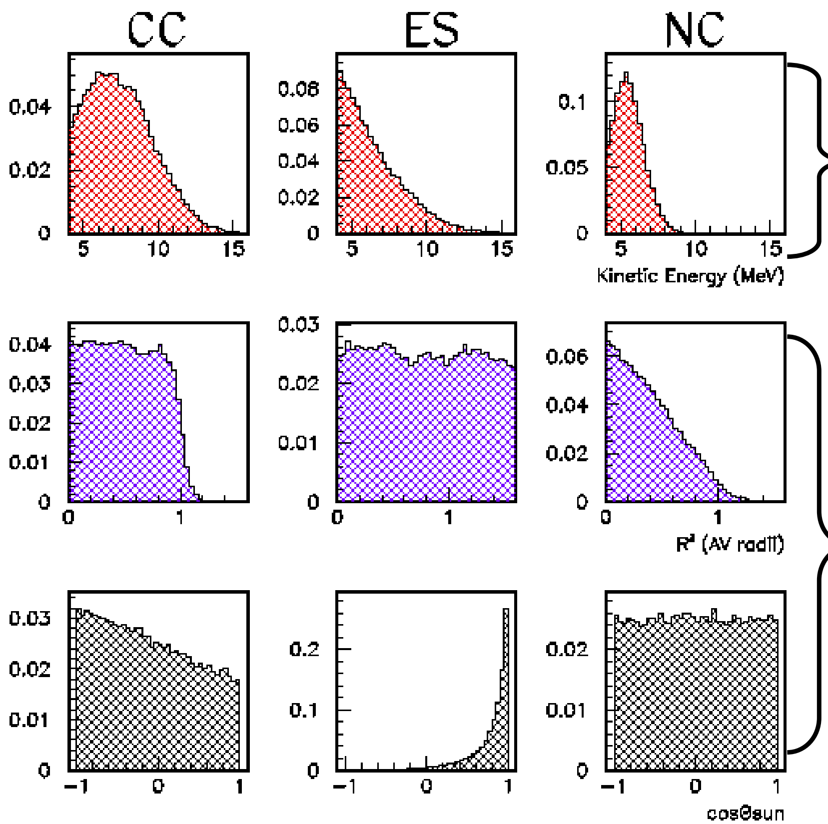
[c.f.: 2928 ν candidates]

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

NC Data Analysis



Extracting the ν Signals



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

Max. Likelihood Fit

Φ^{CC} Φ^{NC} Φ^{ES}

OR

ϕ_e $\phi_{\mu\tau}$

\+ [illegible]

- *PDFs:*
kinetic energy T, *event location* R^3, *and solar angle correlation* cos $\theta_\odot$

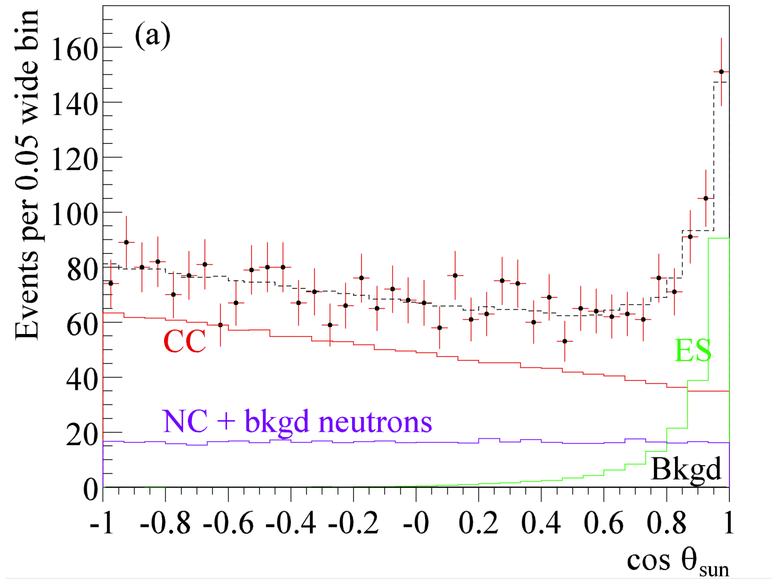
Signal Extraction Results

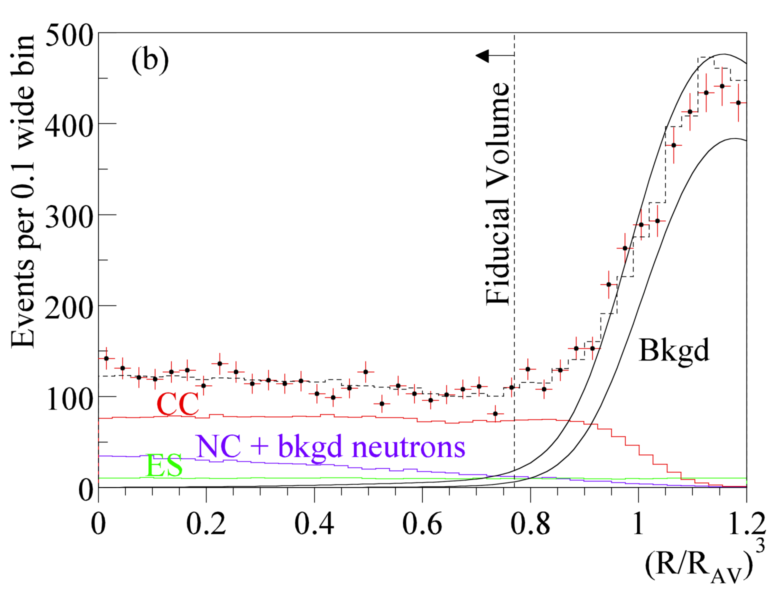
Assume standard ^{8}B □ spectrum

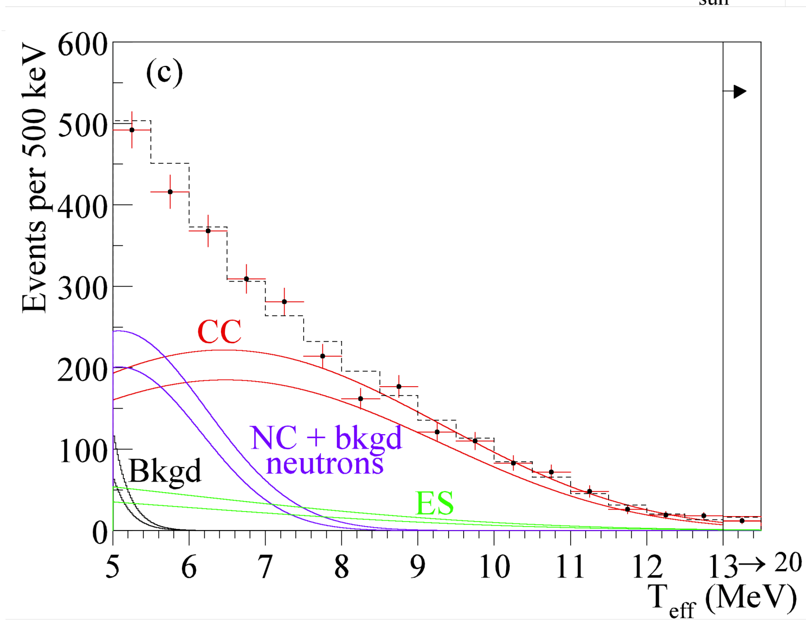
***Null hypothesis*:**

no neutrino flavor mixing

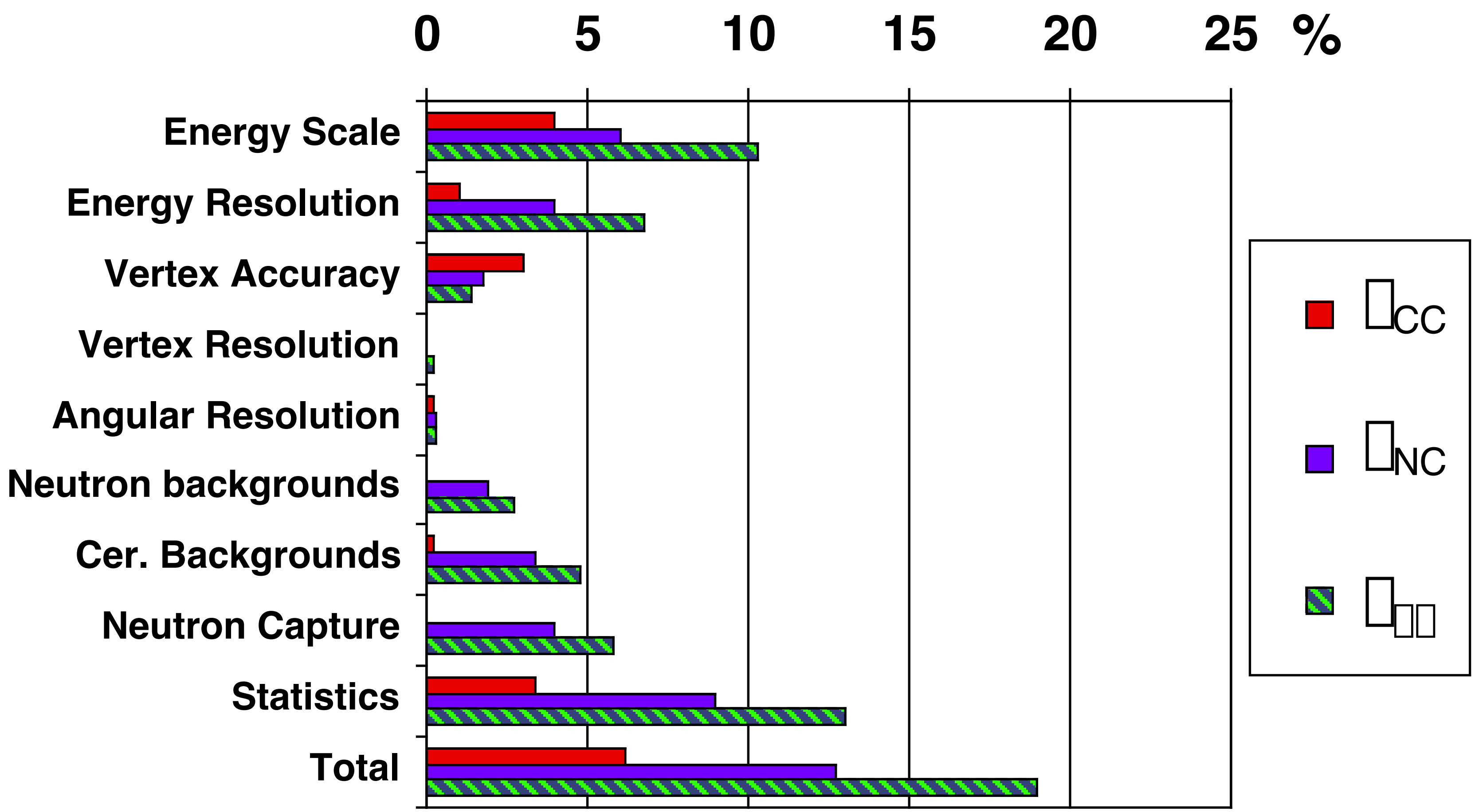
CC	1967.7	$^{+61.9}_{-60.9}$	events
NC	576.5	$^{+49.5}_{-48.9}$	events
ES	263.6	$^{+26.4}_{-25.6}$	events



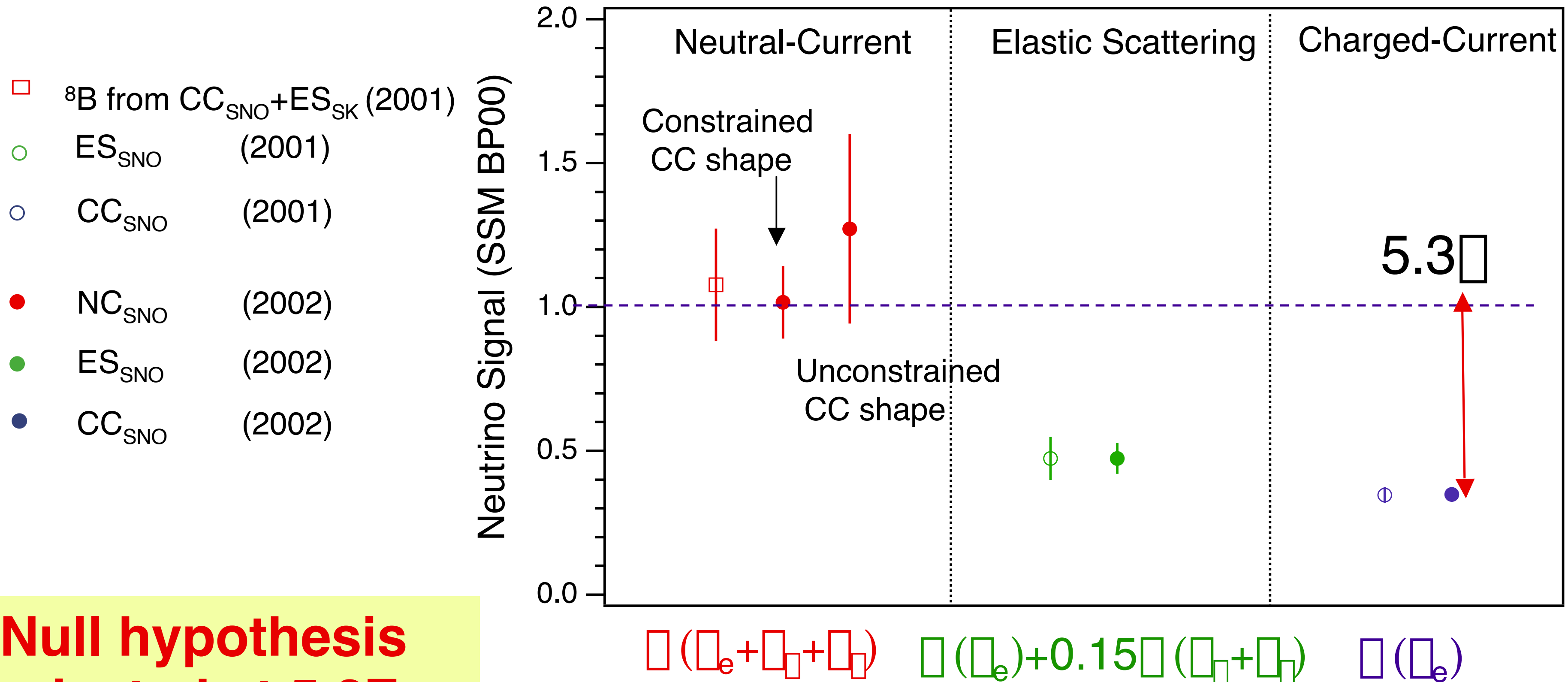




Flux Uncertainties (Shape constrained)



Solar ν Flux Summary



Null hypothesis rejected at 5.3σ

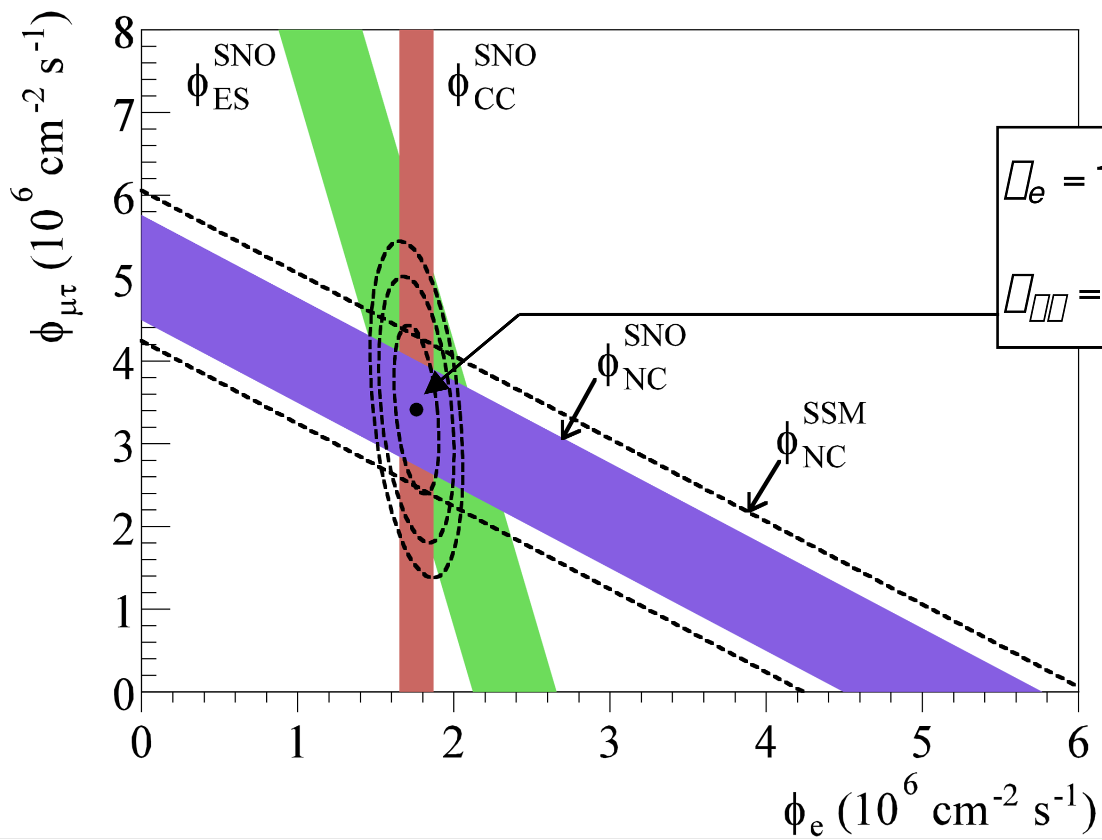
STRONG Evidence for
ν$_e$ → ν$_\mu$ and/or ν$_\tau$

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

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

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

Disappearance and Reappearance



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

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

Note:

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

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

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

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

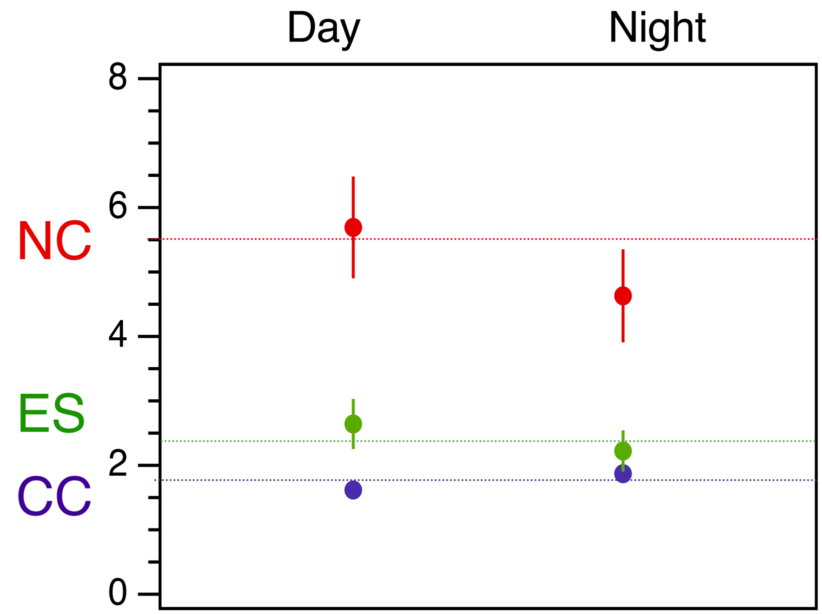
$$\phi_{SSM\ (BP01)} = 5.05^{+1.01}_{-0.81}$$

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

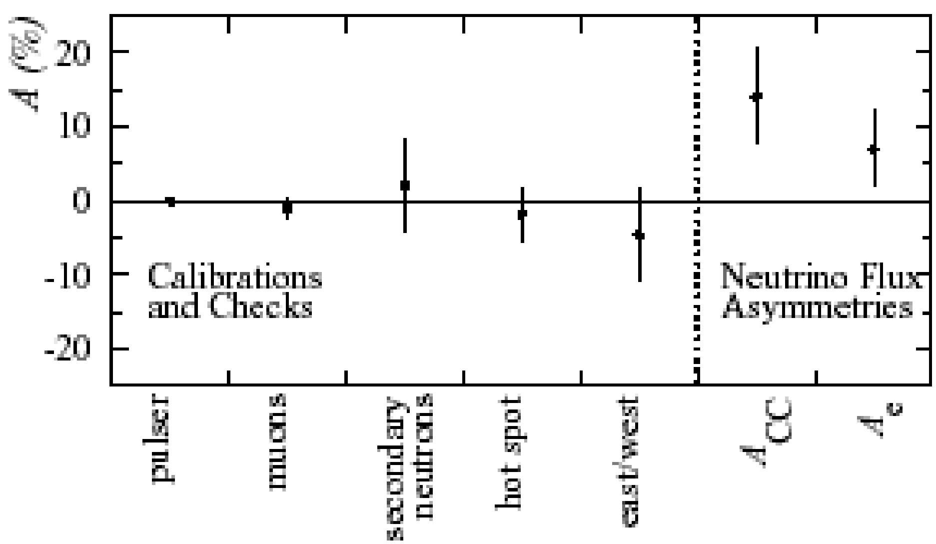
Day Flux vs Night Flux

- *Day:* cos θ_{zenith}>0 (128.5 days)
  Night: cos θ_{zenith}<0 (177.9 days)
- ^{8}B shape constrained extraction

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

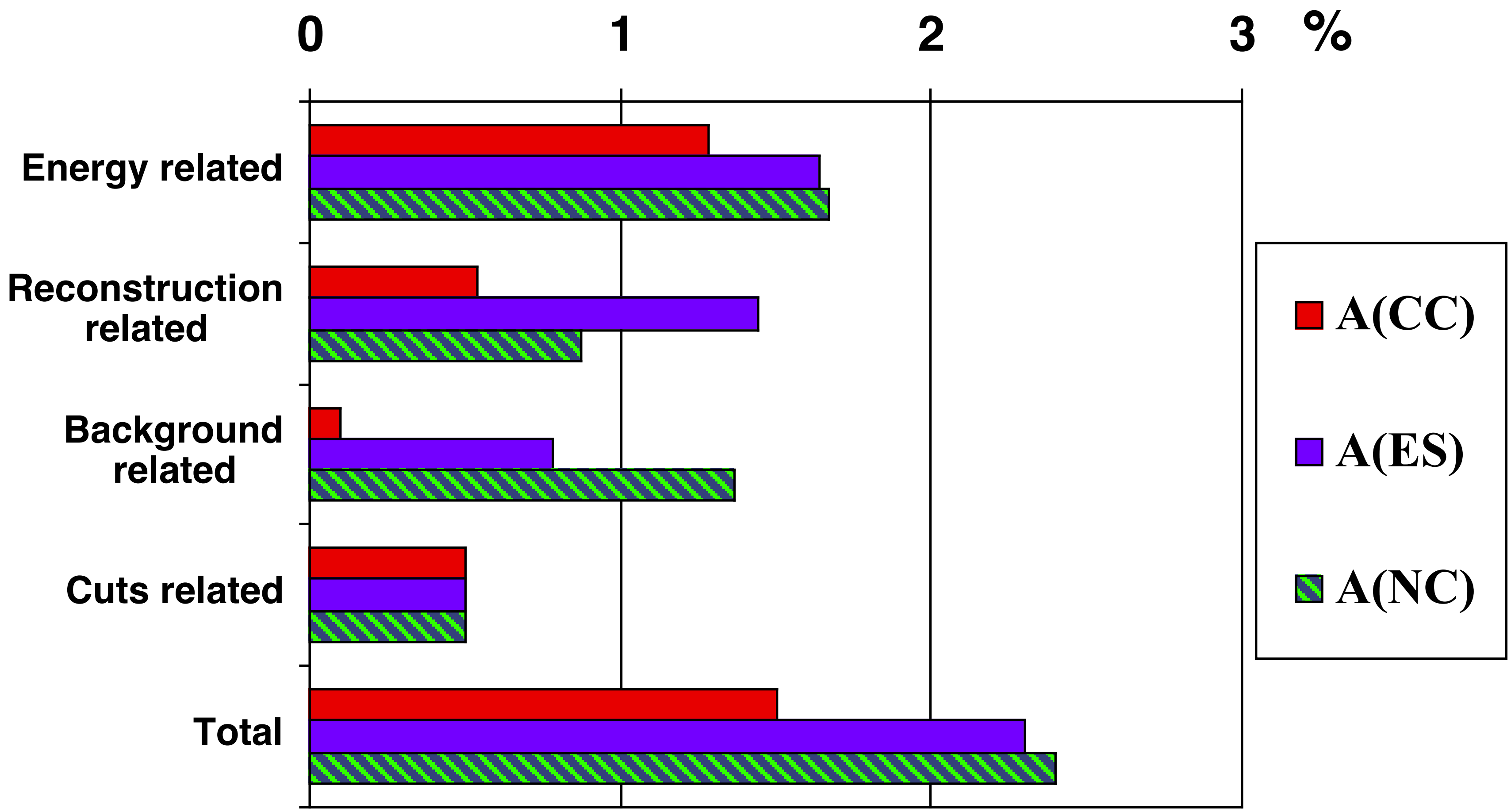


ϕ in units of x10^{6} cm^{-2} s^{-1}



Day/Night Signals	
ϕ	A (%)
CC	+14.0±6.3±1.5
ES	-17.4±19.5±2.4
NC	-20.4±16.9±2.5

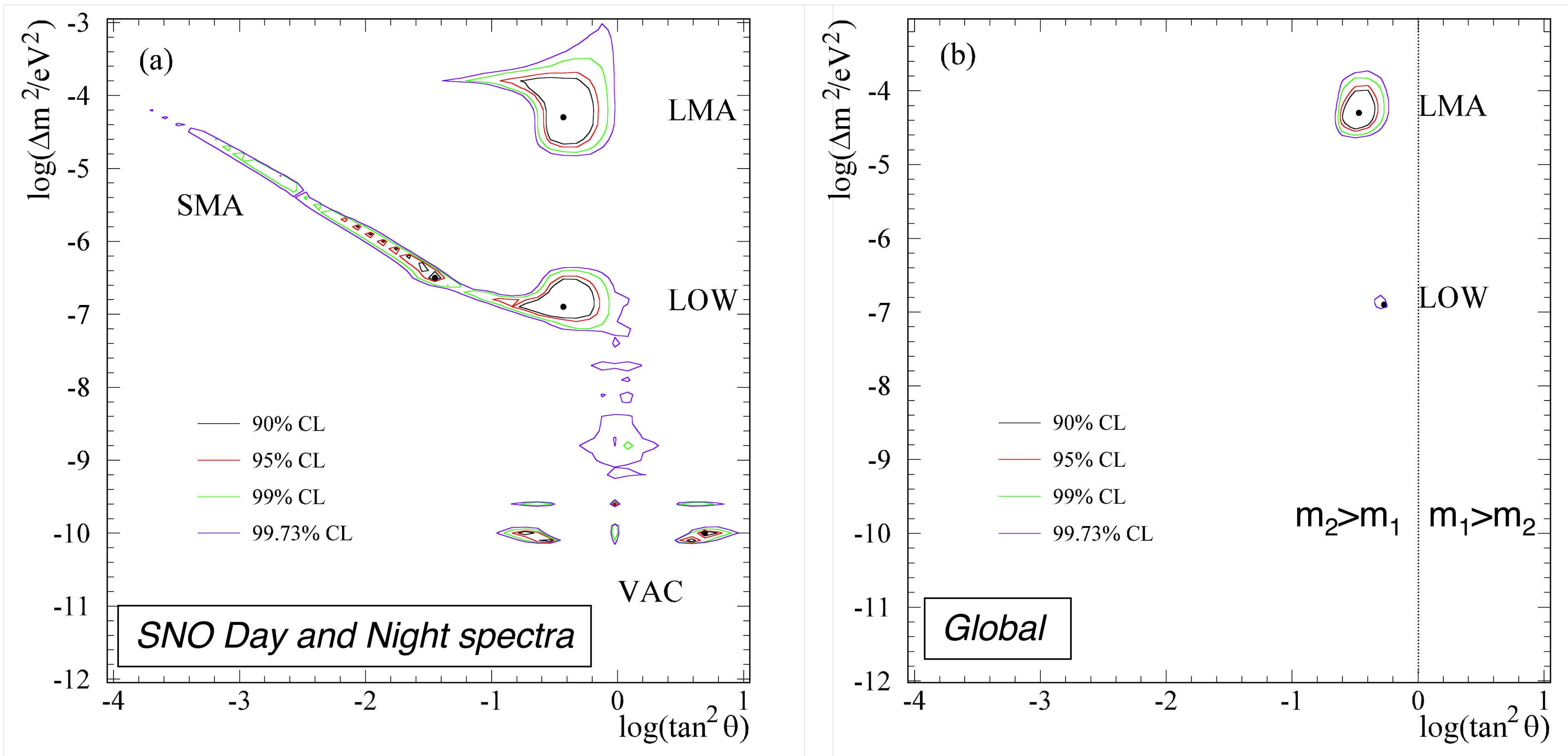
Day-Night Uncertainties



The day-night analysis is currently statistics limited

Global Solar ν Analysis

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



Global χ^2 Analysis Fit Results

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

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

	LMA	LOW
SNO NC	5.86 $\times10^6$ cm^{-2} s^{-1}	4.95 $\times10^6$ cm^{-2} s^{-1}
SNO CC day	1.66 $\times10^6$ cm^{-2} s^{-1}	1.83$\times10^6$ cm^{-2} s^{-1}
SNO A_e	6.4%	5.9%
SK ES	2.30 $\times10^6$ cm^{-2} s^{-1}	2.30 $\times10^6$ cm^{-2} s^{-1}
SK A_{ES}	3.5%	4.4%
Cl rate	3.0 SNU	3.0 SNU
Ga rate	72.8 SNU	61.2 SNU

[Experimental results: SK=2.32x10^6 cm^{-2} s^{-1}, Ga=72.0±4.5 SNU, Cl=2.56±0.23 SNU]

Neutrino Mixing: What do we know now?

$$U_{\alpha i} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \xrightarrow{\text{Atmospheric } \nu} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 0 & -1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

$$\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \xrightarrow{\text{CHOOZ}} \begin{pmatrix} \sim 1 & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}}\sin\theta_{13} & 0 & \sim 1 \end{pmatrix}$$

$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \xrightarrow{\text{Solar } \nu \text{ LMA}} \begin{pmatrix} 0.85 & 0.51 & 0 \\ -0.51 & 0.85 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Present situation:

Solar ν_e mix with $\dfrac{\nu_\mu - \nu_\tau}{\sqrt{2}}$

$$\begin{aligned} \nu_e &= 0.85\nu_1 + 0.51\nu_2 \\ \nu_\mu &= -0.36\nu_1 + 0.60\nu_2 + 0.71\nu_3 \\ \nu_\tau &= 0.36\nu_1 - 0.60\nu_2 + 0.71\nu_3 \end{aligned}$$

CKM vs MNSP

Contrast between V_{CKM} (quark) and U_{MNSP} (lepton)

[*B* ≡ *Big*   *s=small*]

$$V_{CKM} = \begin{pmatrix} 1 & s & s \\ s & 1 & s \\ s & s & 1 \end{pmatrix} \qquad U_{MNSP} = \begin{pmatrix} B & B & s \\ B & B & B \\ B & B & B \end{pmatrix}$$

Present Status & Future of SNO

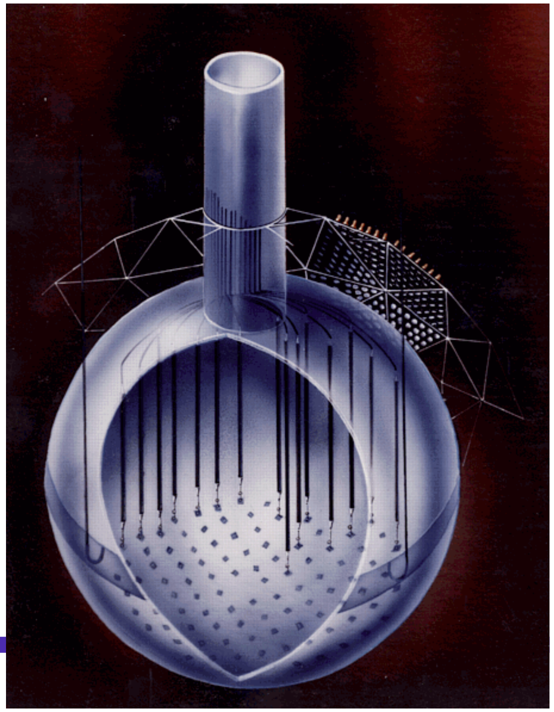
The Salt Phase

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

Neutral Current Detectors

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

- **To be deployed in early 2003**
- Event-by-event separation of n



SNO Summary

Newest SNO results **:**

- $□_e □$ $□_□$ or $□_□$ appearance at 5.3 □
- Total ^{8}B □ flux measured for $E_□$>2.2 MeV
- SSM prediction for total active ^{8}B □ flux verified
- Day-Night results consistent with MSW hypothesis

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

- LMA highly favored ($□m^2 \sim 5.0 \times 10^{-5}$ eV^2)
- No “dark side” and not maximal mixing ($m_1 > m_2$, $\tan^2(□) < 1$)
- Predictions for Borexino & KamLAND

The NC and Day-Night papers (in July 1 issue of PRL), along with a HOWTO guide on using the SNO results are available at the official SNO website:

http://sno.phy.queensu.ca

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Supplementary slides from this point on

How to solve the Solar Neutrino Problem?

VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

Direct Approach to Resolve the Solar-Neutrino Problem

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(Received 27 June 1985)

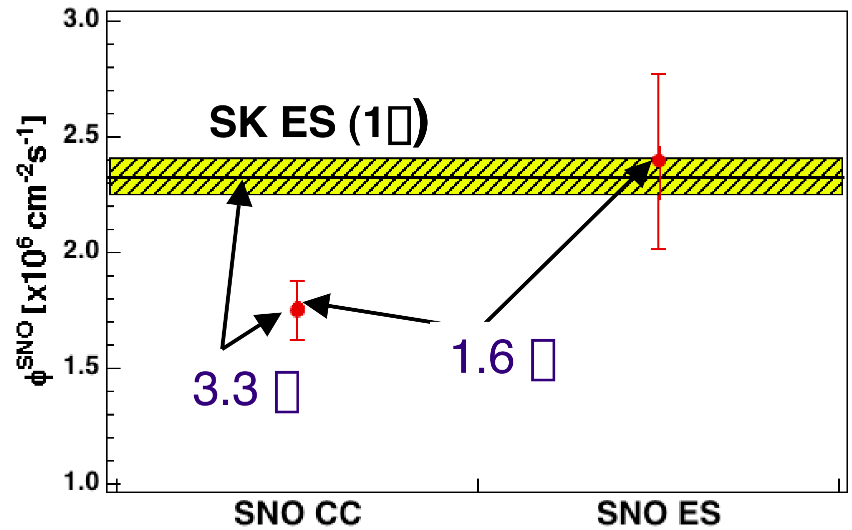
A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis 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.

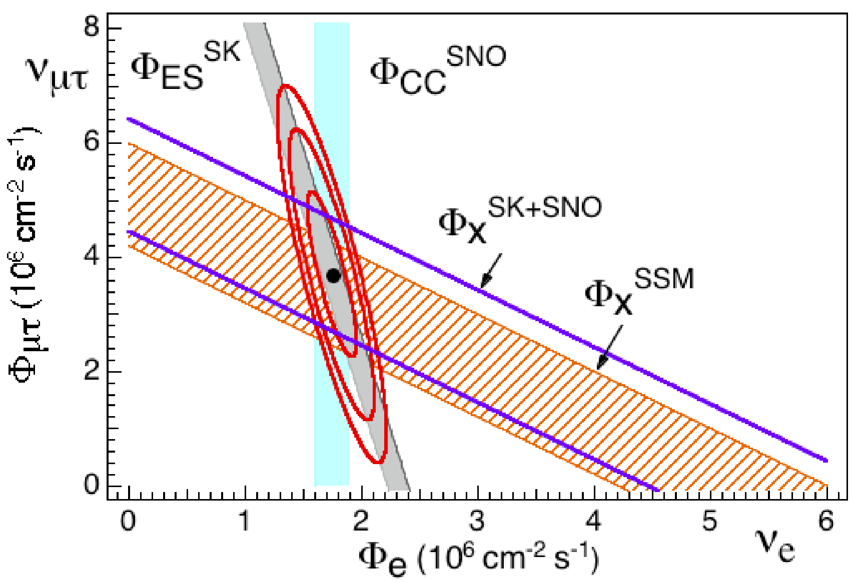
PACS numbers: 96.60.Kx, 14.60.Gh

PRL 55, 1534 (1985)

An experiment which directly addresses the solar-neutrino problem should be sensitive to all neutrino species equally. Such a measurement could determine the total solar-neutrino flux *even if neutrinos oscillate*.

Recap [$T_e > 6.75$ MeV]





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

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

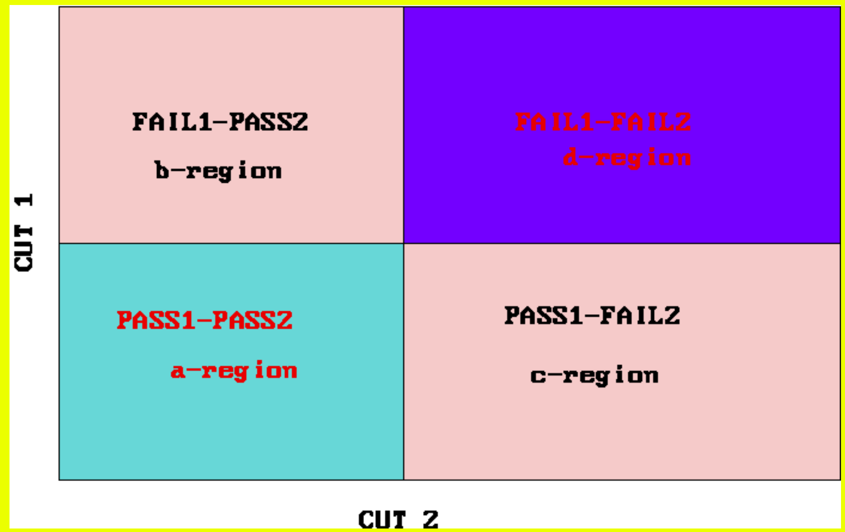
Result 2:

Solar model predictions are verified

Bifurcated Analysis

- Use a subset of the Pass 0 cuts and the HLC as two independent cuts
- Number of residual instrumental background event = K = $y_1 y_2 \square_B$
- K < 3 events (95% CL)

Bifurcated analysis



Pass Cut 1: a+c = $\square_1 \square_\square + y_1 \square_B$

Pass Cut 2: a+b = $\square_2 \square_\square + y_2 \square_B$

Pass Cuts 1&2: a = $\square_1 \square_2 \square_\square + y_1 y_2 \square_B$

Total Data: S= $\square_\square + \square_B$

$\square_i$=neutrino acceptance for cut i

y_i=leakage of background for cut I

$\square_\square$=number of neutrino events

$\square_\square$=number of background events

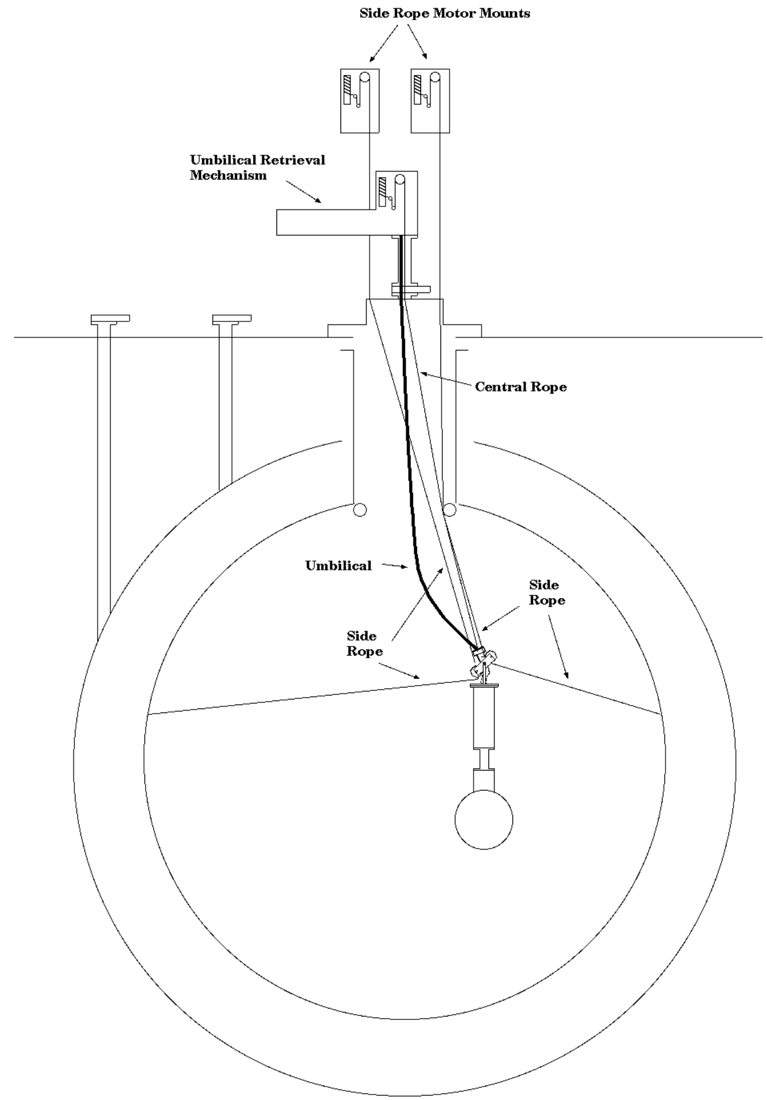
Understanding the Detector Response

Monte Carlo

- Cherenkov production (e^-, □)
- Photon propagation and detection
- Neutron transport and capture
- Event Reconstruction

Calibration

• Charge Pulsers	Electronic
• Pulsed Laser	337nm to 620 nm
• ^{16}N	6.13 MeV □s
• ^{3}H(p,□)^{4}He	19.8 MeV □s
• ^{8}Li	<13.0 MeV □'s
• ^{252}Cf	neutrons
• U/Th Background	^{214}Bi & ^{208}Tl □□□s



Energy Calibration Uncertainties

Absolute Energy Calibration Uncertainties

Time drift	0.25%
Position Dependence	0.72%
^{16}N source	0.46%
Rate dependence	0.39%
Threshold dependence	0.45%
Gain variation	0.28%
Channel accounting	0.00%
Background noise	0.00%
Timing calibration	0.50%
Total	**1.21%**

Energy Response functions

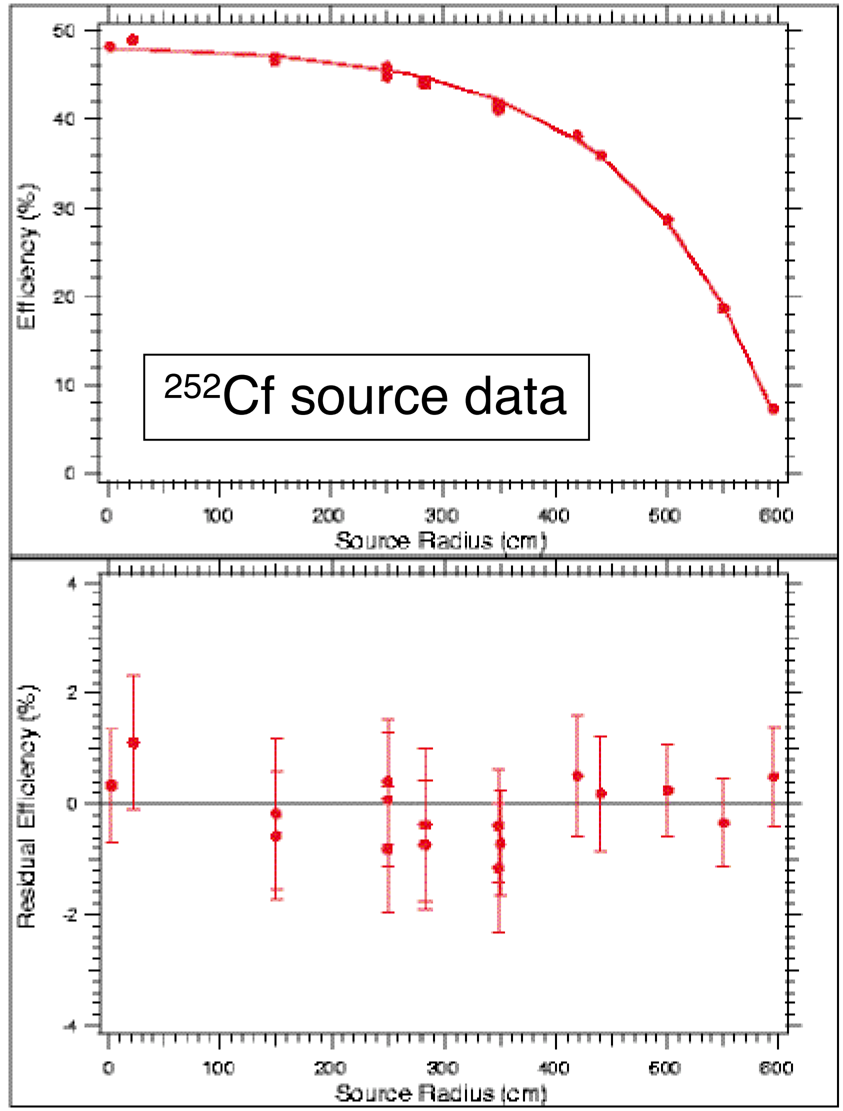
$$R(E_e, E_{eff}) = \frac{1}{\sqrt{2\pi}\,\sigma_E(E_e)} \exp\left[-\frac{1}{2}\left(\frac{E_{eff} - E_e}{\sigma_E(E_e)}\right)^2\right]$$

$$\sigma_E(E_e) = -0.6837 + 0.3308\sqrt{E_e - 0.511} + 0.04253(E_e - 0.511)$$

$$\frac{\Delta\sigma_E(E_e)}{\sigma_E(E_e)} = 0.045 + 0.00401(E_e - 5.486)$$

Neutron Capture Efficiency

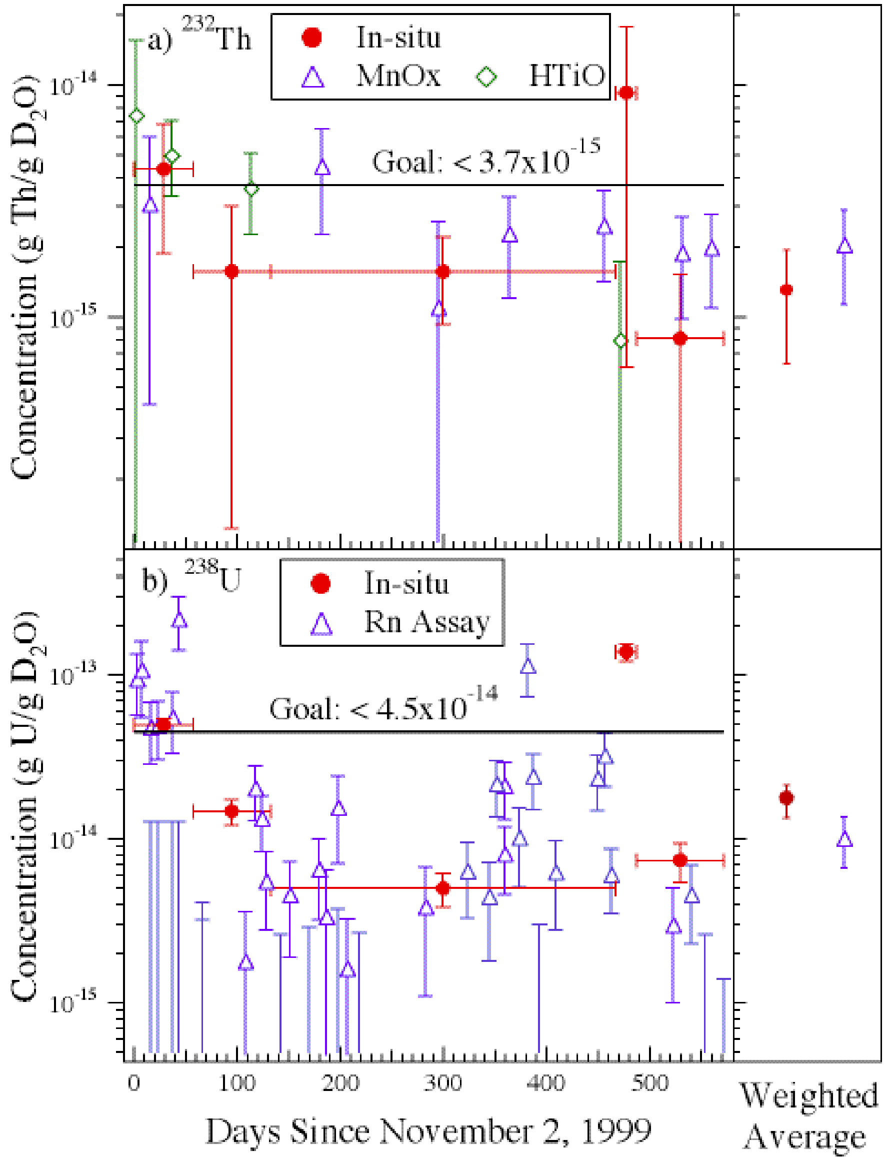
Analytic Prediction n capture efficiency			
Isotope	**Abundance**	**Point Source at Center**	**Uniform Source**
D	99.9176%	49.11%	29.34%
H	0.0824%	29.76%	17.79%
16-O	99.9195%	9.20%	5.49%
17-O	0.0485%	5.36%	3.20%
18-O	0.0320%	0.02%	0.00%
Escape		6.55%	44.15%
Total		**100%**	**100%**



Measured:

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

pd background from D_2O, AV, H_2O radioactivity



	D_2O (10^{-15} g/g D_2O)	H_2O (10^{-14} g/g H_2O)	AV (10^{-12} g/g)
[Th]	1.63 ± 0.58	9.1 ± 2.7	$0.90^{+0.60}_{-0.53}$
[U]	$17.8^{+3.5}_{-4.3}$	75.5 ± 33.0	$0.27^{+0.07}_{-0.03}$

Monte Carlo

pd n detected (306.4 d)	44^{+8}_{-9} counts	11^{+6}_{-4} counts	16^{+6}_{-7} counts

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

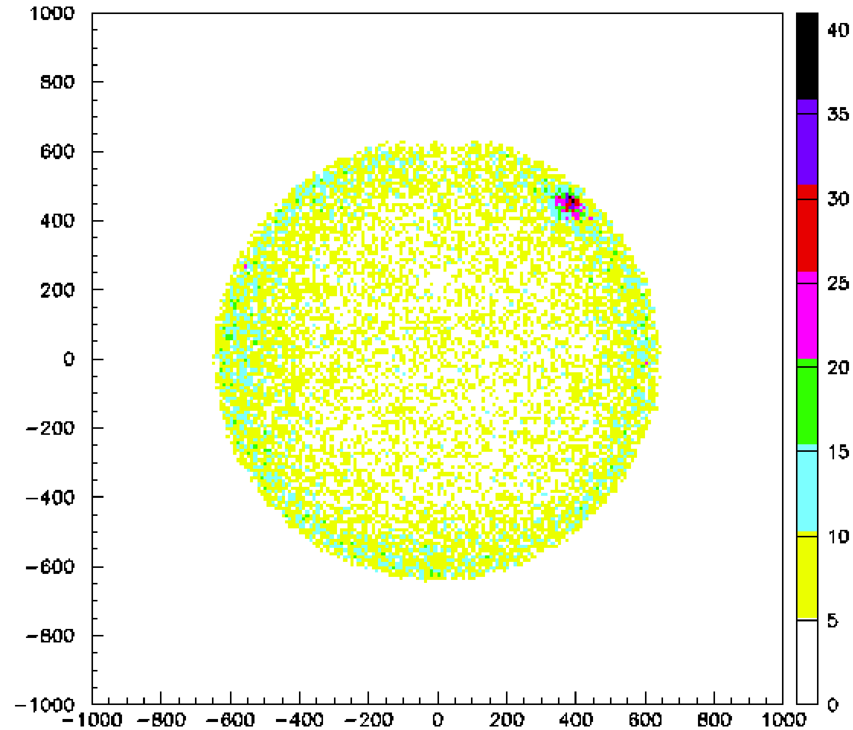
The photodisintegration background is small compared to the SSM expectation

U and Th in/on the Acrylic Vessel

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

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

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



Z vs X projection

Cherenkov Tail — D_2O

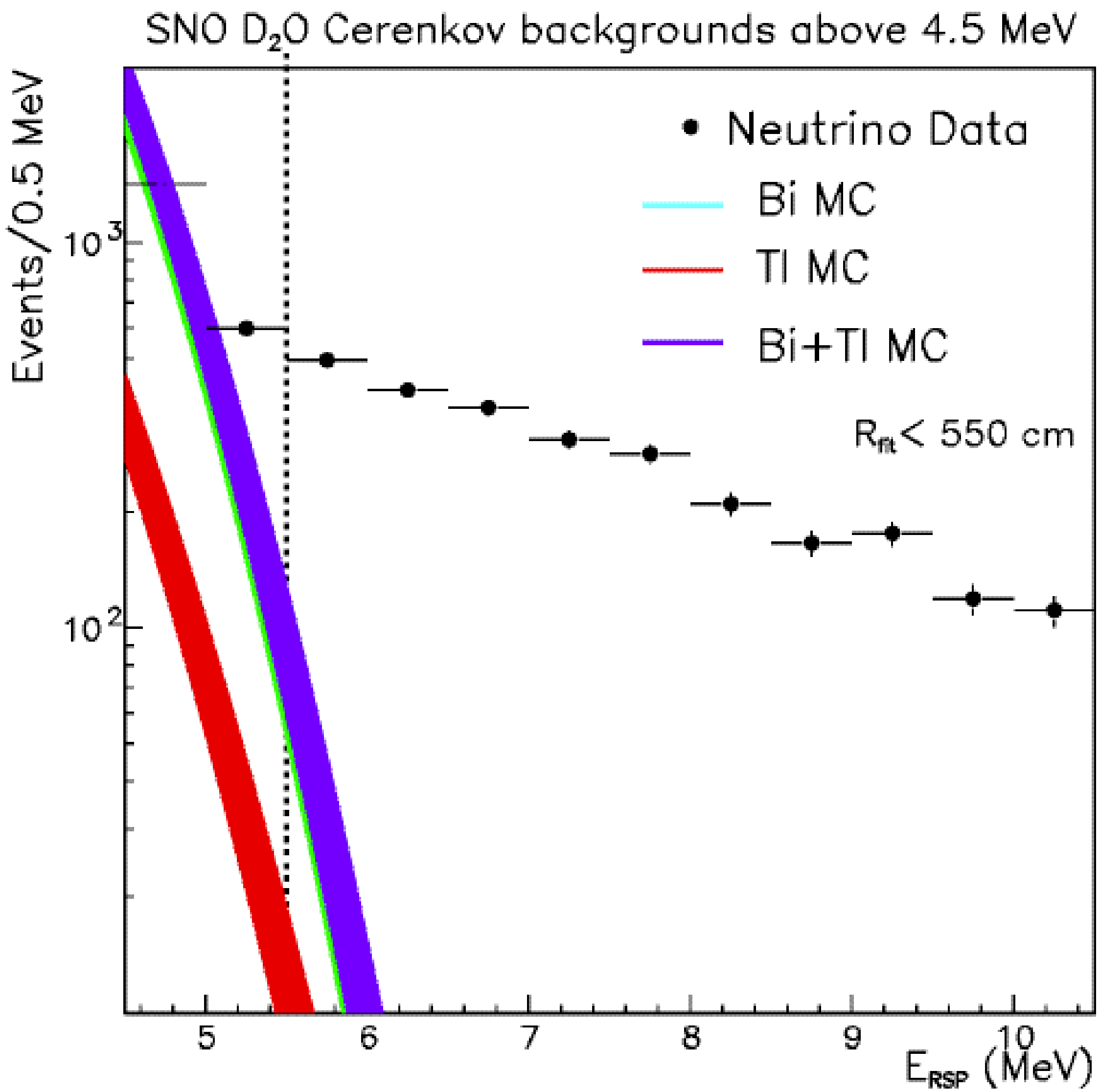
- Monte Carlo of detector response well calibrated in the D_2O region
  ⇒ *Determine Cherenkov tail background due to D_2O radioactivity by Monte Carlo, using the U and Th concentration obtained above.*

- MC predictions cross checked with a Th calibration source

T>5 MeV, R<550cm:

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

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



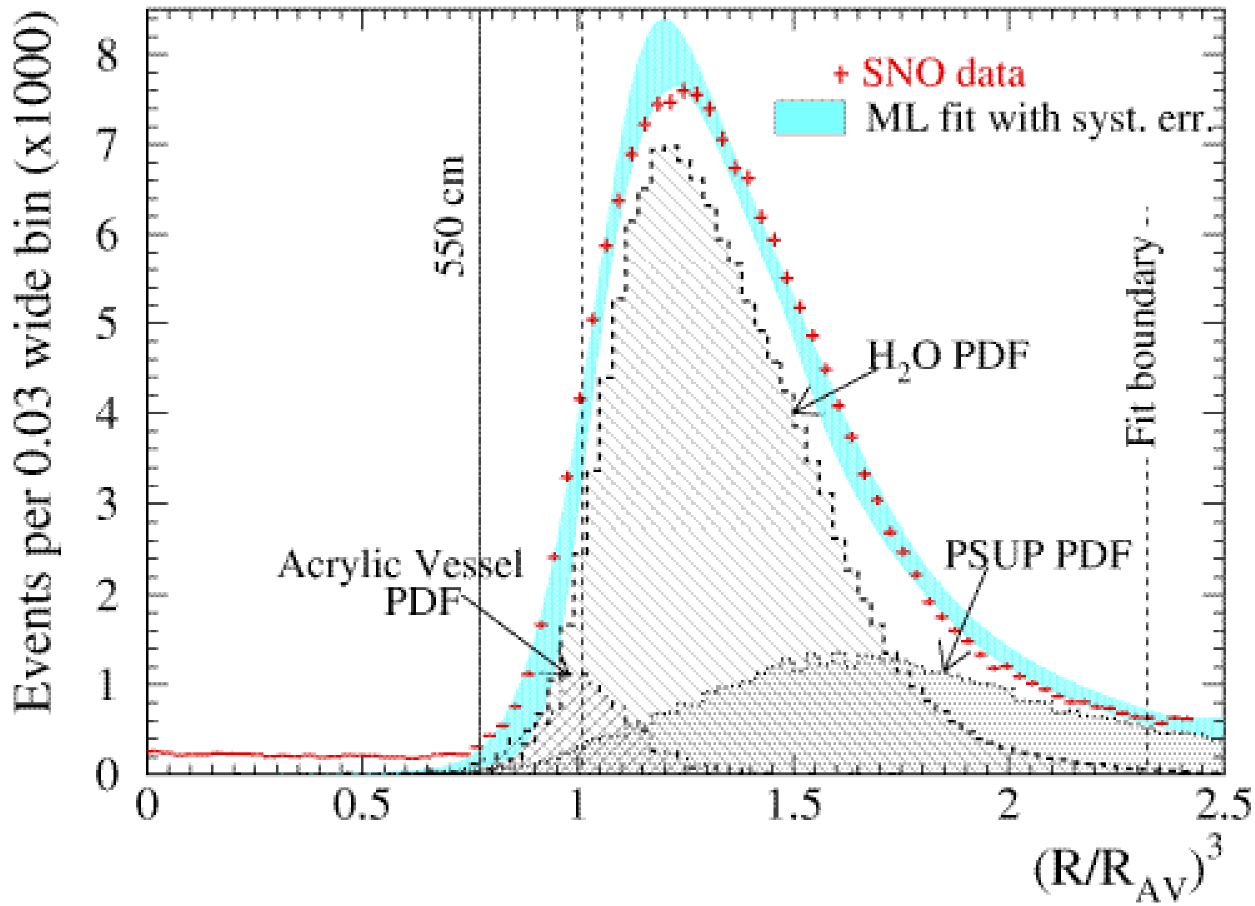
Cherenkov Tail

- Determined from U/Th source calibration and Monte Carlo
- Consistent with expectation based on measured U and Th concentration

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

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

[c.f.: 2928 □ candidates]



A_e vs A_{total}

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

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

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

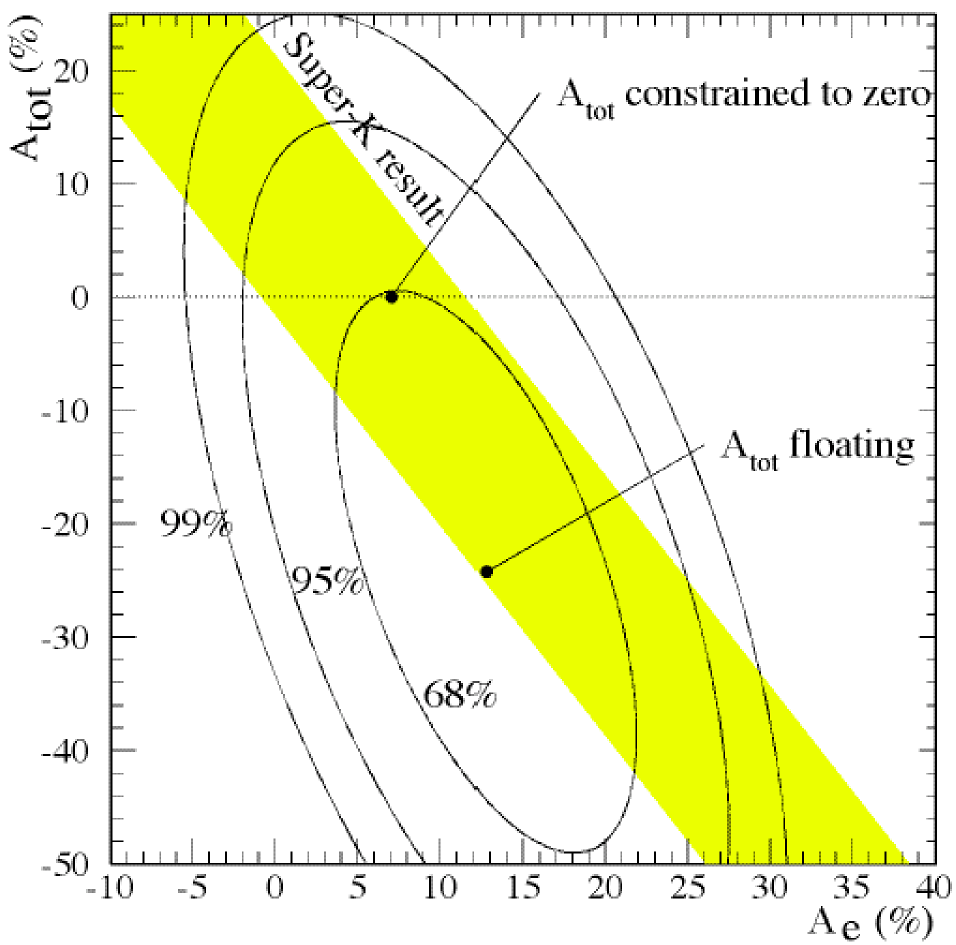
- Signal Extraction in ϕ_e, ϕ_{Total}:

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

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

- Signal Extraction in ϕ_e, ϕ_{Total} + A_{total}=0:

$$A_e = 7.0 \pm 4.9^{+1.3}_{-1.2}\%$$
$$A_e^{SK} = 5.3 \pm 13.7^{+2.0}_{-1.7}\%$$



Does the sun shine “brighter” at night?

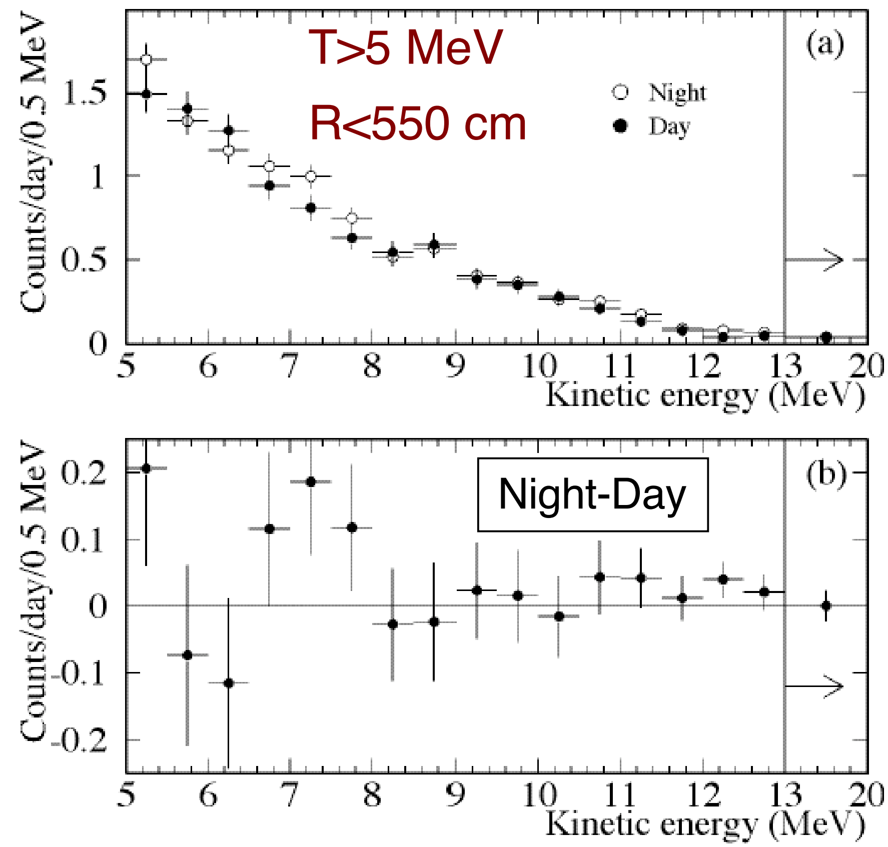
- Data divided into two sets
  (to test statistical bias)

- Sub-divide data into two zenith angle bins:

  Day: cos θ_z>0 (128.5 days)

  Night: cos θ_z<0 (177.9 days)

- Extract Φ^{CC}, Φ^{NC}, and Φ^{ES} in these 2 bins (^{8}B shape constrained fit)



Day: 9.23±0.27 events d^{-1}

Night: 9.79±0.24 events d^{-1}

*Signal and background included

Systematic Uncertainties (D-N)

Shape constrained

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

The D-N analysis is currently statistics limited

Cosmological Implications

1. SNO + CHOOZ: $|m_1^2 - m_2^2| < 10^{-3}$ eV^2

2. Super-Kamiokande: $|m_2^2 - m_3^2| \sim 2.5\times10^{-3}$ eV^2

3. ^{3}H β decay (Mainz exp.): $|U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 < (2.2)^2$ eV^2

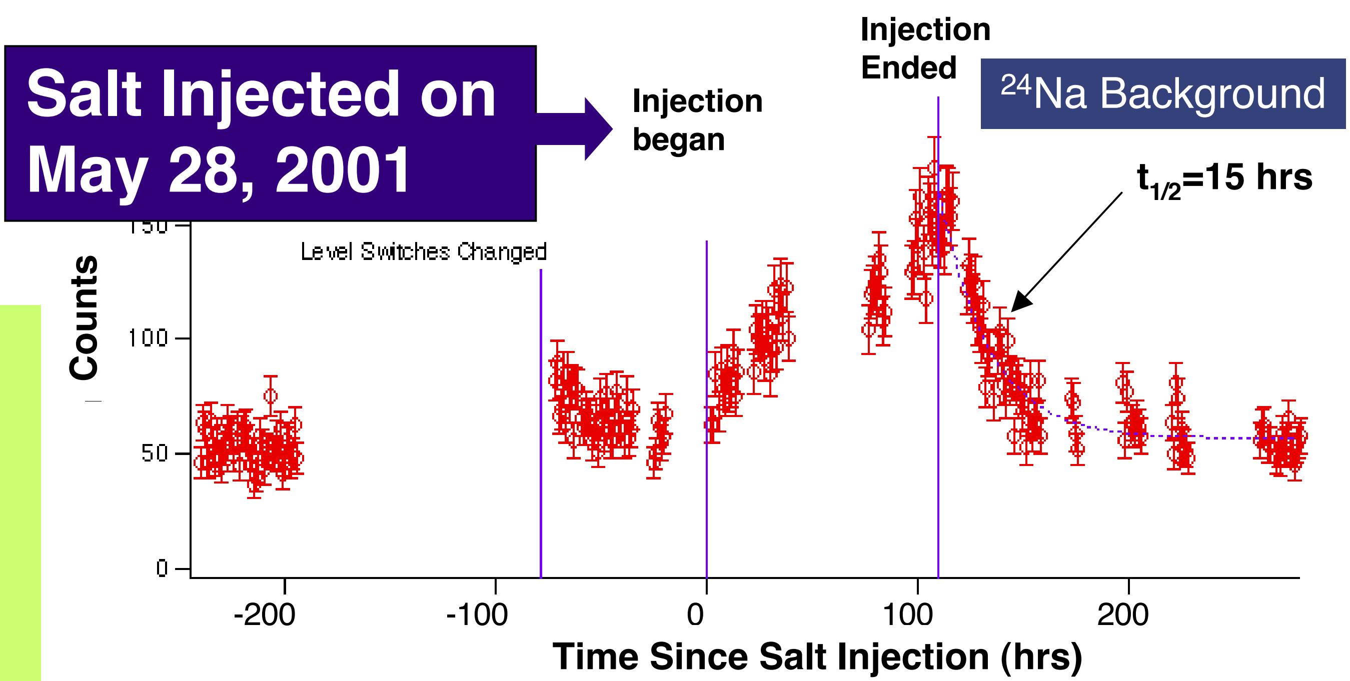
Sum of neutrino masses Σm_ν: $0.05 < \Sigma m_\nu < 6.6$ eV

Limit on closure density $\Rightarrow$ $0.001 < \Omega_\nu < 0.14$

Salt Phase

Detector is in GOOD shape

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



ν in the Standard Electroweak Model (I)

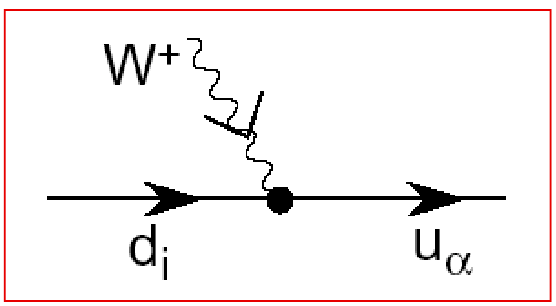
Quark Sector

$$\begin{matrix} \text{I} & \text{II} & \text{III} \\ \begin{pmatrix} u \\ d' \end{pmatrix}_L & \begin{pmatrix} c \\ s' \end{pmatrix}_L & \begin{pmatrix} t \\ b' \end{pmatrix}_L \\ (u)_R & (c)_R & (t)_R \\ (d')_R & (s')_R & (b')_R \end{matrix}$$

- *Weak Interaction for quarks*

– consider the absorption of a W+

$$\mathcal{L}_{udW} = \frac{-g}{\sqrt{2}} \sum_{\substack{\alpha=u,c,t \\ i=d,s,b}} \overline{u_{L\alpha}}\gamma^{\mu}\mathbf{V}_{\alpha i} d_{Li} W^{+}_{\mu} + h.c.$$

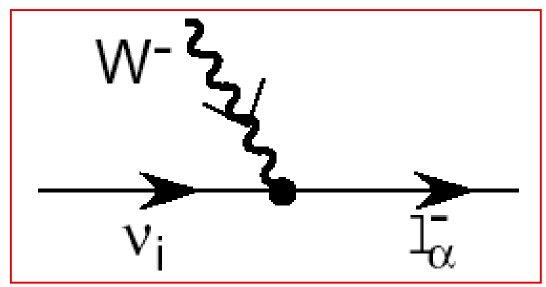


Lepton Sector

$$\begin{matrix} \text{I} & \text{II} & \text{III} \\ \begin{pmatrix} e \\ \nu_e \end{pmatrix}_L & \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L & \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L \\ (e)_R & (\mu)_R & (\tau)_R \end{matrix}$$

- *Similar Langrangian for leptons*

$$\mathcal{L}_{l\nu W} = \frac{-g}{\sqrt{2}} \sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}} \overline{l_{L\alpha}}\gamma^{\mu}\mathbf{U}_{\alpha i}\nu_{Li} W^{-}_{\mu} + \frac{-g}{\sqrt{2}} \sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}} \overline{\nu_{Li}}\gamma^{\mu} U^{\dagger}_{i\alpha} l_{L\alpha} W^{+}_{\mu}$$

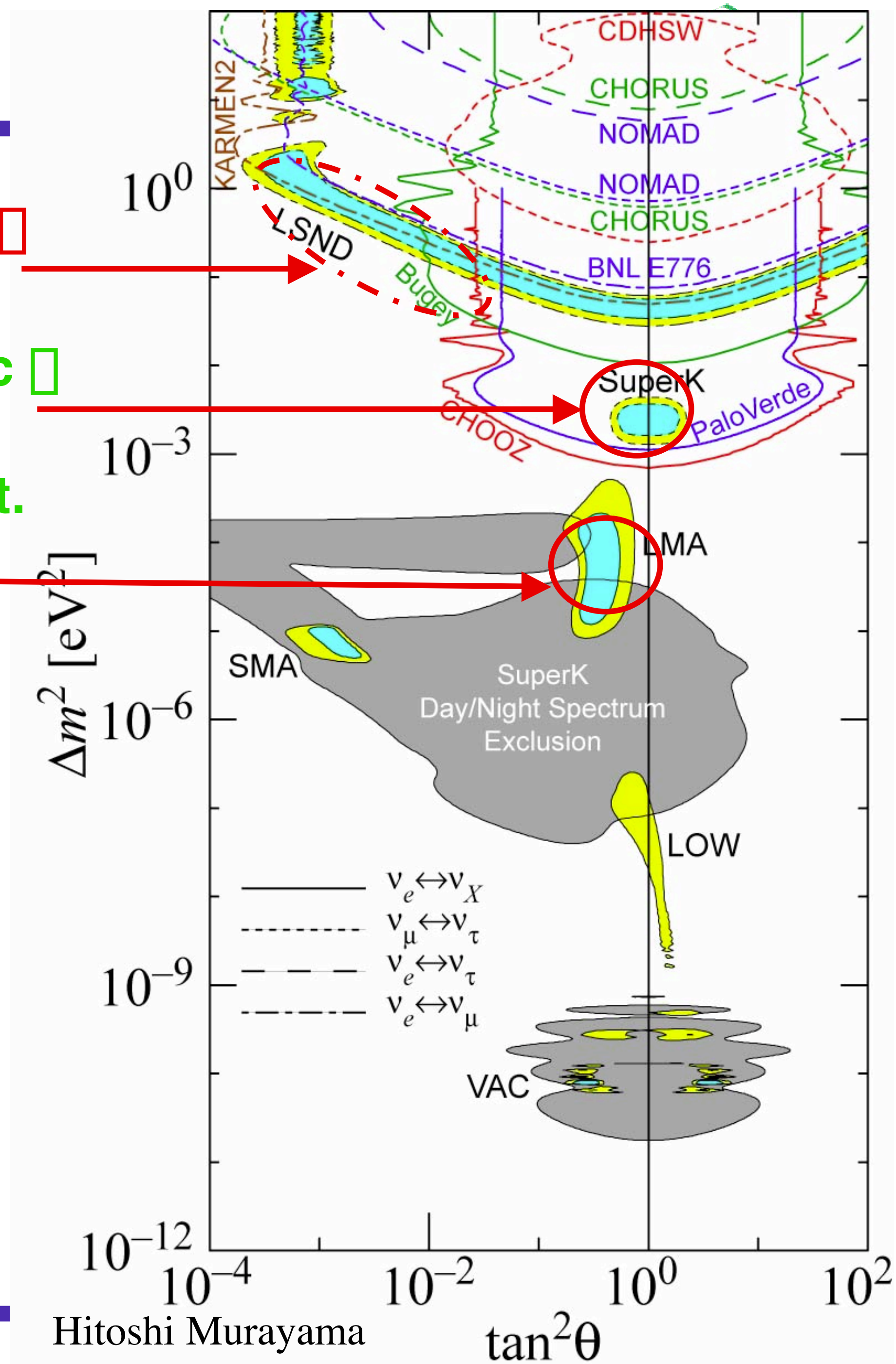


□ After April 2002

Accelerator □
MiniBoone

Atmospheric □
MINOS
Off-axis expt.

Solar □
SNO
KamLAND
Borexino



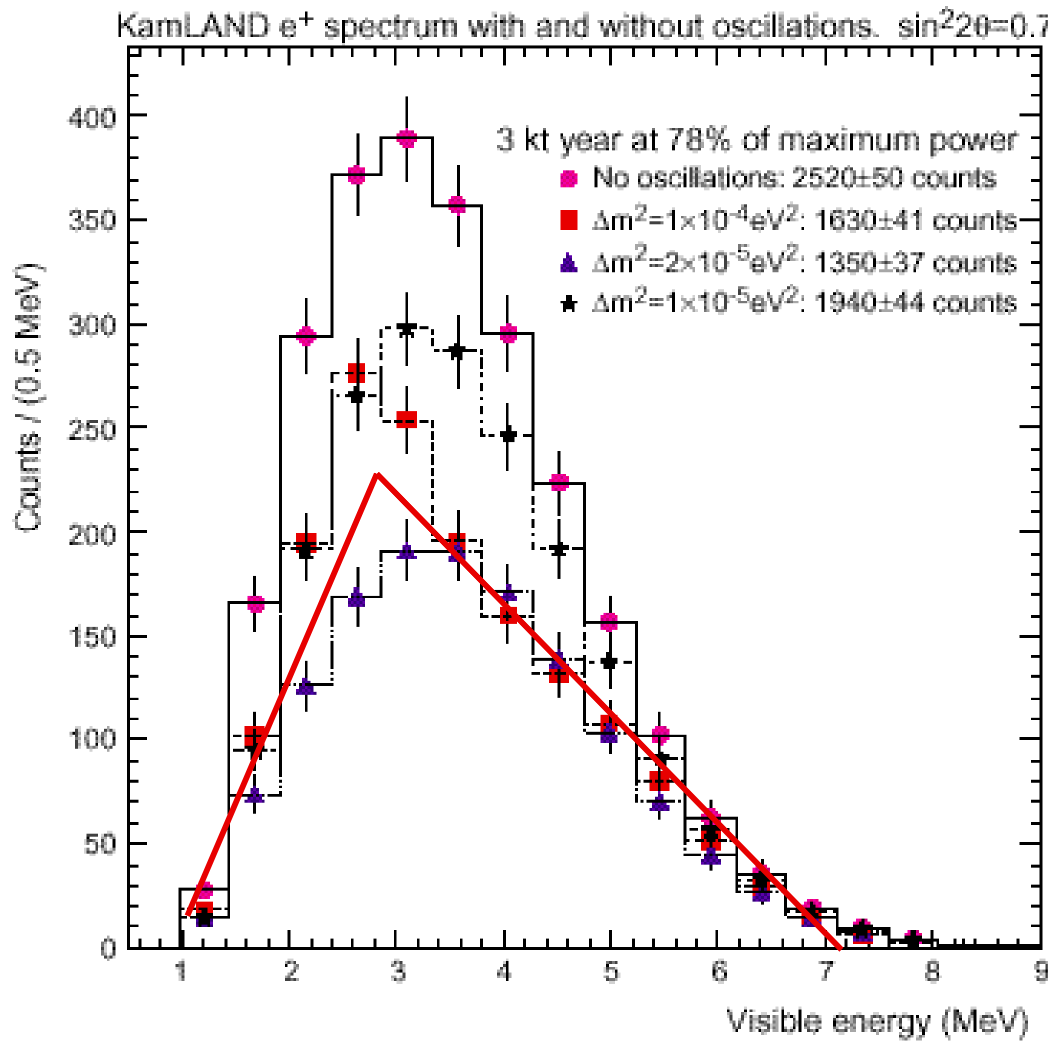
<u>Outstanding Issues</u>

- Precision determination of parameters, 3 family mixing
- Absolute □ mass scale
- Sterile neutrinos?
- Modifications to Standard Model
- Origins of □ mass

Prediction for KamLAND

Global fit:

LMA Δm^2=5x10^{-5} eV^2



LMA Solution?

LARGE MIXING SCENARIO?

⇒ **KamLAND** (Kamioka, Japan)

reactor $\bar{\nu}$ @ "right" baseline for probing the currently favored LMA region

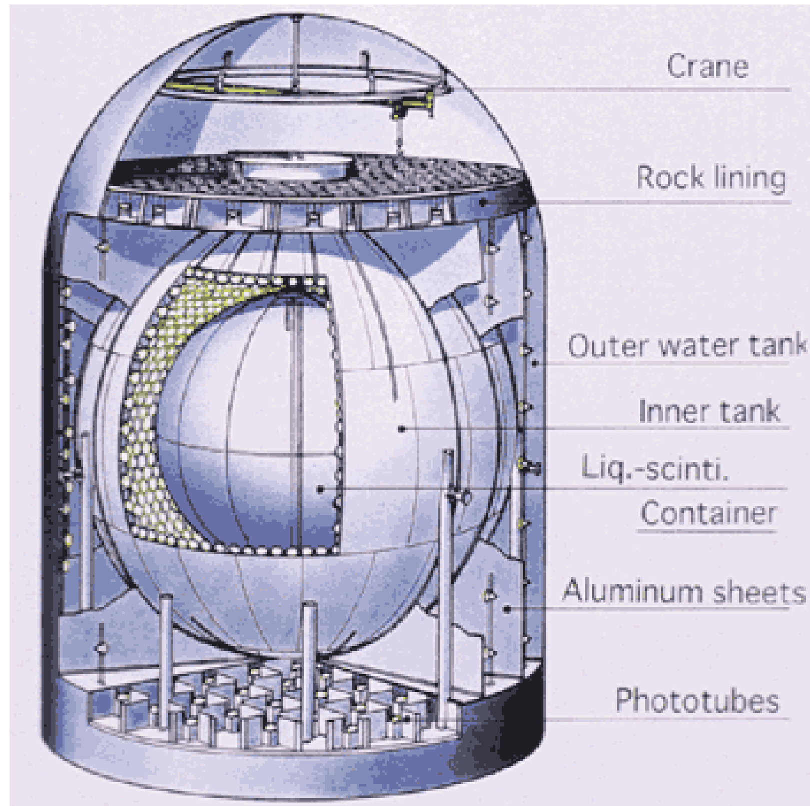
1 kt liquid scintillator as target

$$\bar{\nu}_e + p \to n + e^+$$

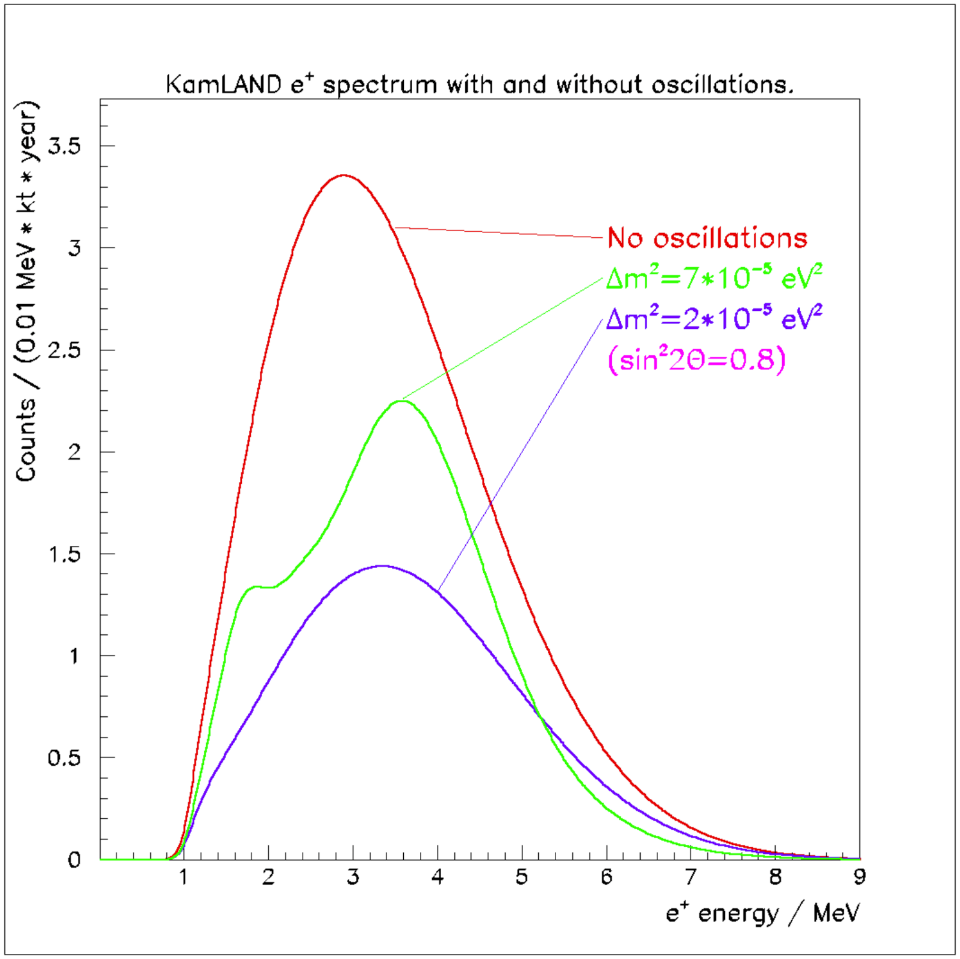
2x coincidence

$$e^+ + e^- \to 2\gamma$$

$$n + p \to d + \gamma \text{(2.2 MeV)}$$



Reactor physics at KamLAND



- No oscillation scenario, expect:
  ~150 events in 3 months
- If LMA, expect:
  ~110 events in 3 months
- ~ 3 statistical significance in 3 months

Data taking began on Jan. 22, 2002

LOW solution?

LOW: large D-N asymmetry in ^{7}Be flux
$\Rightarrow$ **Borexino** (Gran Sasso, Italy)

$\Rightarrow$ $23^{+10}_{-13}\%$ (3σ)

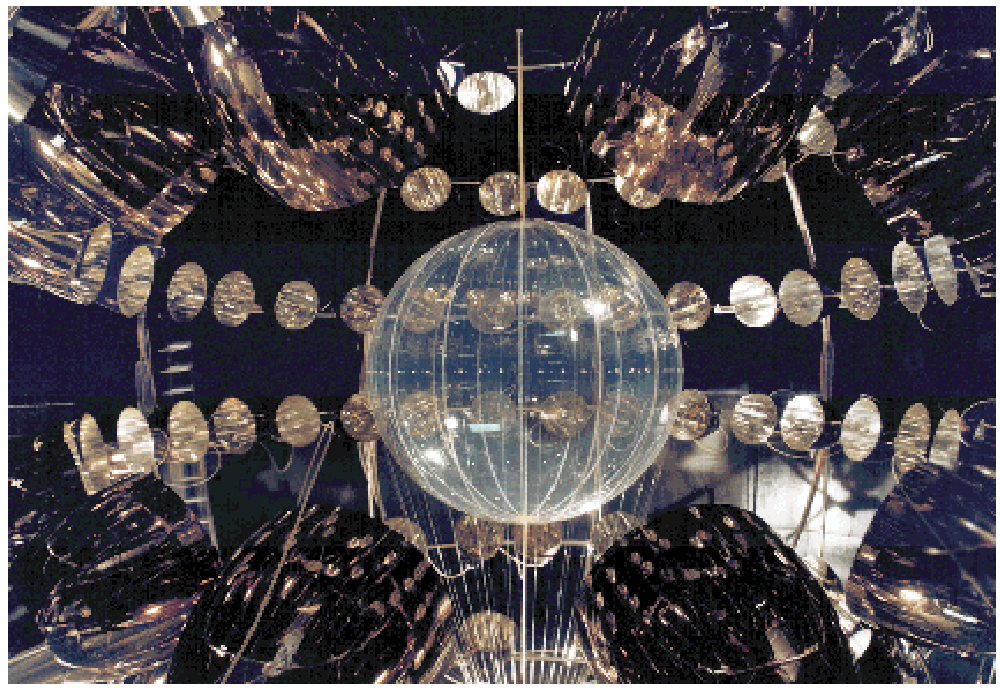
Bahcall et al. hep-ph/0204314

300t liquid scintillator as target.
Measure the ^{7}Be ν flux by elastic scattering:

$$\nu + e \rightarrow \nu + e$$

Very stringent radioactive background requirements

Data-taking will begin in 2003



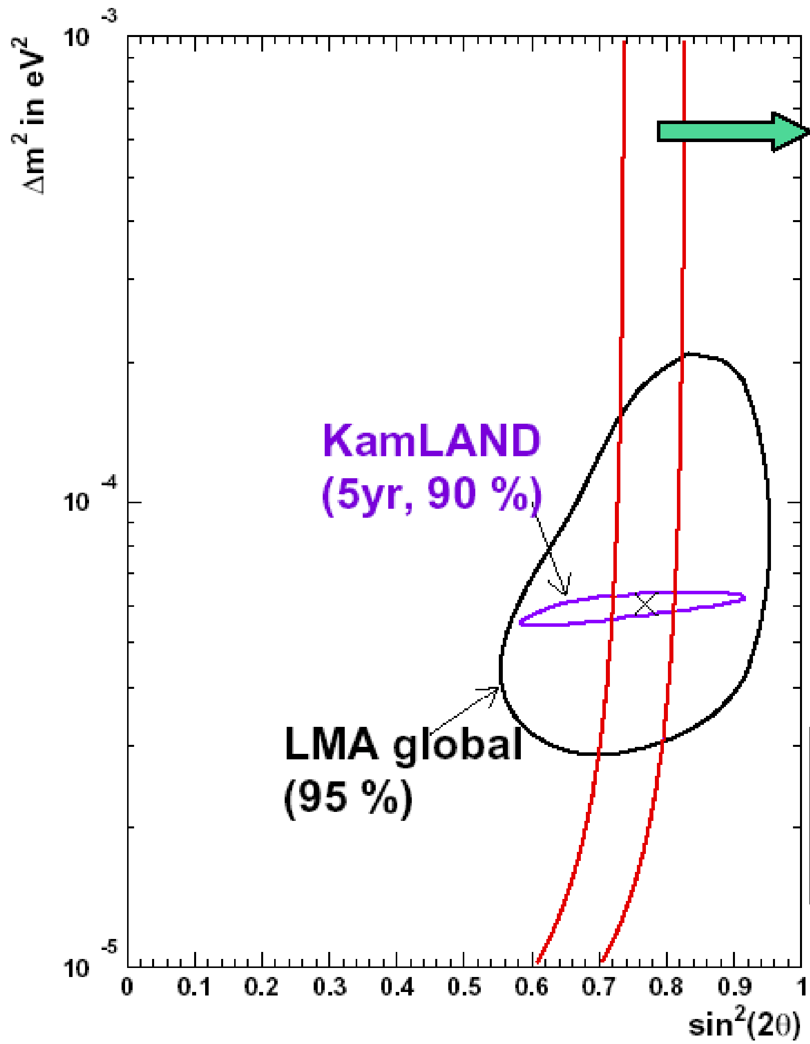
Borexino prototype ("Counting Test Facility")

Low E solar ν experiment

Goals:

- Precision measurement of $\theta_{12,}$ test unitarity of MNSP matrix
- Constrain on active-sterile ν mixing
- Test of solar models

Future solar experiments



- pp neutrino flux measurement (90 % C.L.) by :
  - 10 ton detector
  - νe scattering experiment
  - 5 years data
  - Statistical error + SSM flux error(1%)
- Accuracy of mixing angle : $\sin^2 2\theta = 0.77 \pm 0.03$ (stat.+SSM)

Precise determination of oscillation parameters by KamLAND and pp experiments.

Nakahata, LowNu2002

Future Experiments

Next Generation Solar Neutrino Experiments

		Fiducial Mass		Threshold (keV)			BP00 rate (per year)			
Expt.	**Type**	**Tons**	**of**	**ES**	**CC**	**NC**	**pp+ pep**	**^{7}Be**	**^{8}B**	**CNO**
HERON	LHe rotons, scintillator	5	He	50			3025	1500	2	125
HELLAZ	Gas TPC	7	He	180			4000			
CLEAN	Scintillator	12.5	Ne	10			9000			
XMASS	Scintillator		Xe							
LENS	Scintillator	5	^{176}Yb		301.45		570	400	32	136
MOON	Scintillator	3.3	^{100}Mo		168		409	129	14	34
CI	Hybrid	2200	^{37}Cl		814		230	1200	5900	420
GaAs	Ionization		^{71}Ga							
LiF	Bolometer	0.9	^{7}Li		862	487	27	29		