New Results from the Sudbury Neutrino Observatory:

• Direct Evidence for Neutrino Flavor Transformation

• Day & Night Energy Spectra

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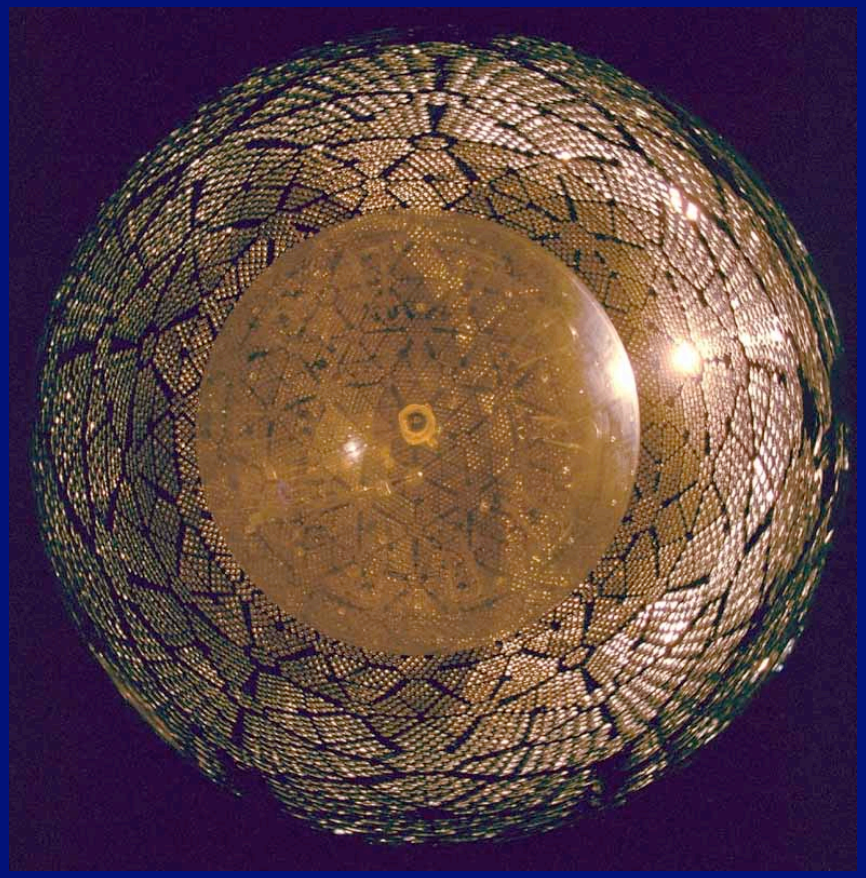
The Sudbury Neutrino Observatory

- The Solar Neutrino Problem & Neutrino Oscillations
- The SNO Detector and Physics Program
- SNO's Neutral Current Measurement from Pure D_2O
- Day & Night Measurements from SNO
- Prospects & Implications



pp Chain & Standard Solar Model

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

$p+p \rightarrow {}^2H+e^+ + \nu_e$ [*pp* ν]

$p+e+p \rightarrow {}^2H + \nu_e$ [*pep* ν]

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

85%

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

15%

$^3He+p \rightarrow {}^4He+e^+ + \nu_e$ [*hep* ν]

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

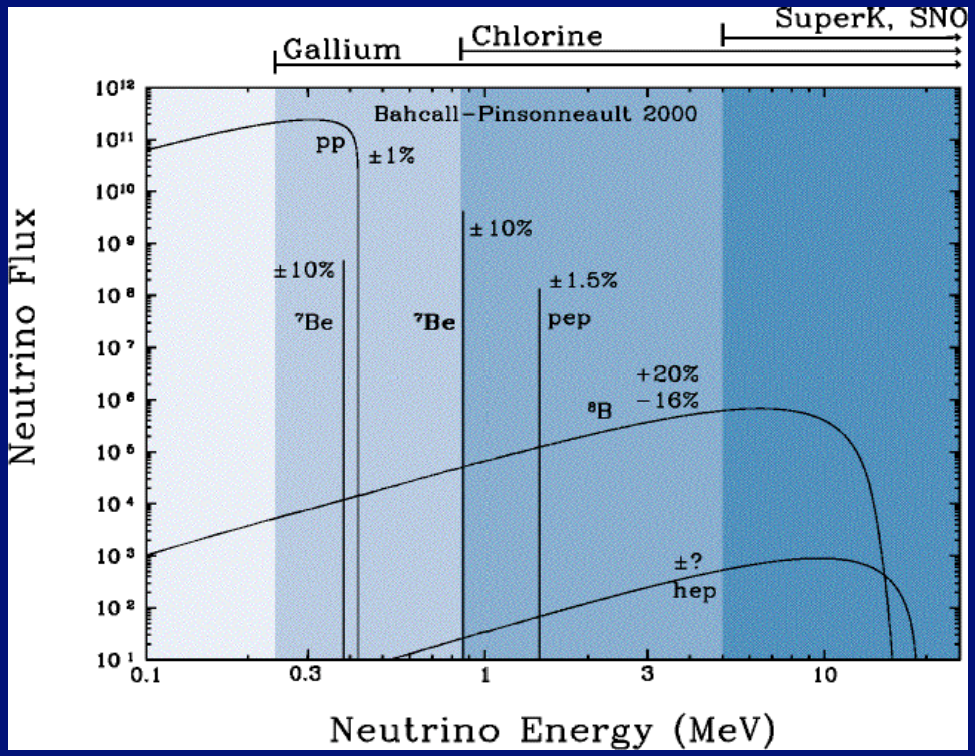
0.02%

$^7Be+p \rightarrow {}^8B+\gamma$
$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$
$^8Be^* \rightarrow {}^4He+{}^4He$
[^{8}B ν]

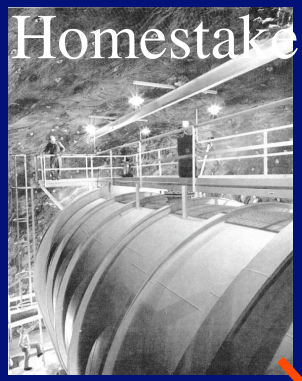
$^7Be+ e^- \rightarrow {}^7Li+\nu_e$
$^7Li+p \rightarrow {}^4He+{}^4He$
[^{7}Be ν]

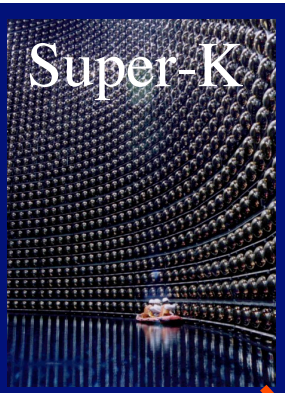
Detailed computer model of solar evolution

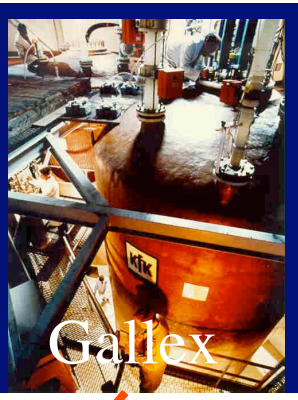
Standard Solar Model

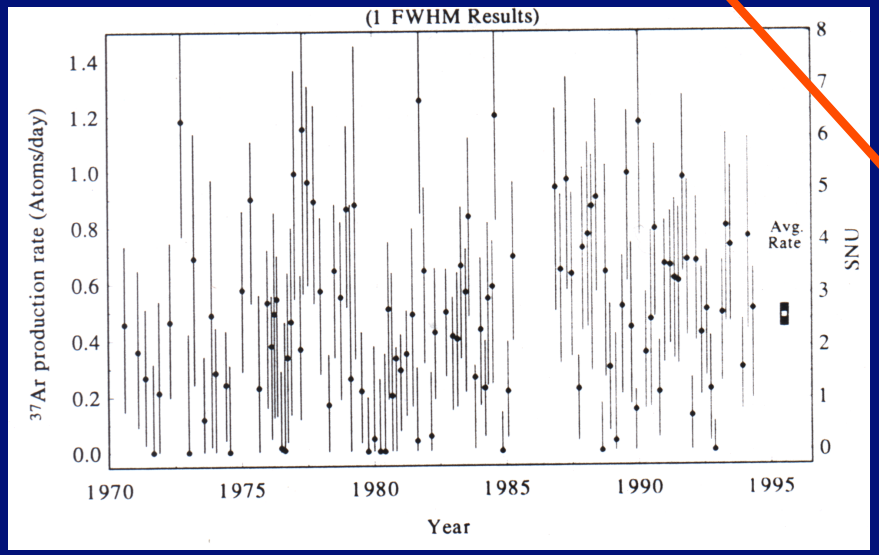


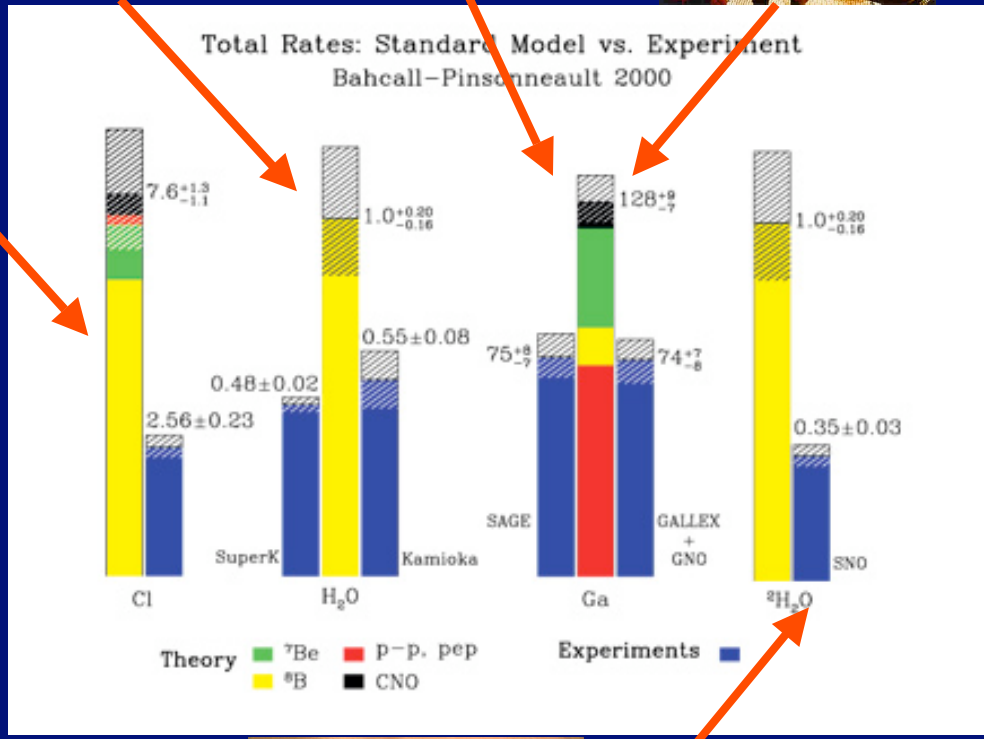
Solar Neutrino Problem











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	$\nu_x + e \rightarrow \nu_x + e$
Sudbury Neutrino Observatory	$\nu_e + d \rightarrow p + p + e$
	$\nu_x + d \rightarrow \nu_x + p + n$
	$\nu_x + e \rightarrow \nu_x + e$

The Sudbury Neutrino Observatory

NIM A449, 127 (2000)

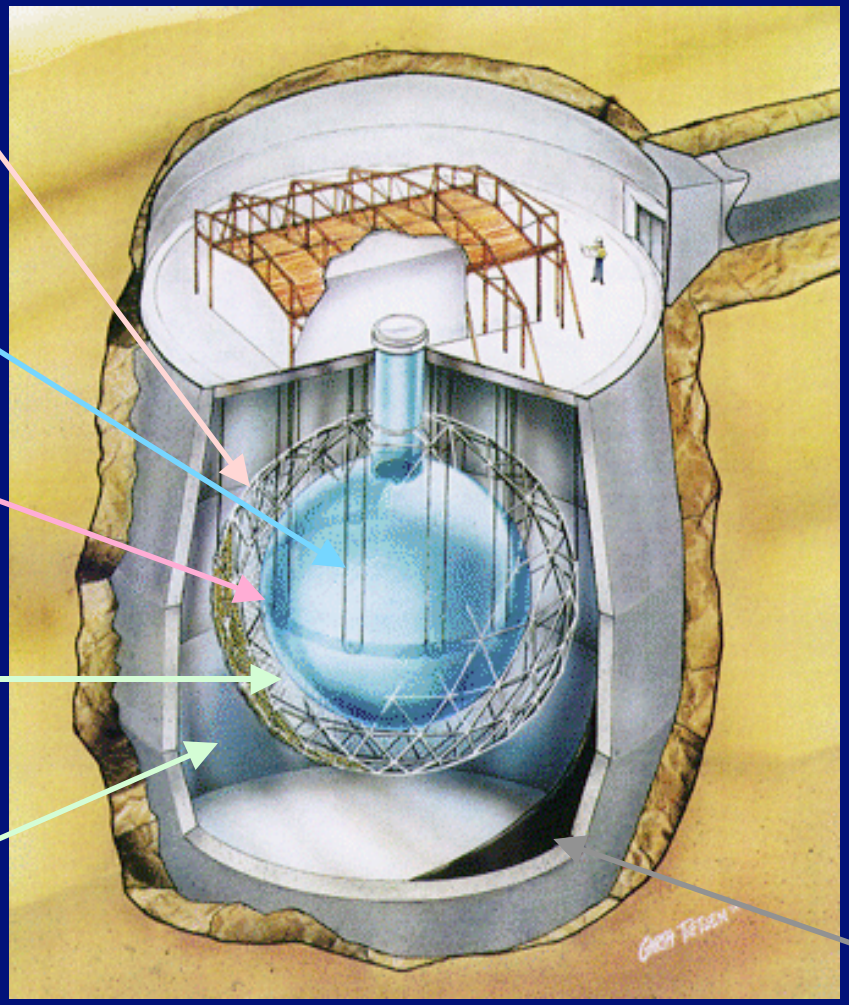
17.8 m Diameter Support Structure for 9456 PMTs, 56% coverage

1006 Metric Tons D_2O

12.01 m Diameter Acrylic Vessel

1700 Metric Tons Inner Shielding H_2O

5300 Tons Outer Shield H_2O

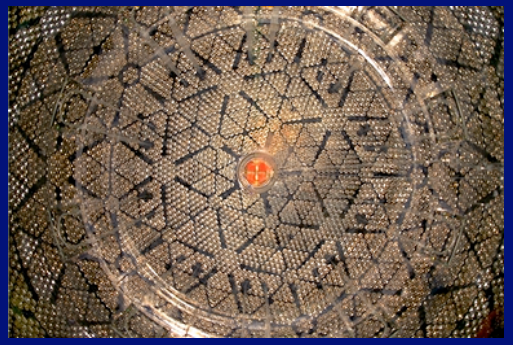


Clean Room Construction

Ultra-low Activity Components

Ultra-Pure Water D_2O & H_2O

Urylon Liner and Radon Seal



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
  (θ = 6.25 MeV, η_n ~ 30%)

- D_2O + NaCl ~1yr
  CC, **ES**, enhanced **NC**
  (θ = ~8.6 MeV, η_n ~ 86%
  ~45% above threshold)

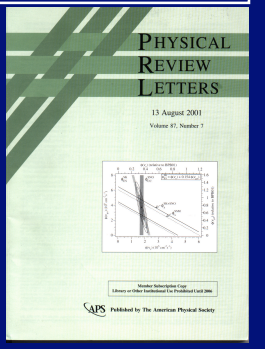
- D_2O + NCDs (^{3}He Prop. Counters)
  Concurrent **CC** & **NC**, **ES**
  (η_n ~ 37%)
  ($n + {}^3He \rightarrow p + t + 760$ keV)

SNO's Major Signals for □ Transformation

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

← SNO

← Super-K, SNO



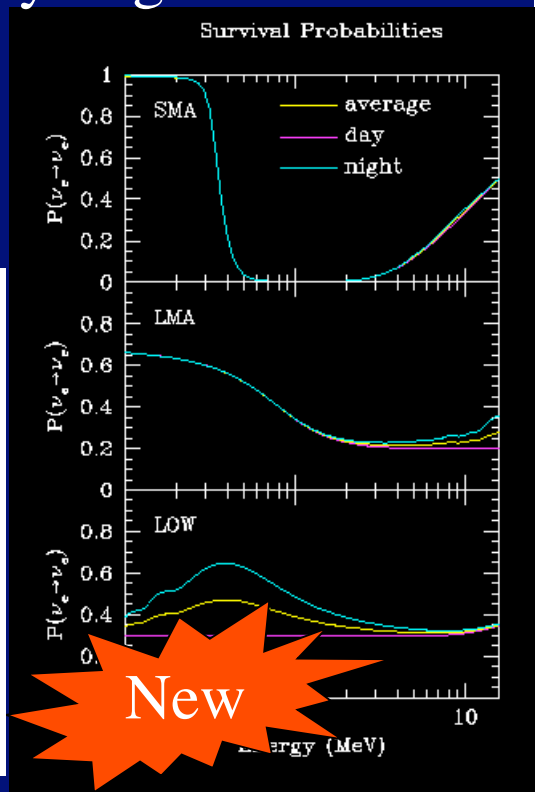
PRL **87**, 071301

New

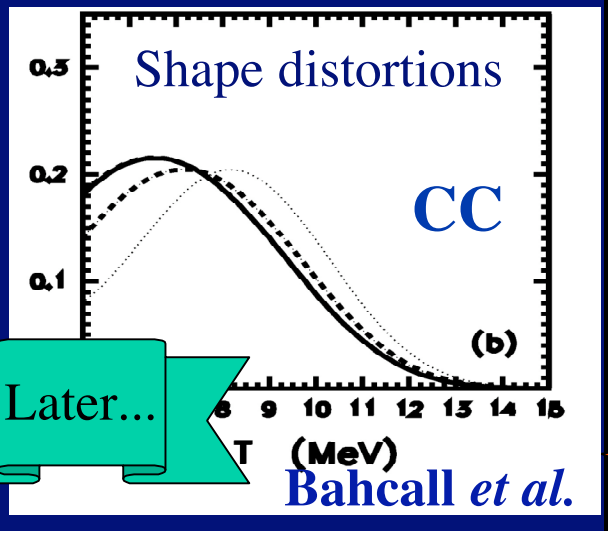
$$\frac{CC}{NC} = \frac{\phi_e}{\phi_e + \phi_\mu + \phi_\tau}$$

← SNO Day/Night differences

← SNO



Later...



2001 Analysis SNO CC + Super-K ES

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

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

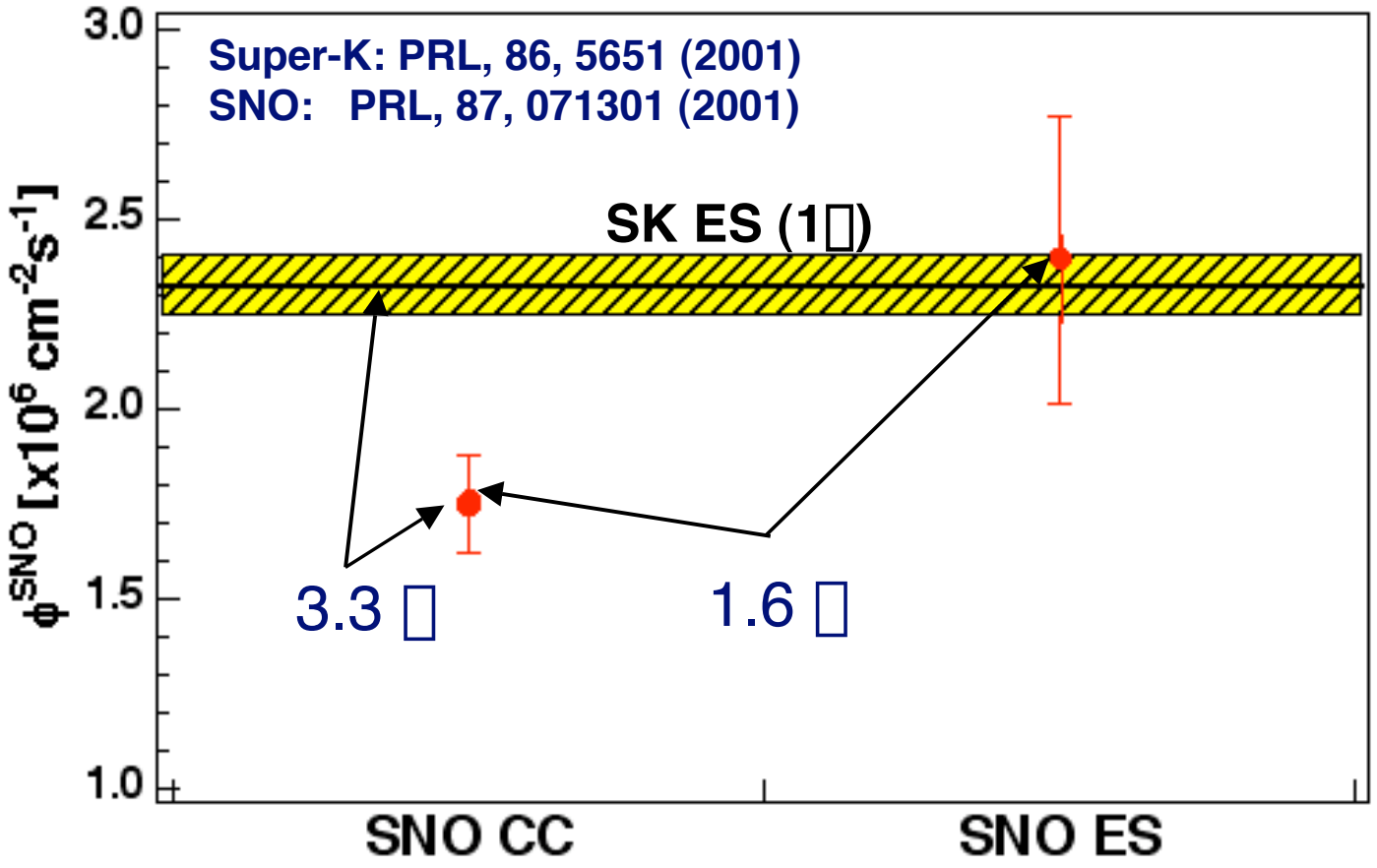
*S. Fukuda, *et al.*, PRL **86**, 5651 (2001)

cf. SSM (BPB01):

$$\phi^{SSM}(\nu_e) = 5.05^{+1.01}_{-0.81} \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

$$\phi(\nu_{e,\mu,\tau}) = 3.69 \pm 1.13 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$
$$\phi(\nu_x) = 5.44 \pm 0.99 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

Evidence for Solar Neutrino Transformation - 2001



Flavor Changing Appearance at 3.3 □

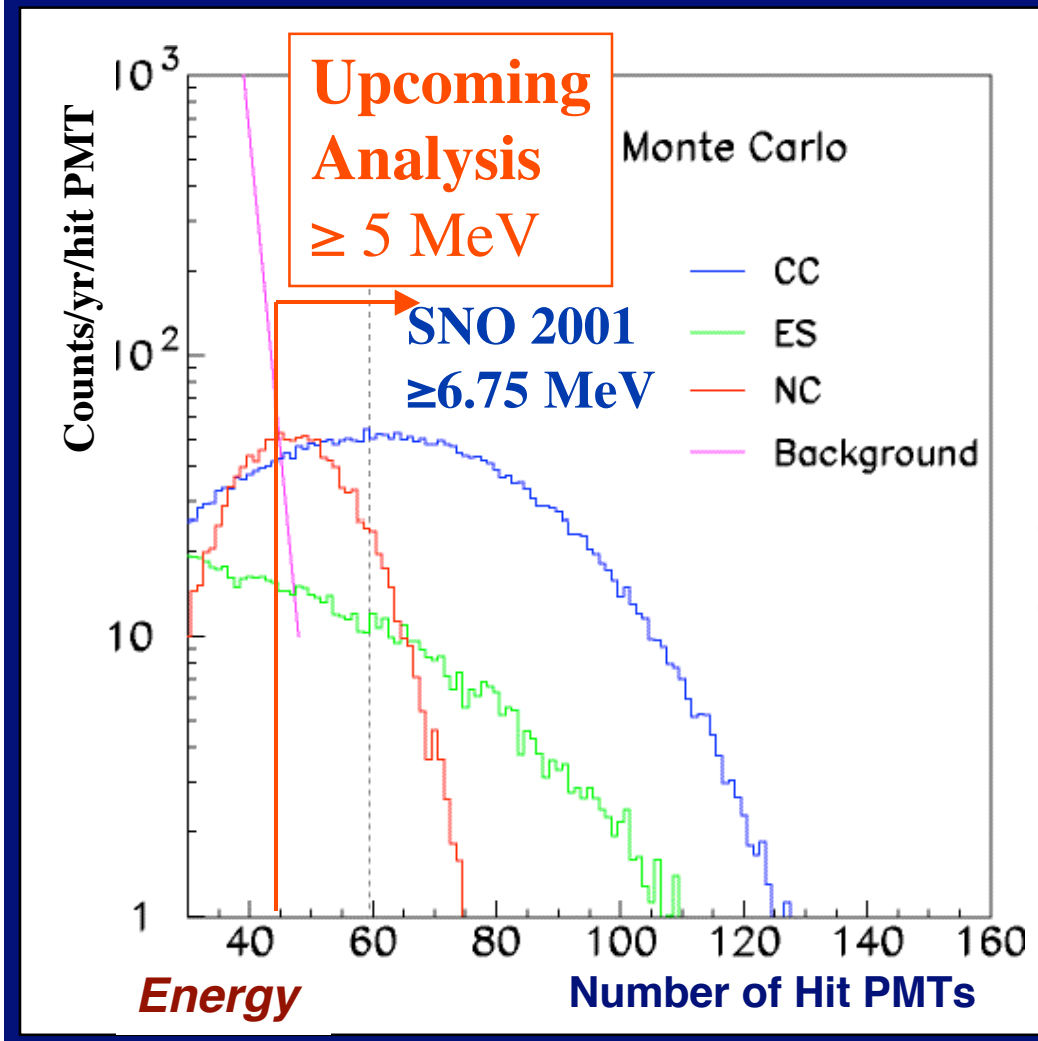
Solar model predictions are verified

Conclusion

□$_e$□ □□,□

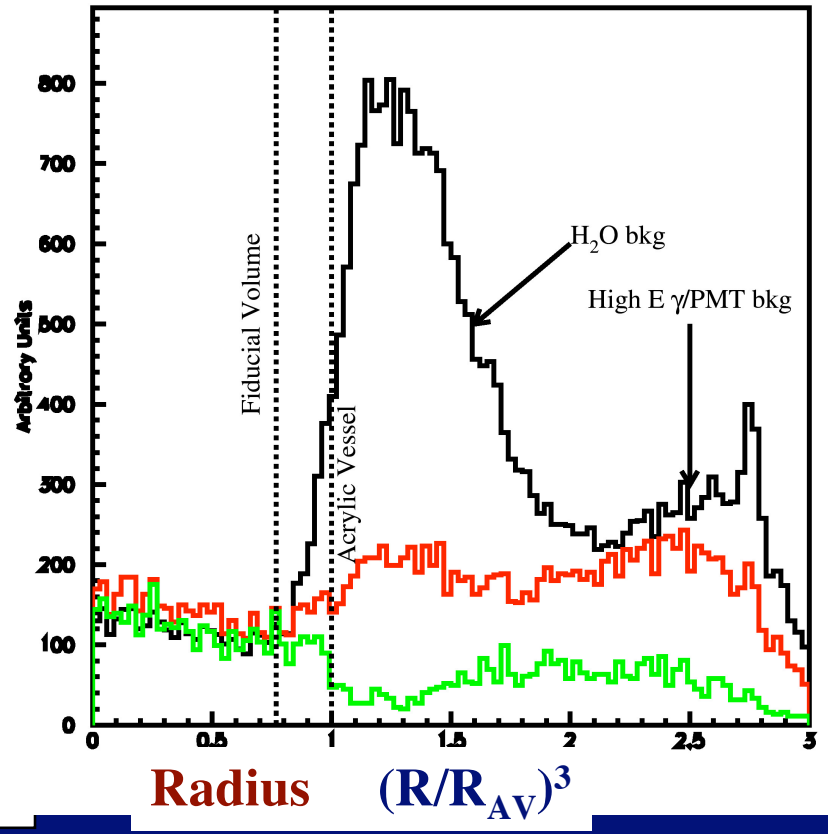
This year: Neutral Current from Pure D_2O

Lower Energy Threshold (below the peak of neutrons)



Thresholds

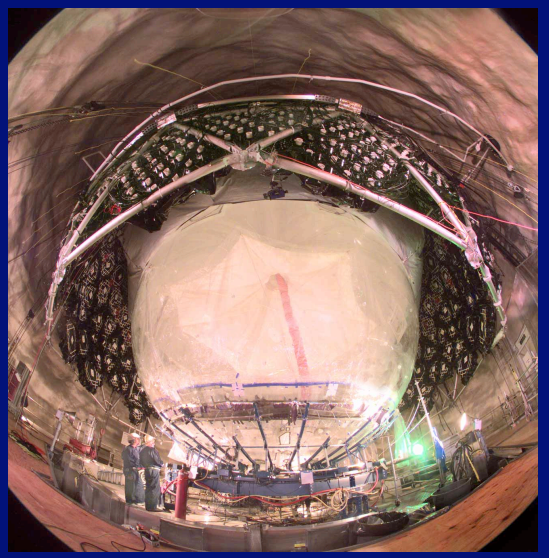
Backgrounds



Neutral Current from D_2O

Characterize Backgrounds

- D_2O backgrounds
- AV Backgrounds
- H_2O Backgrounds
- PMT □□□ backgrounds
- High Energy □'s



Two Types of Backgrounds

- Real Neutrons
  Photodisintegration
- Misidentified Events
  Cerenkov tails of □'s

Understand Neutron Capture & Detection

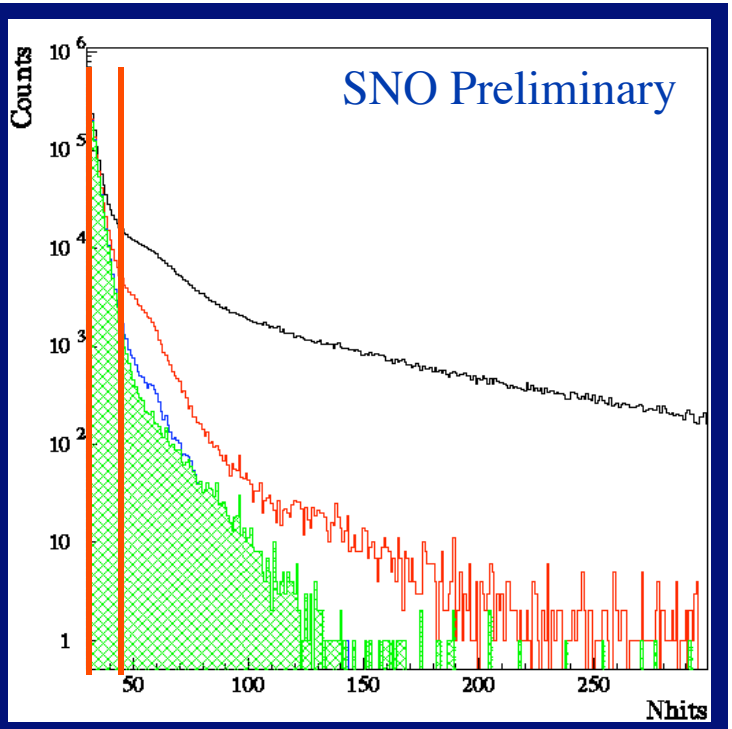
D_2O Photodisintegration Backgrounds

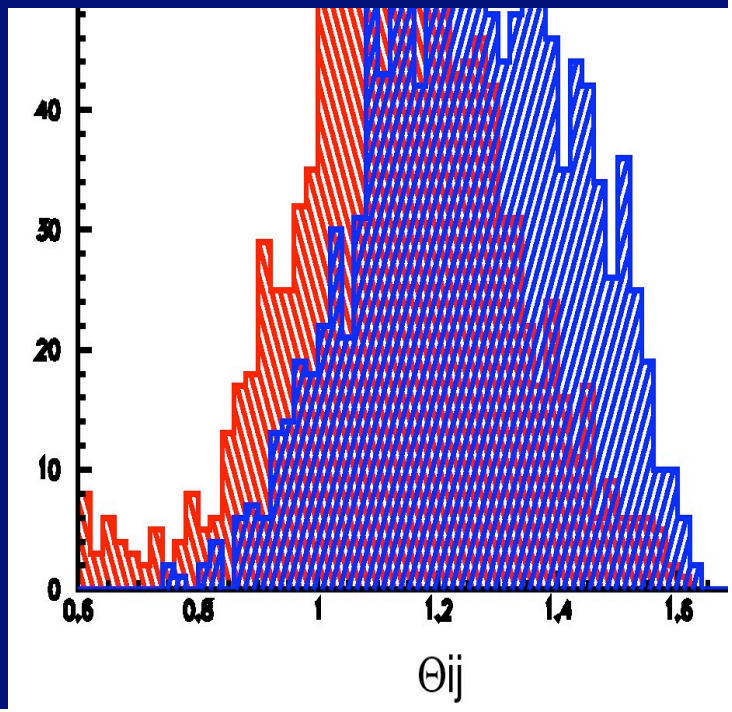
- *Ex situ* Radiochemical Assays of U & Th (offline calibration)
  - Th: MnOx, HTiO
  - U: MnOx, HTiO, Radon Assays
    - ~400 tonnes
    - Proven sensitivity
    - Isotopic selectivity

- *In situ* measurements

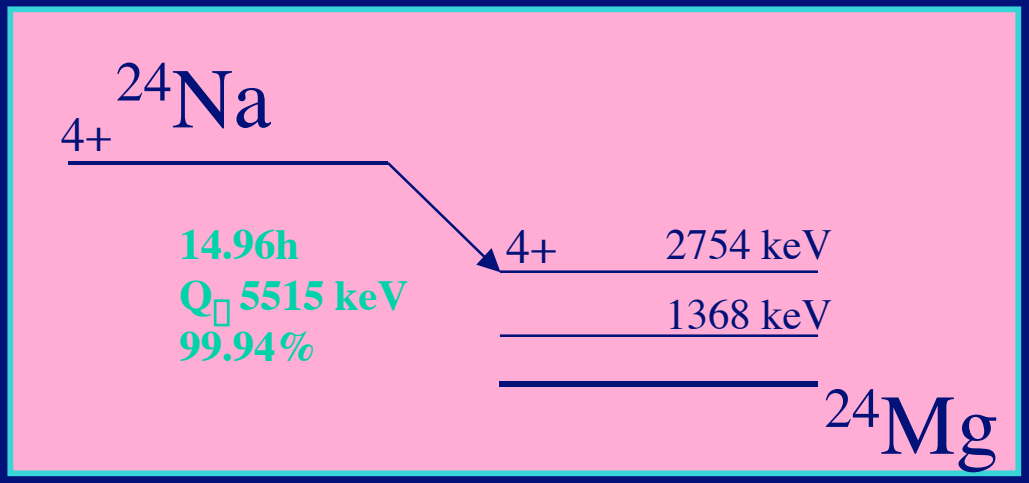
D_2O Backgrounds - *in situ*

- Low Energy Window
- Measures "bottom of the chain" 2.6 and 2.4 MeV γ's
- Limited Fiducial Volume (≤4.5m)
- Integrates over β livetime
- Resolves U and Th by isotropy
  - Bi mostly β - anisotropic cerenkov signals
  - Tl β + γ- isotropic cerenkov signals
- Calibrated with Radon & ^{24}Na



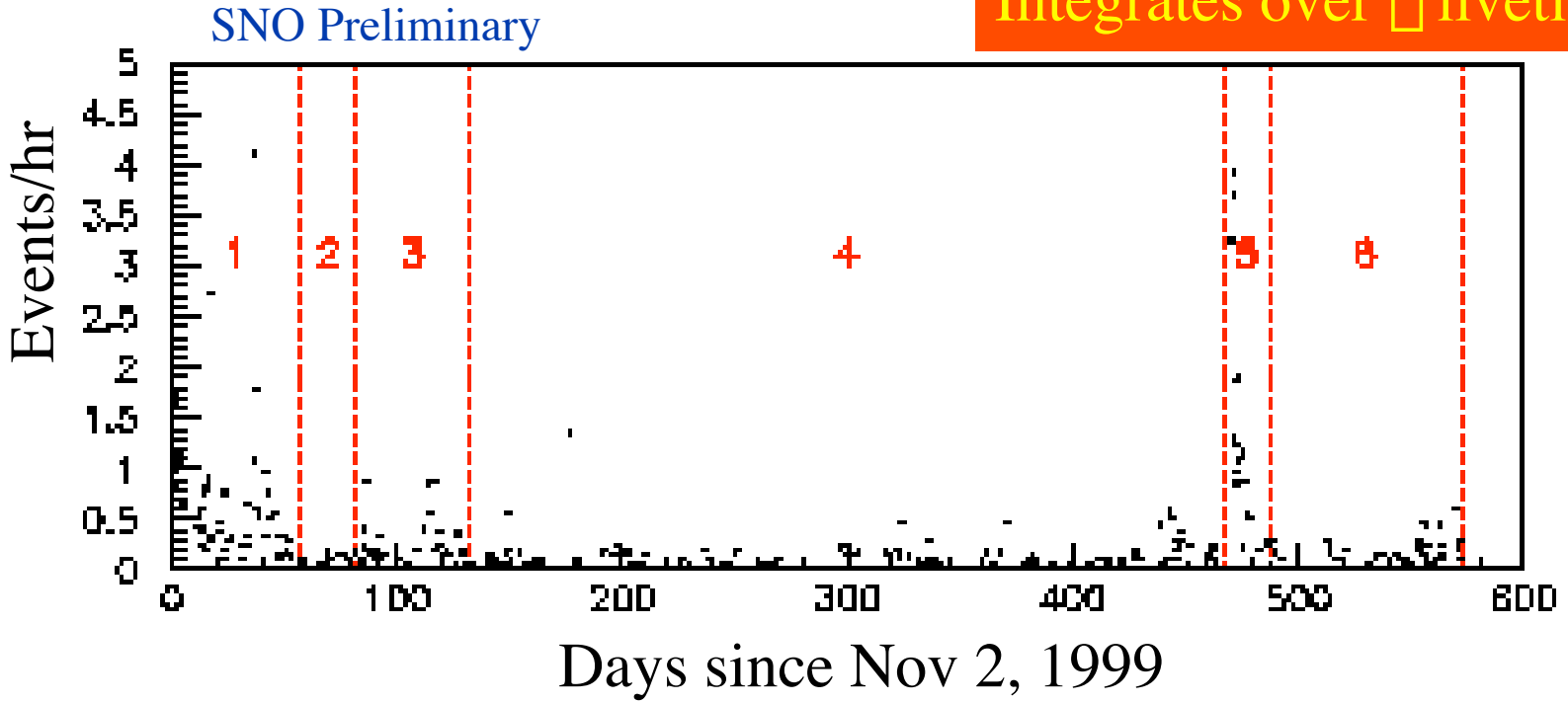


D_2O Backgrounds - *in situ*



Activated salt water in storage tanks & with "hot" neutron source in the AV

Integrates over β livetime



D_2O Backgrounds: U and Th in the D_2O

D_2O Photodisintegration Backgrounds Dominate

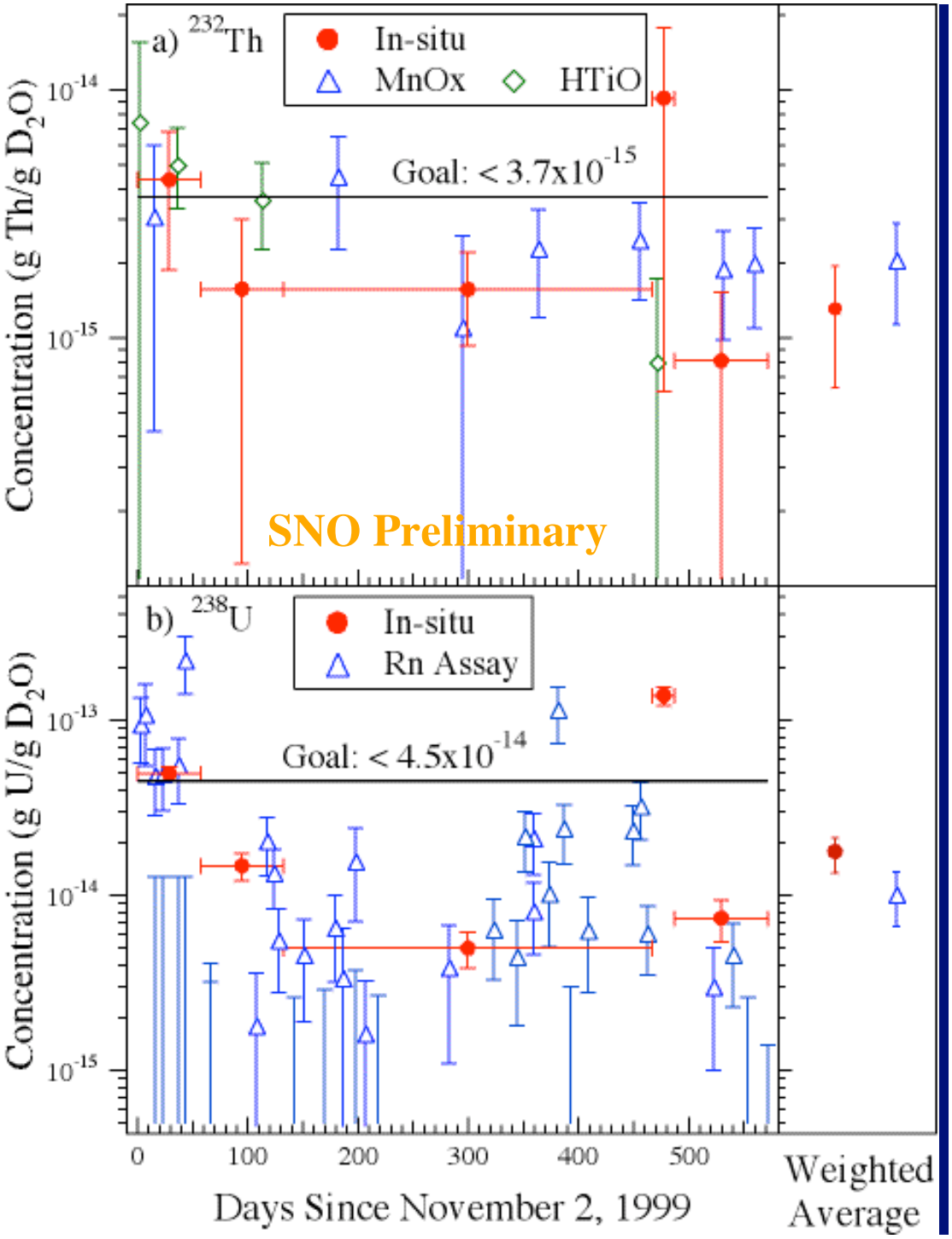
44^{+8}_{-9}

Events in ~310 livedays

D_2O Cerenkov Backgrounds

20^{+13}_{-6}

Events in ~310 livedays



Acrylic Vessel Backgrounds

Original Target was (2 ppt)

60 μg Th or U

Ex situ Bulk Acrylic assayed

$7.5^{+1.7}_{-1.5}$ μg Th, $6.2^{+1.4}_{-1.1}$ μg U

On Surfaces Inner/Outer

0.87±0.17 μg ^{232}Th

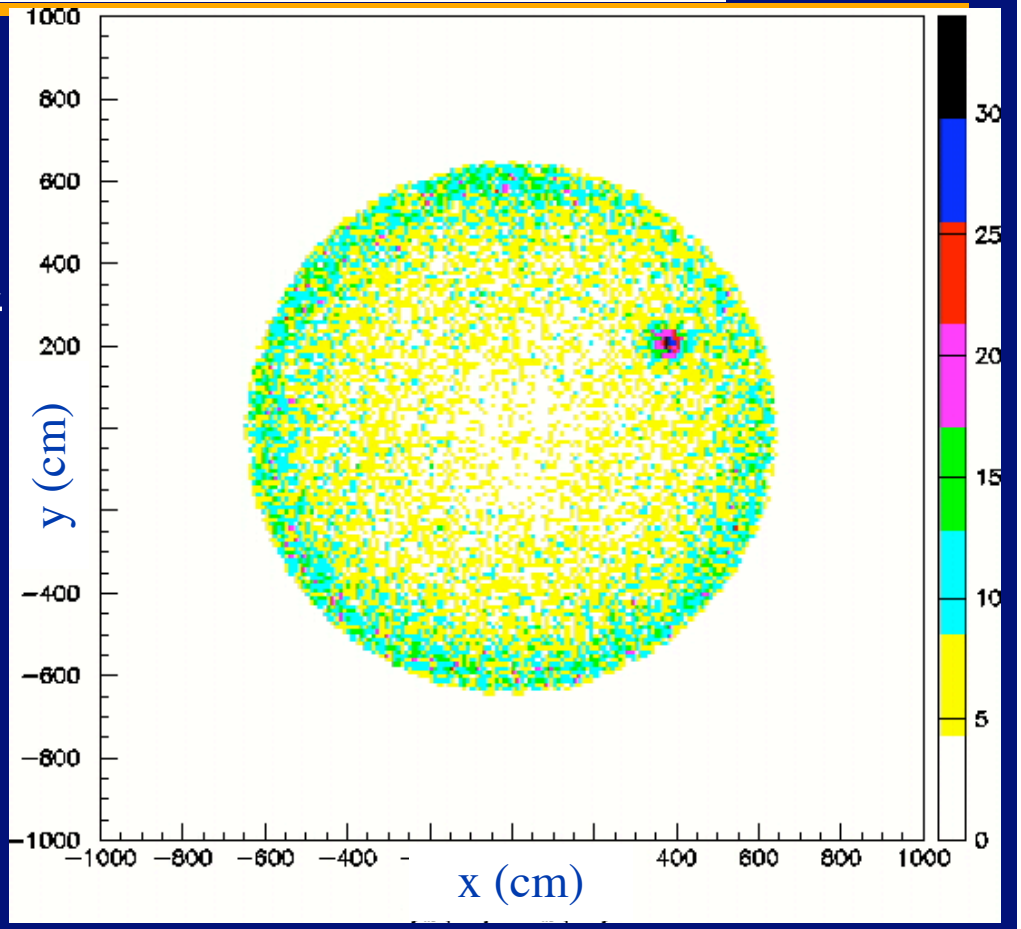
0.96±0.19

0.16±0.04 μg ^{238}U

0.18±0.04

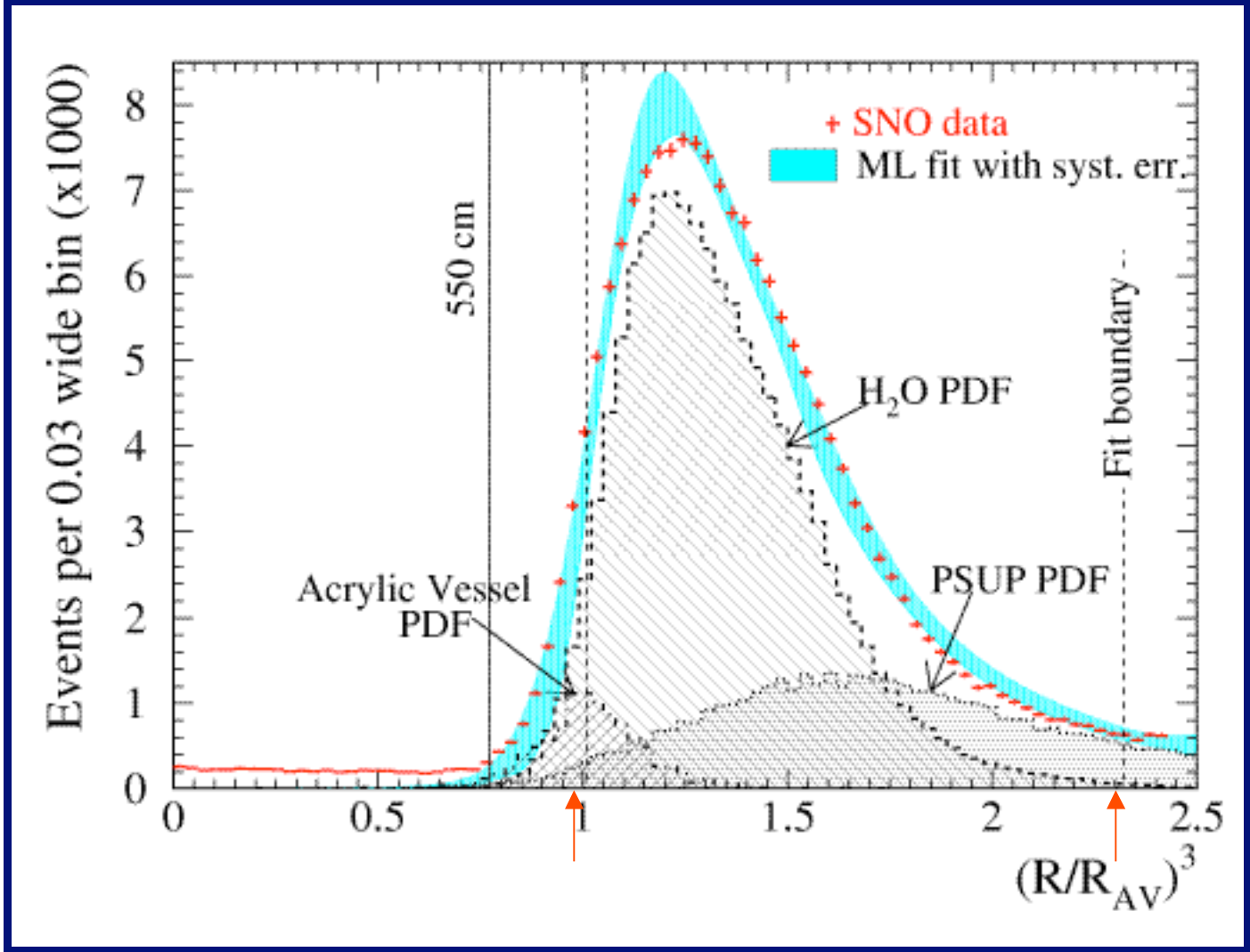
Single spot -

$$= 10 \pm 1(stat.)^{+8.5}_{-3.5}(sys)\,\mu g \;\; 'Th'$$



$15.8^{+6.0}_{-6.8}$ Photodisintegration Events

Modeling of External Cerenkov Backgrounds



Used U and Th encapsulated sources to form PDFs -- fit to data between AV and PMTs

Neutron Detection in Pure D_2O

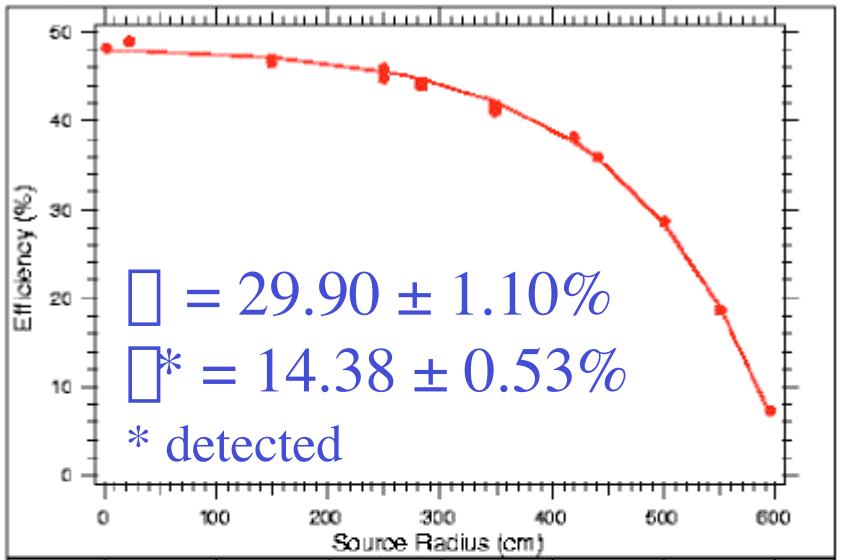
Deploy ^{252}Cf Neutron Source in D_2O analyze signals for 6.25 MeV □ray

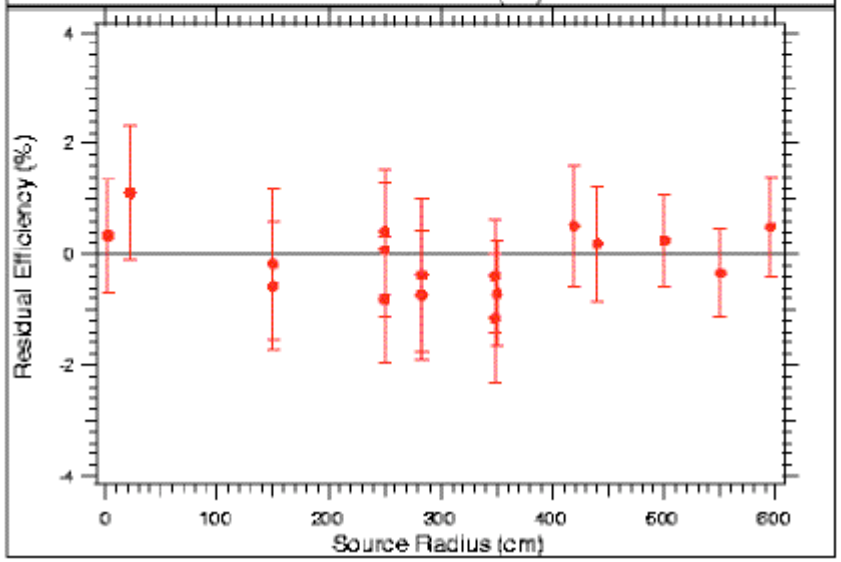
- Energy Response
- Radial Response
- Capture Efficiency

Competition with capture on hydrogen (2.2 MeV) □produces a strong radial variation of d(n,□)

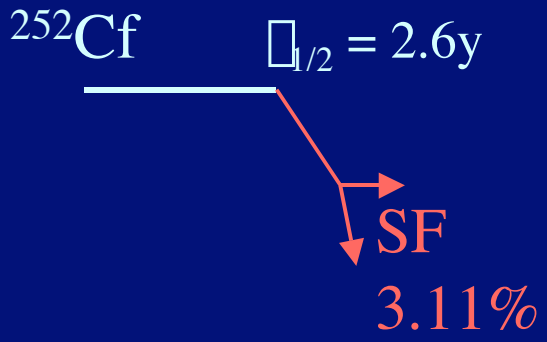
Direct counting

Multiplicity (3.8 n/fission)





Neutron Capture in SNO



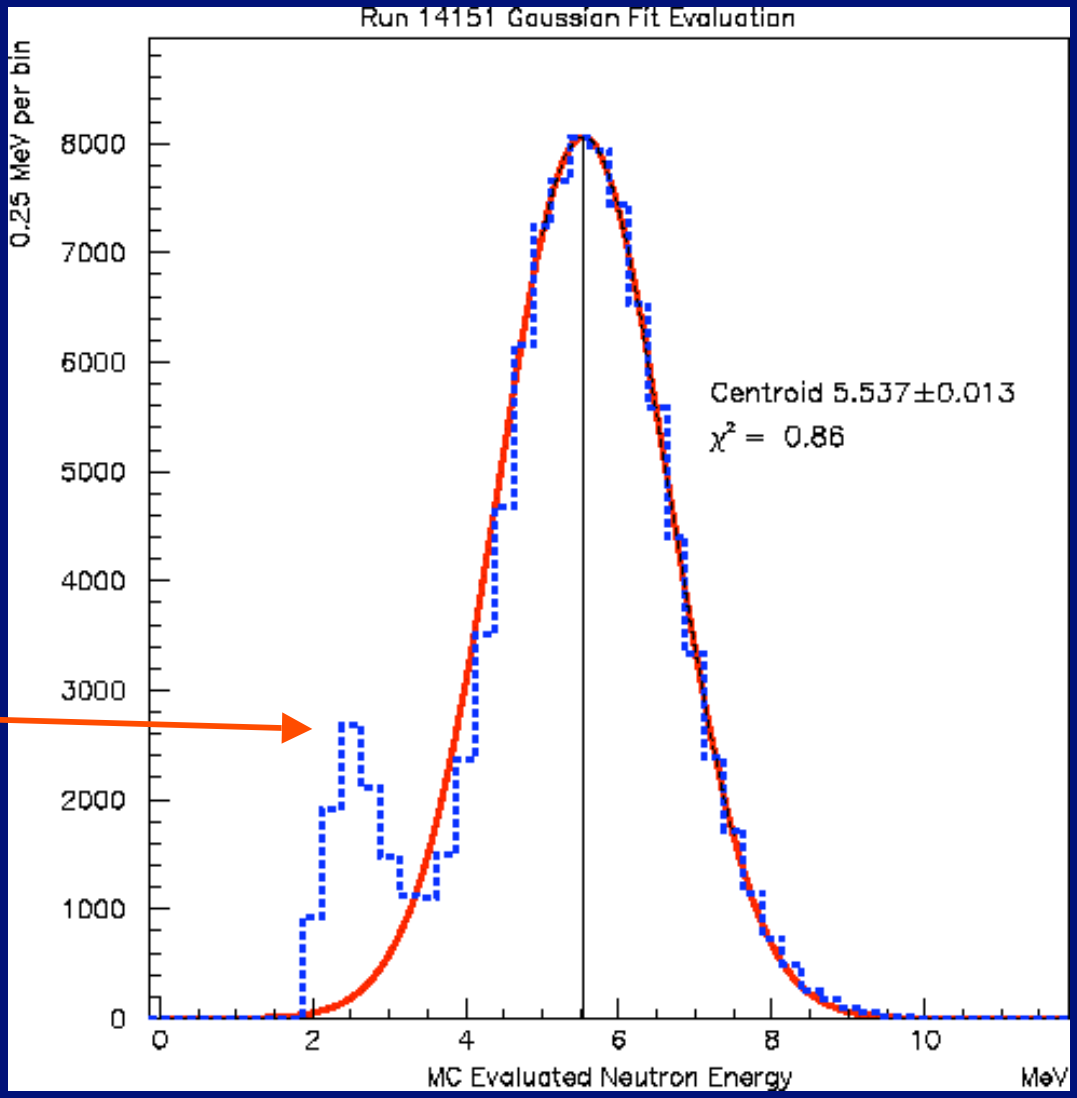
SNO's Neutron Capture in Pure D2O Phase		
	Point Source at Center	Uniform Source
D	49.11%	29.34%
H	29.76%	17.79%
16O	9.20%	5.49%
17O	5.36%	3.20%
18O	0.02%	0.00%
Escape	6.55%	44.15%
Total	100%	100%

Neutron Detection in Pure D_2O

Energy Response
d(n,γ) 6.25 MeV
0.52 mb

$^{16}O(n,\gamma)$ 1087 2184 870 ^{17}O

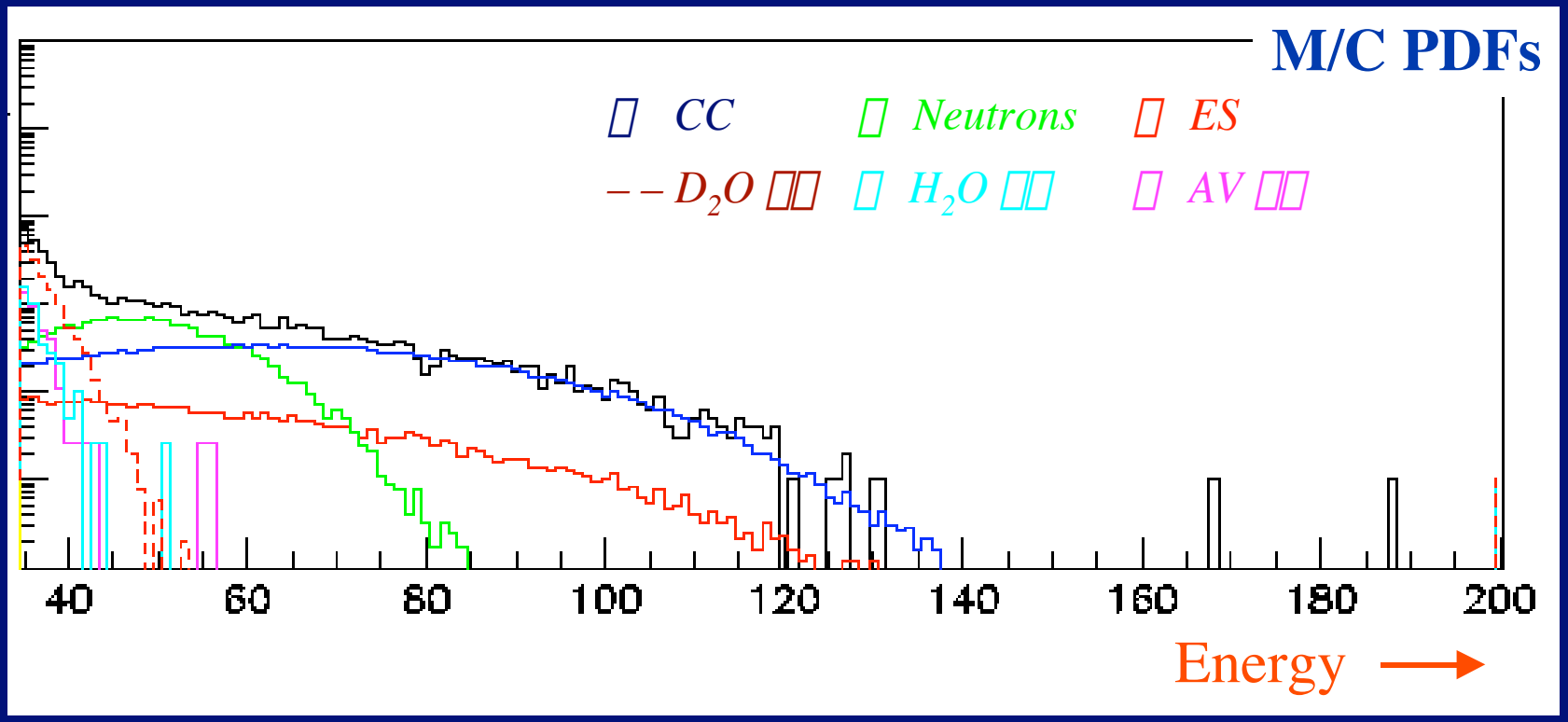
~0.19 mb



SNO's Backgrounds Summation

Neutron and Cherenkov Background Events			
Source	Events	Uncertainty	
D_2O photodisintegration	44	+8	-9
H_2O + AV photodisintegration	27	+8	-8
Atmospheric β's	4	+1	-1
^{238}U Fission	«1		
$^{2}H(\gamma,\beta)pn$	2	+0	-0.2
$^{17}O(\gamma,n)$	«1		
Terrestrial and reactor γ's	1	+3	-1
External Neutrons	«1		
Total Neutron Background	78	+12	-12
D_2O Cherenkov	20	+13	-6
H_2O Cherenkov	3	+4	-3
AV Cherenkov	6	+3	-6
PMT Cherenkov	16	+11	-8
Total Cherenkov	45	+18	-12

D_2O Low E Threshold NC Analysis

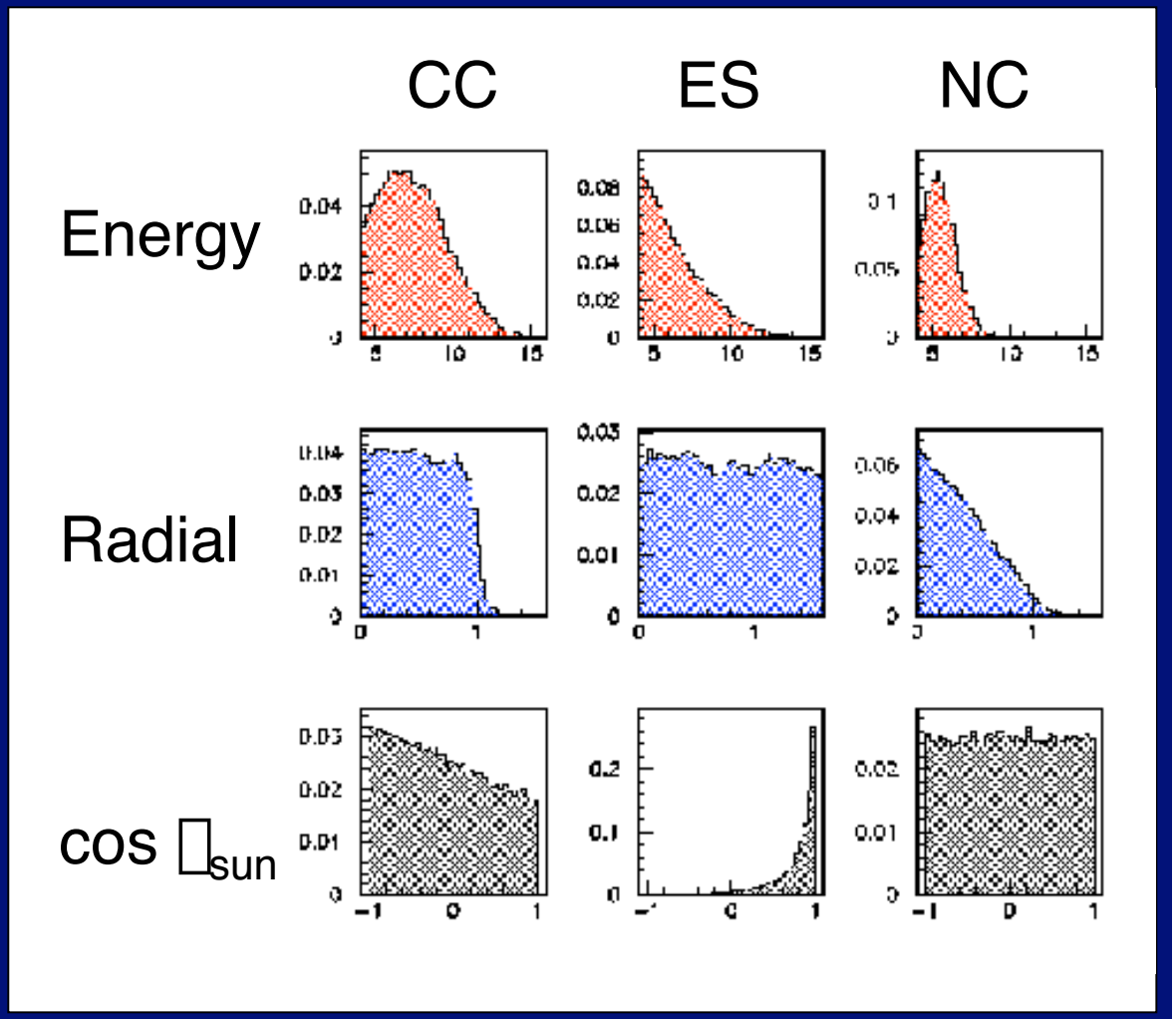


- Photodisintegration Backgrounds Measured
- Cerenkov Tails estimated
- Fit CC, ES and Neutrons PDFs

Physics extraction

Maximum-likelihood analysis in terms of calibrated PDFs & constrained backgrounds

Events	450,188,649
NHIT 100	191,312,560
Anal Thresh	10,088,842
Data Cleaning	7,805,238
High Level Cuts	3,418,439
Fiducial Volume	67,343
E Thresh	3,440
Mu Follower	2,981
Frati Follower	2,928



SNO's NC Analysis - 2002

$$CC = 1967.7^{+61.9}_{-60.9}\ events$$

$$\phi^{SNO}_{CC} = 1.76^{+0.06}_{-0.06}(stat.)^{+0.09}_{-0.09}(syst.)10^{6}\ cm^{-2}\ s^{-1}$$

$$ES = 263.6^{+26.4}_{-25.6}\ events$$

$$\phi^{SNO}_{ES} = 2.39^{+0.24}_{-0.23}(stat.)^{+0.12}_{-0.12}(syst.)10^{6}\ cm^{-2}\ s^{-1}$$

$$NC = 576.5^{+49.5}_{-48.9}\ events$$

$$\phi^{SNO}_{NC} = 5.09^{+0.44}_{-0.43}(stat.)^{+0.46}_{-0.43}(syst.)10^{6}\ cm^{-2}\ s^{-1}$$

$T_{eff} \geq 5$ MeV
$R \leq 550$cm
306.4 livedays
Nov 2, 1999 - May 28, 2001

Assuming ^{8}B Standard Shape
C.E. Ortiz *et al.*, PRL **85**, 2909 (2000)

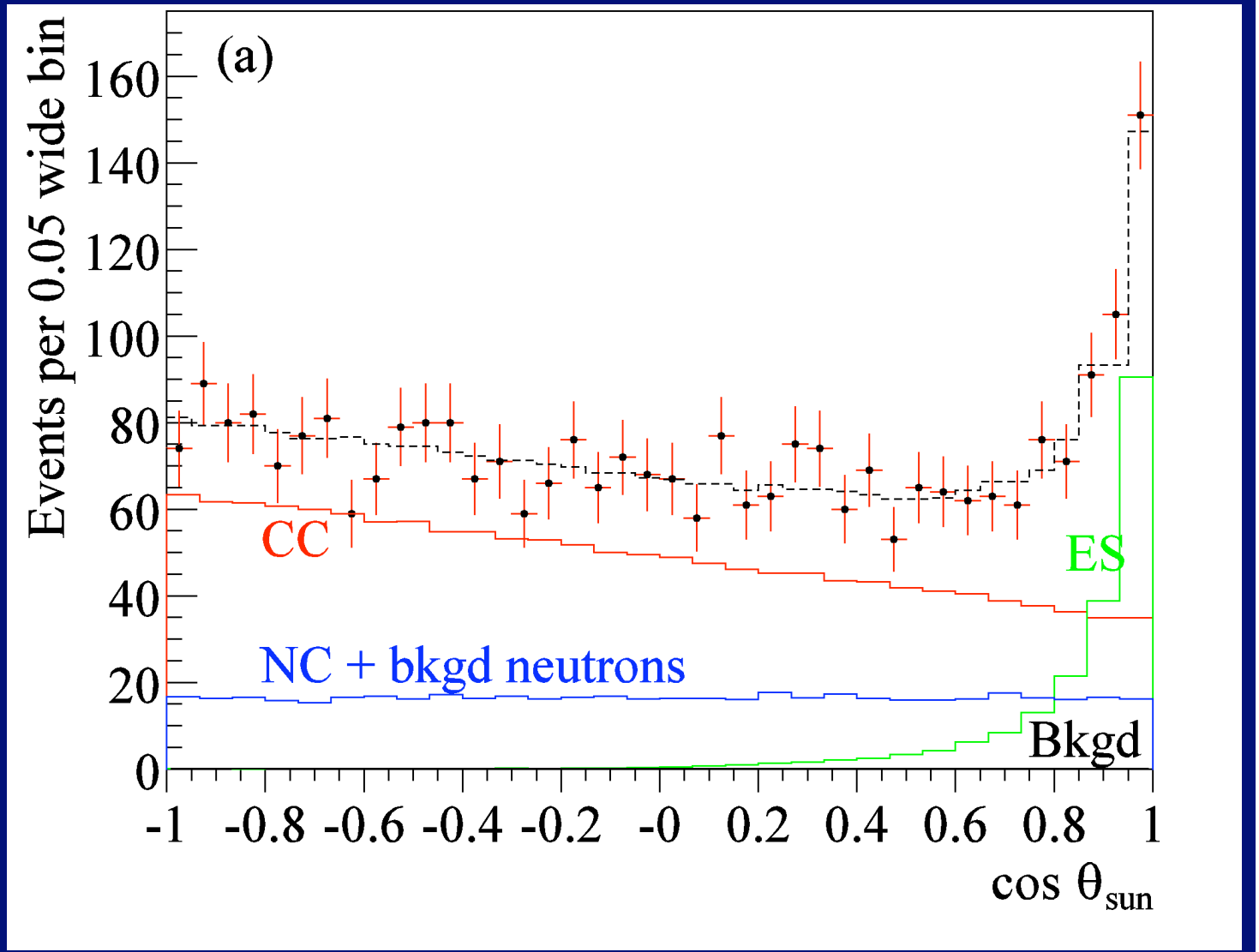
SNO's NC Analysis - 2002

2002	2001
$\phi_{CC}^{SNO} = 1.76^{+0.06}_{-0.06}(stat.)^{+0.09}_{-0.09}(syst.)$ $10^6 cm^{-2} s^{-1}$	$\phi_{CC}^{SNO01} = 1.75^{+0.07}_{-0.07}(stat.)^{+0.12}_{-0.11}(syst.)$ $\pm 0.5(theor.) 10^6 cm^{-2} s^{-1}$
$\phi_{ES}^{SNO} = 2.39^{+0.24}_{-0.23}(stat.)^{+0.12}_{-0.12}(syst.)$ $10^6 cm^{-2} s^{-1}$	$\phi_{ES}^{SNO01} = 2.39^{+0.34}_{-0.34}(stat.)^{+0.16}_{-0.14}(syst.)$ $10^6 cm^{-2} s^{-1}$
	$\phi_{ES}^{S-K} = 2.32^{+0.03}_{-0.03}(stat.)^{+0.08}_{-0.07}(syst.)$ $10^6 cm^{-2} s^{-1}$
$\phi_{NC}^{SNO} = 5.09^{+0.44}_{-0.43}(stat.)^{+0.46}_{-0.43}(syst.)$ $10^6 cm^{-2} s^{-1}$	$\phi_{total}^{SNO01} = 5.44^{+0.99}_{-0.99} 10^6 cm^{-2} s^{-1}$

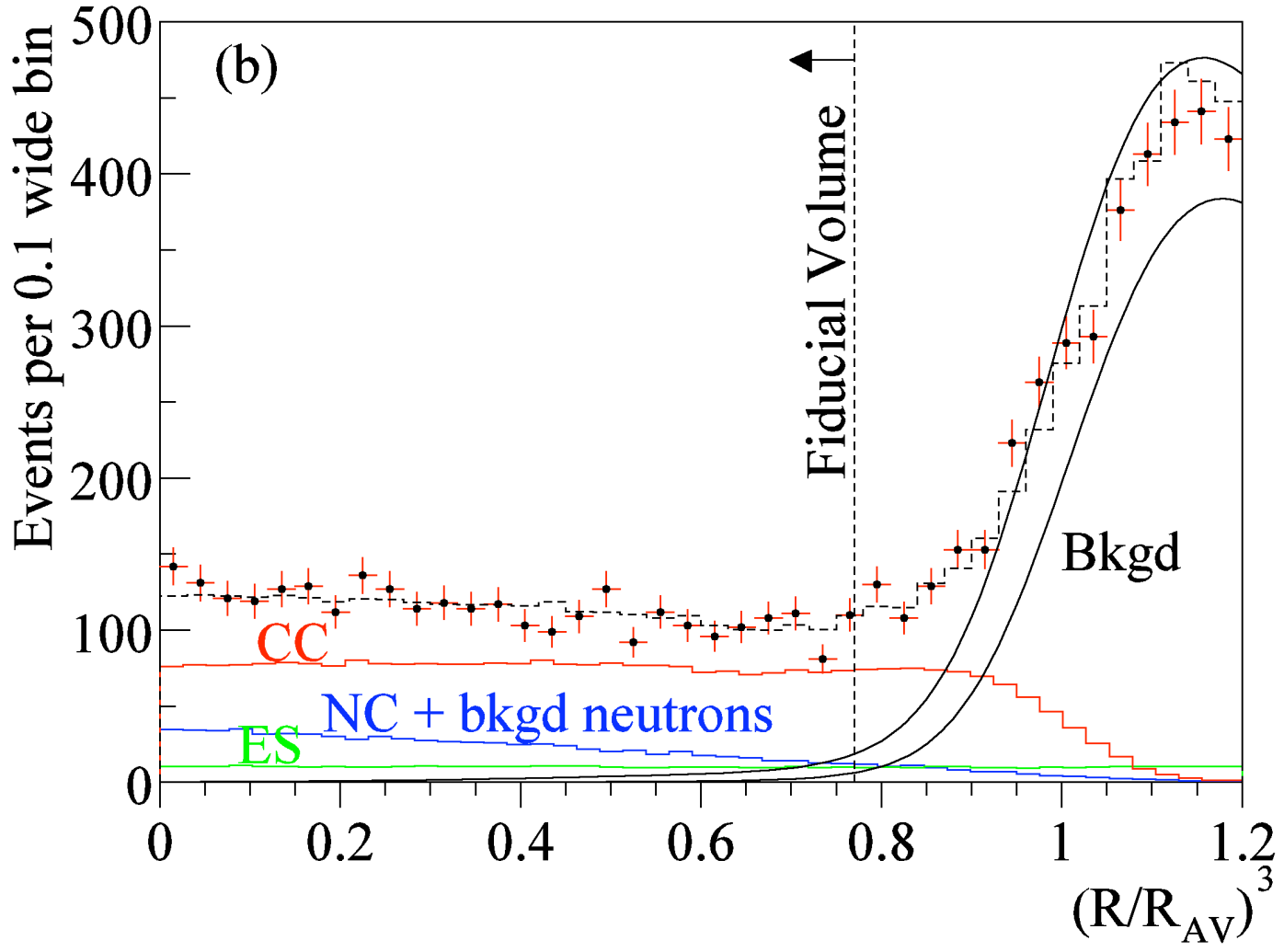
Angle to the Sun

$R \leq 550$ cm

$T_{eff} \geq 5$ MeV

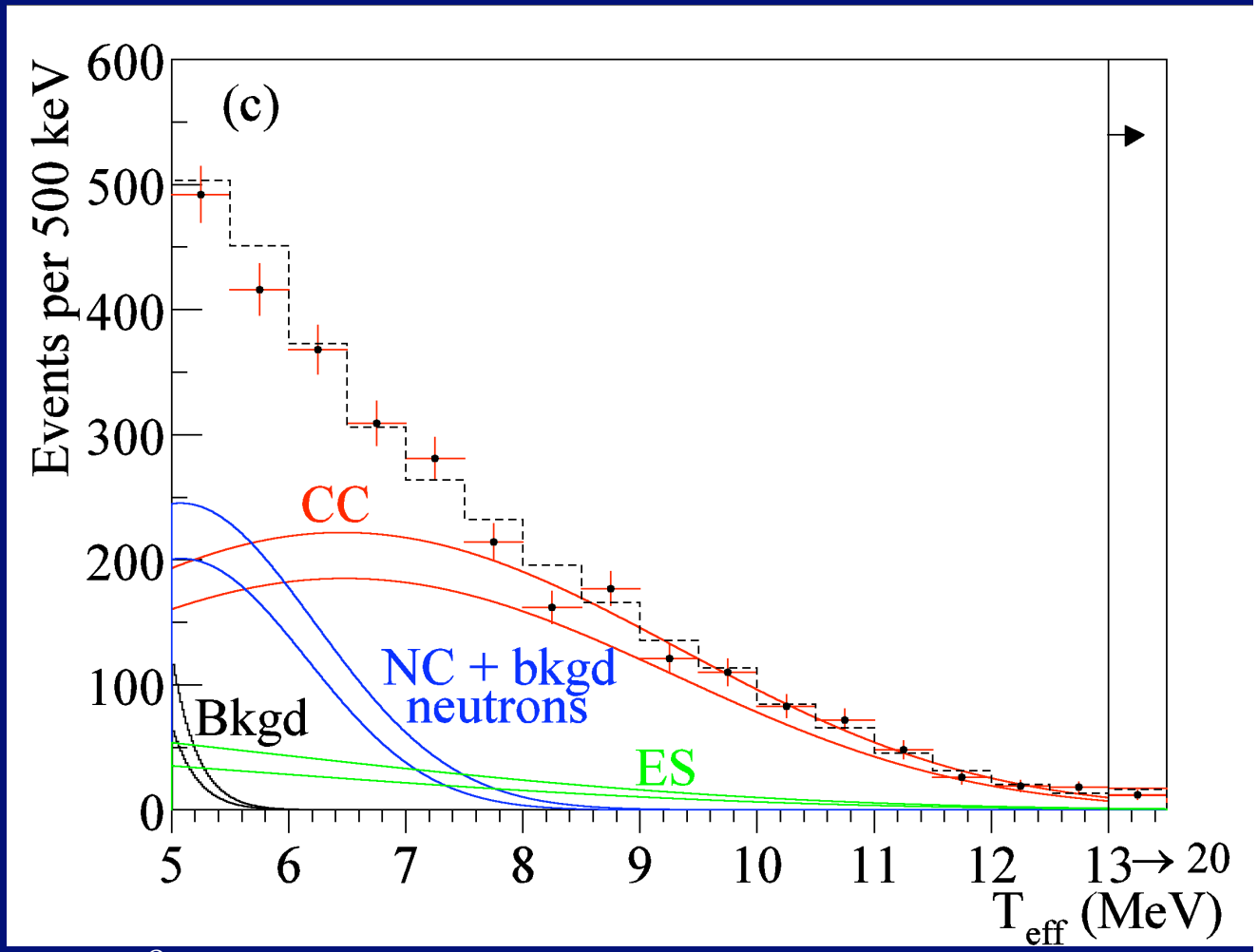


Radial Distribution



Backgrounds independently fixed

Kinetic Energy Distributions



±1 □ errors shown

^{8}B shape constraint invoked

Change of Variables - ϕ_e & $\phi_{\mu\tau}$

$$\phi_{CC} = \phi_e$$

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

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

$$\phi = \frac{1}{6.48}$$

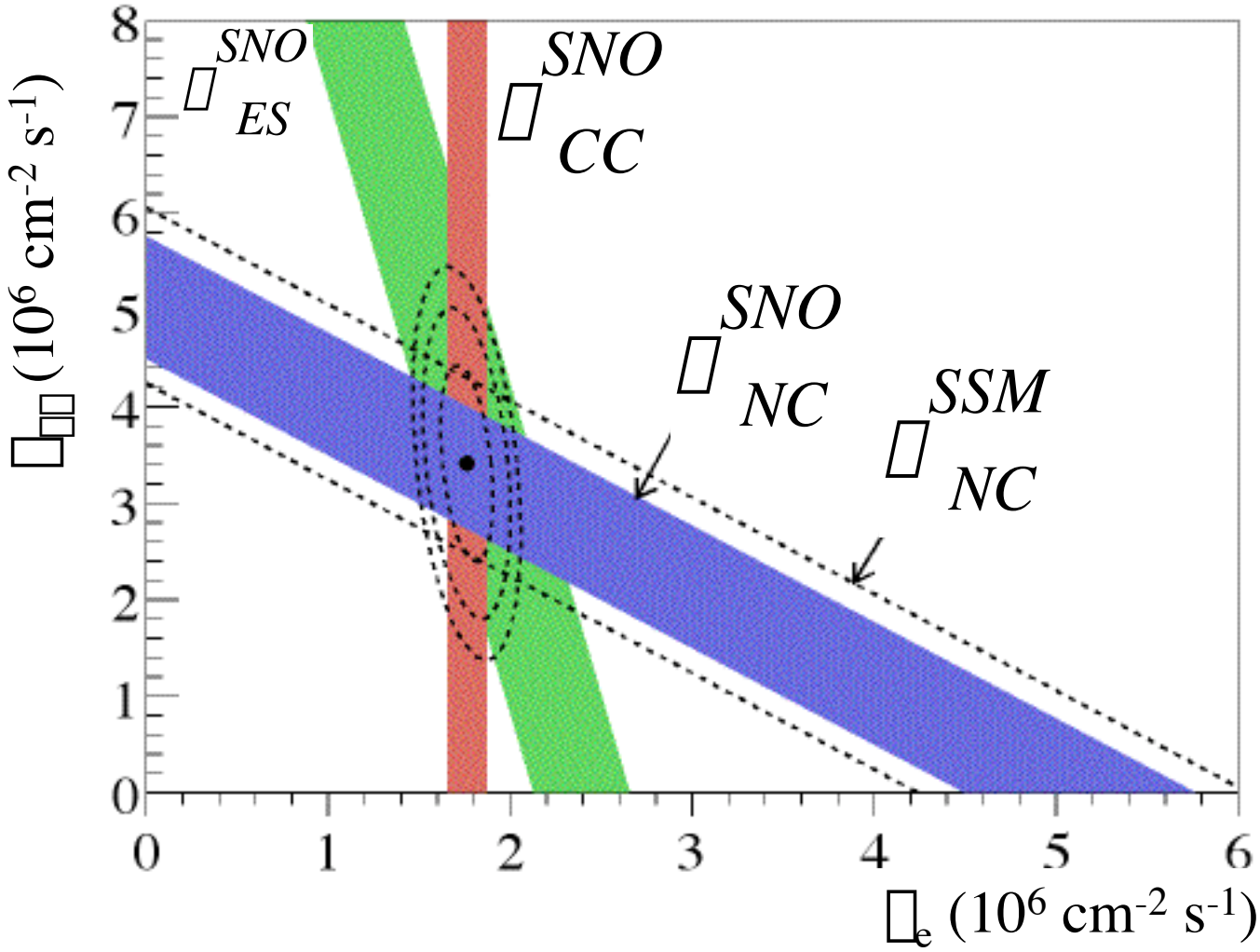
$$\phi_e = 1.76^{+0.05}_{-0.05}(stat.)^{+0.09}_{-0.09}(syst.) x 10^6 \, cm^{-2} s^{-1}$$

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

Can also just compare
CC: $1.76 \pm 0.06 \pm 0.09$ 10^6 cm^{-2} s^{-1}
NC: $5.09 \pm .0.44 \pm .046$ 10^6 cm^{-2} s^{-1}

5.3 σ Appearance

Neutrino Appearance Experiment!



SSM: BPB Astrophy J **555**, 990 2001

Using Super-K ES: 5.3 ->5.5

Systematic Uncertainties on Fluxes

Source	CC Uncertainty (%)	NC Uncertainty (%)	□□□ Uncertainty (%)
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
Energy Non-linearity ¶	±0.1	±0.4	±0.6
Vertex Resolution ¶	±0.0	±0.1	±0.2
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 p-d ¶	±0.0	-1.5, +1.6	-2.0, +2.2
External Source p-d ¶	±0.1	-1.0, +1.0	±1.4
D_2O Cherenkov ¶	-0.1, +0.2	-2.6, +1.2	-3.7, +1.7
H_2O Cherenkov	±0.0	-0.2, +0.4	-0.2, +0.6
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
Cut Acceptance	-0.2, +0.4	-0.2, +0.4	-0.2, +0.4
Experimental Uncertainty	-5.2, +5.2	-8.5, +9.1	-13.2, +14.1
Cross Section §	±1.8	±1.4	±1.2

¶ CC NC anti-correlation

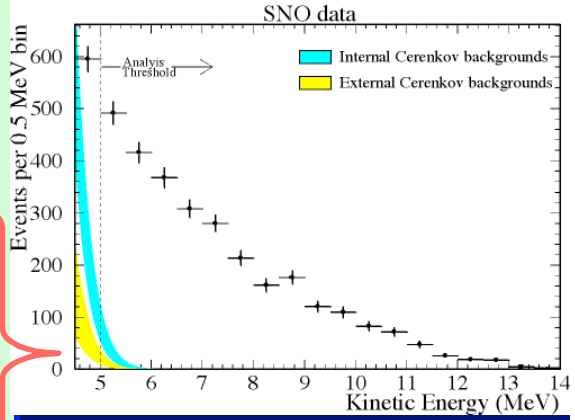
§ gA uncertainty -0.60%

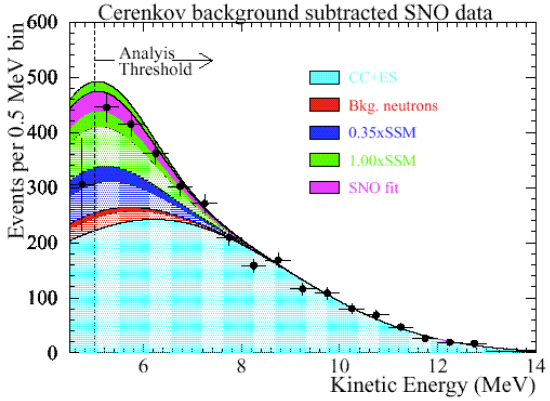
NSGK and BCK differences -0.60%

Radiative corrections uncertainties 1% CC 0.5% NC

Theoretical Cross section Uncertainties 1%

Neglect of real photons 0.7% CC





Model Independent NC Analysis

Relax ^{8}B Shape Constraint:

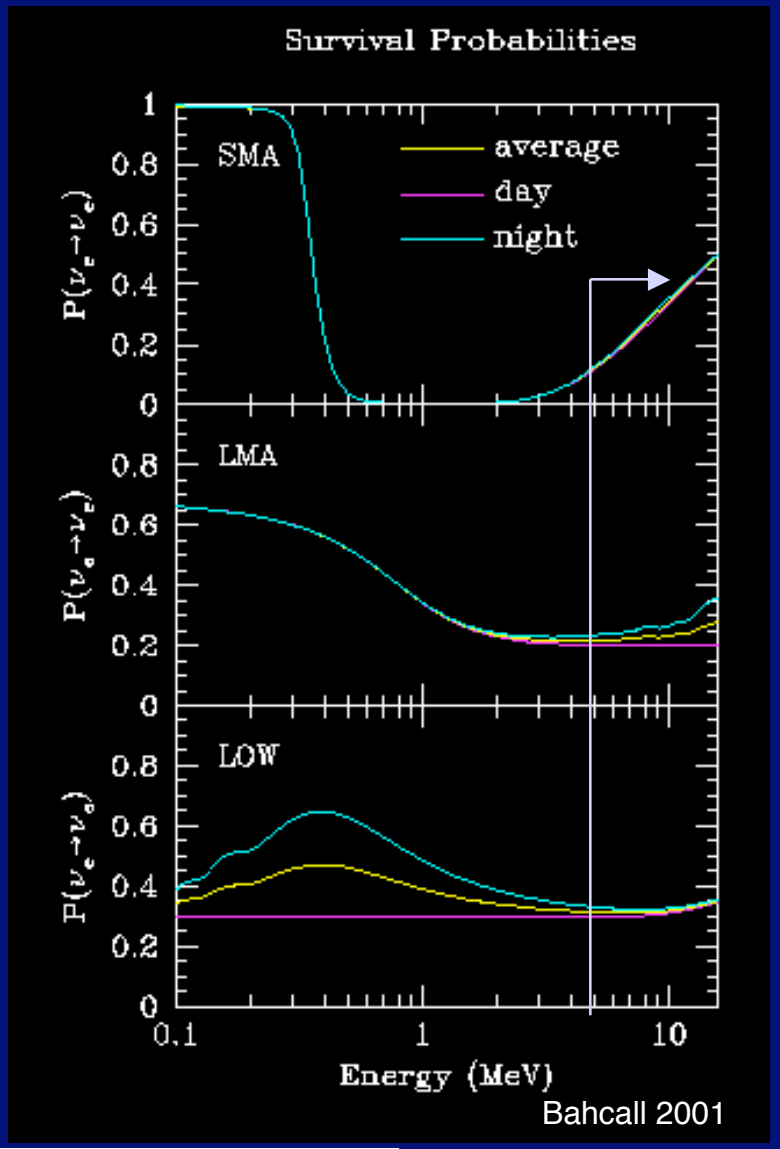
Fit only with $(R/R_{AV})^3$ and $\cos(\theta_{sun})$

$$\phi_{SNO}^{NC} = 6.42^{+1.57}_{-1.57}(stat.)^{+0.55}_{-0.58}(syst.) \times 10^{6}\, cm^{-2} s^{-1}$$

Day Night Analysis 2002

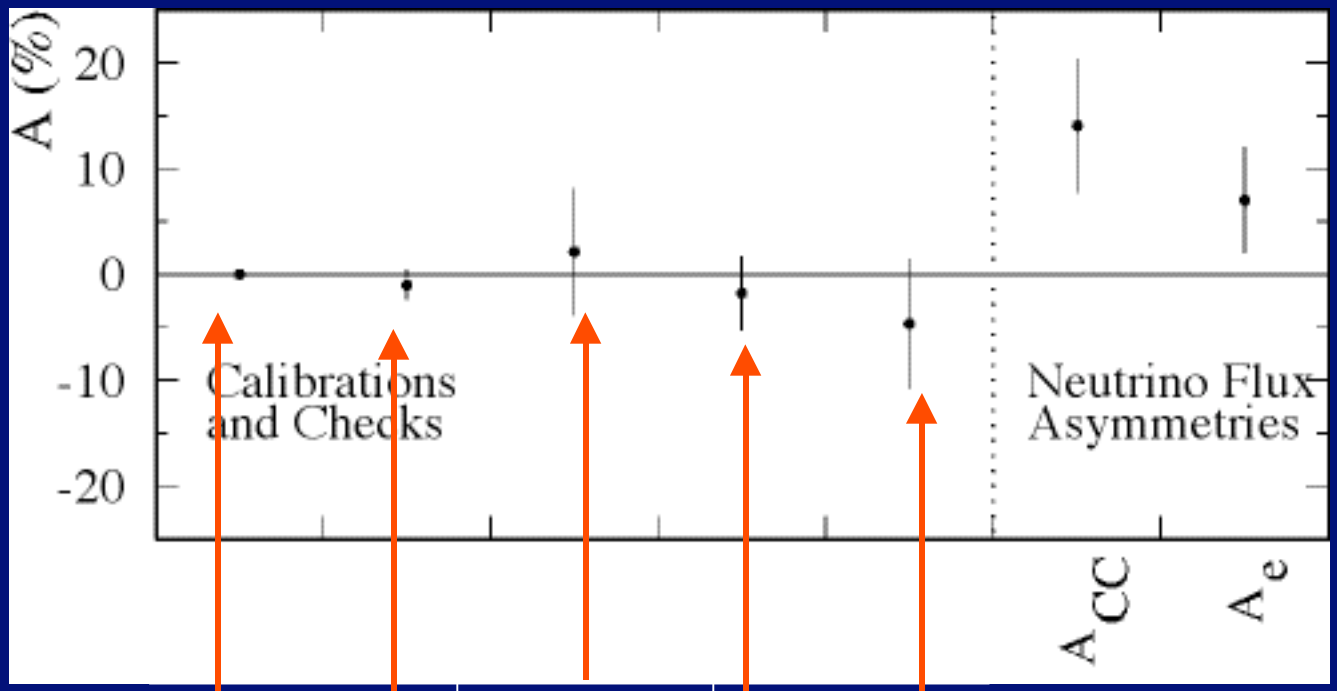
$$A = 2\frac{\Phi_N - \Phi_D}{\Phi_N + \Phi_D}$$

- Statistical Test with Blind data set: ~50% unanalyzed until cuts were frozen



Bahcall 2001

Day-Night Spectra Checks & Asymmetries



5 hz pulser

muons in SNO

muon generated neutrons

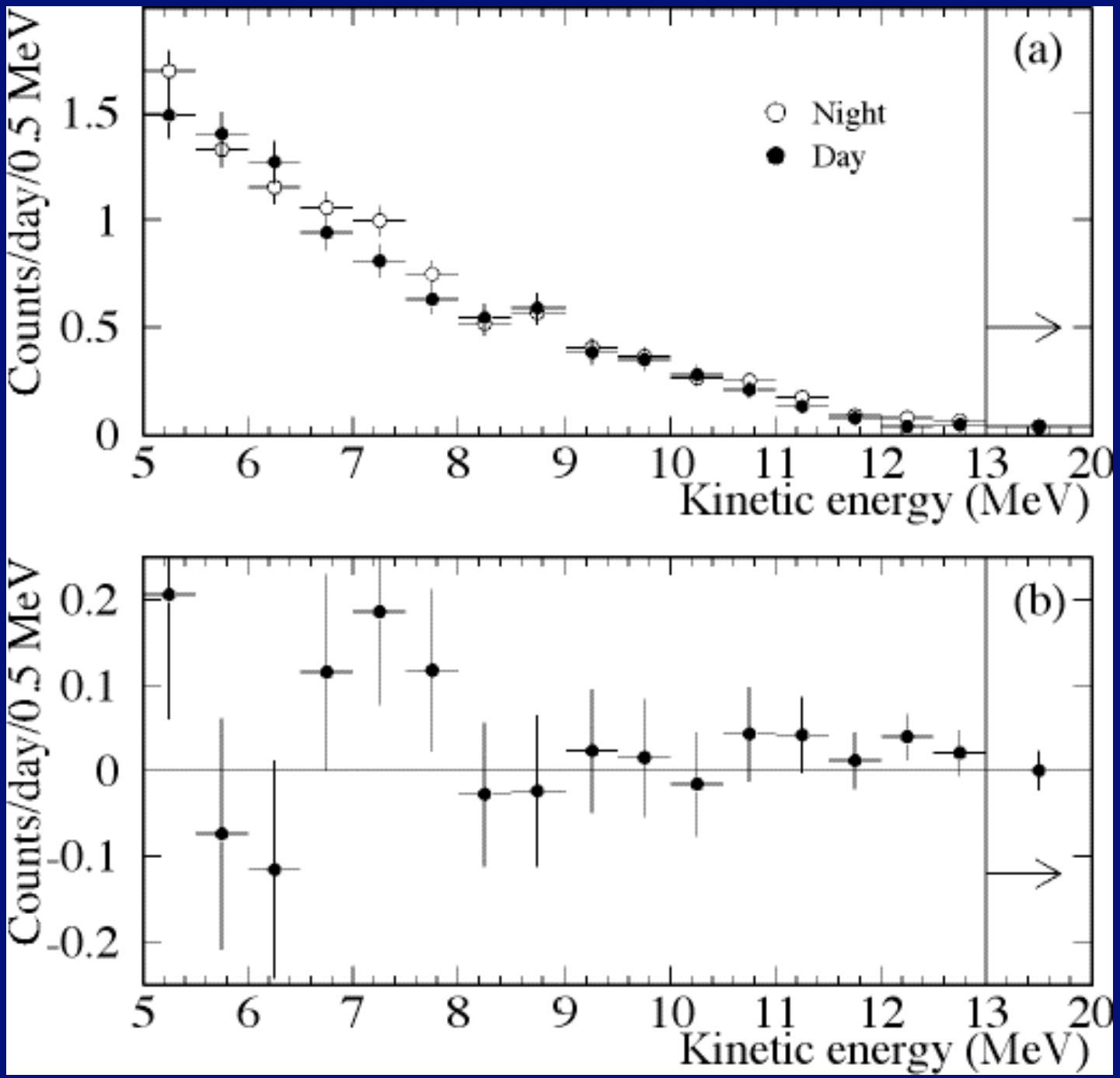
AV Low Energy hot spot

East/West Divison

$A_{CC} = +14.0 \pm 6.3 \pm 1.5\%$

$A_e = +7.0 \pm 4.9 \pm 1.3\%$

$A_{tot} \equiv 0.0$



Day/Night Energy Spectra

Night/Day Energy Difference Spectra

Day Night Signals

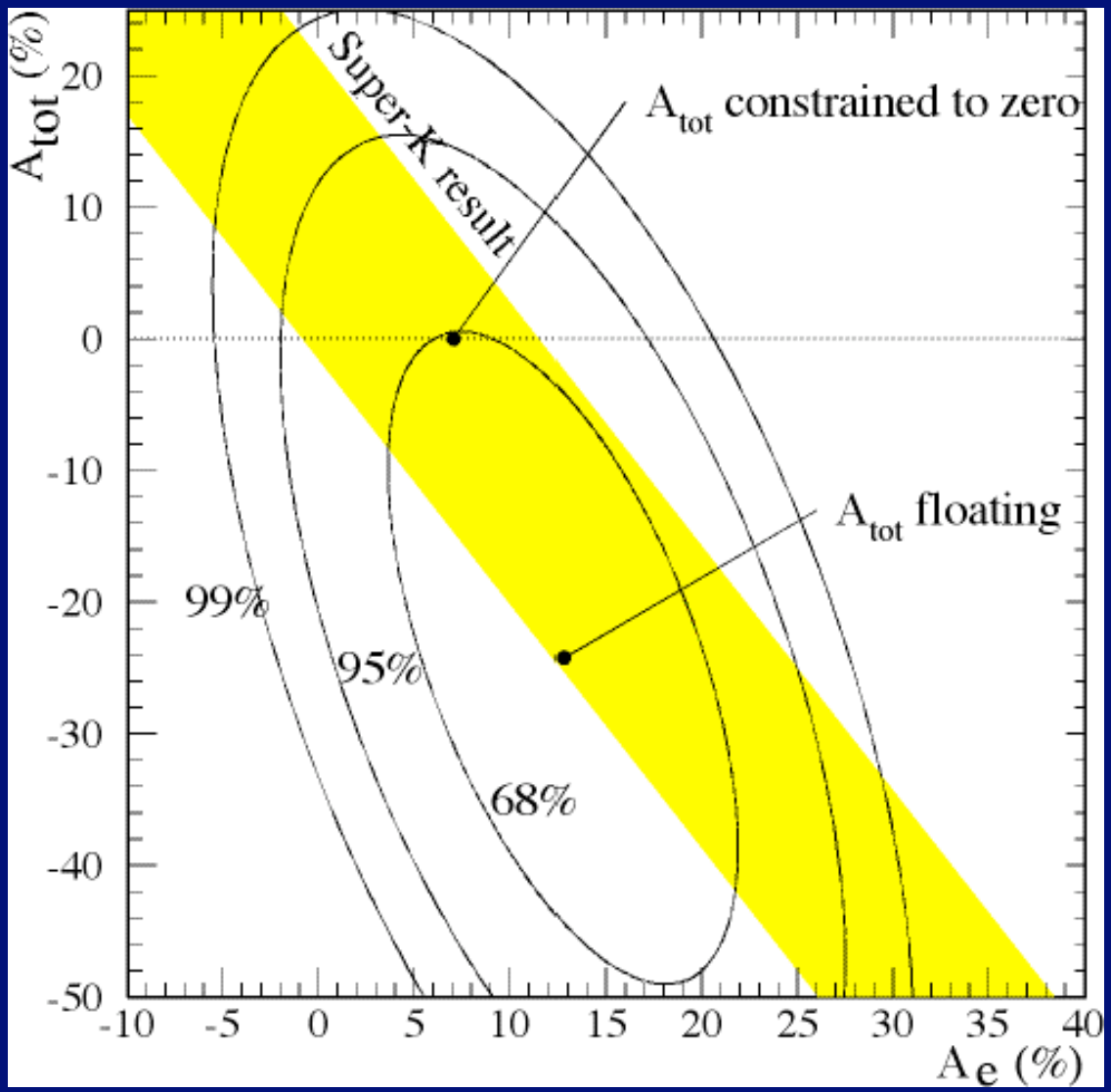
Day/Night Signals							
	Set 1 1e+6/cm2/s		Set 2 1e+6/cm2/s		Combine 1e-16/cm2/s		
Signal	□D	□N	□D	□N	□D	□N	A%
CC	1.53±0.12	1.95±0.10	1.69±0.12	1.77±0.11	1.62±0.08±0.08	1.87±0.07±0.10	+14.0±6.3±1.5
ES	2.91±0.52	1.59±0.38	2.35±0.51	2.88±0.47	2.64±0.37±0.12	2.22±0.30±0.12	-17.4±19.5±2.4
NC	7.09±0.97	3.95±0.75	4.56±0.89	5.33±0.84	5.69±0.66±0.44	4.63±0.57±0.44	-20.4±16.9±2.5

Asymmetry Constraints	
Constraint	Asymmetry
no additional constraints	A_{CC}=14.0±6.3±1.5 A_{NC}=-20.4±16.9±2.5
□ES=(1-□)□e +□□tot	Ae=12.8±6.2±1.5 Atot=-24.2±16.1±2.5 correlation -0.602
□ES=(1-□)□e +□□tot Atot=0	Ae=7.0±4.9±1.3
□ES=(1-□)□e +□□tot Atot=0 A_{ES}(SK)=3.3%±2.2±1.3%	Ae(SK)=5.3±3.7±2.0 SK A_{ES} SNO total ^{8}B

Day Night Signals

Day/Night Systematics Systematic	□ACC %	□AES %	□ANC %
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+H_2O □□□backgrounds	0.00	0.60	0.20
D_2O □□□, 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

Comparison to SuperK



With $A_{tot} = 0$

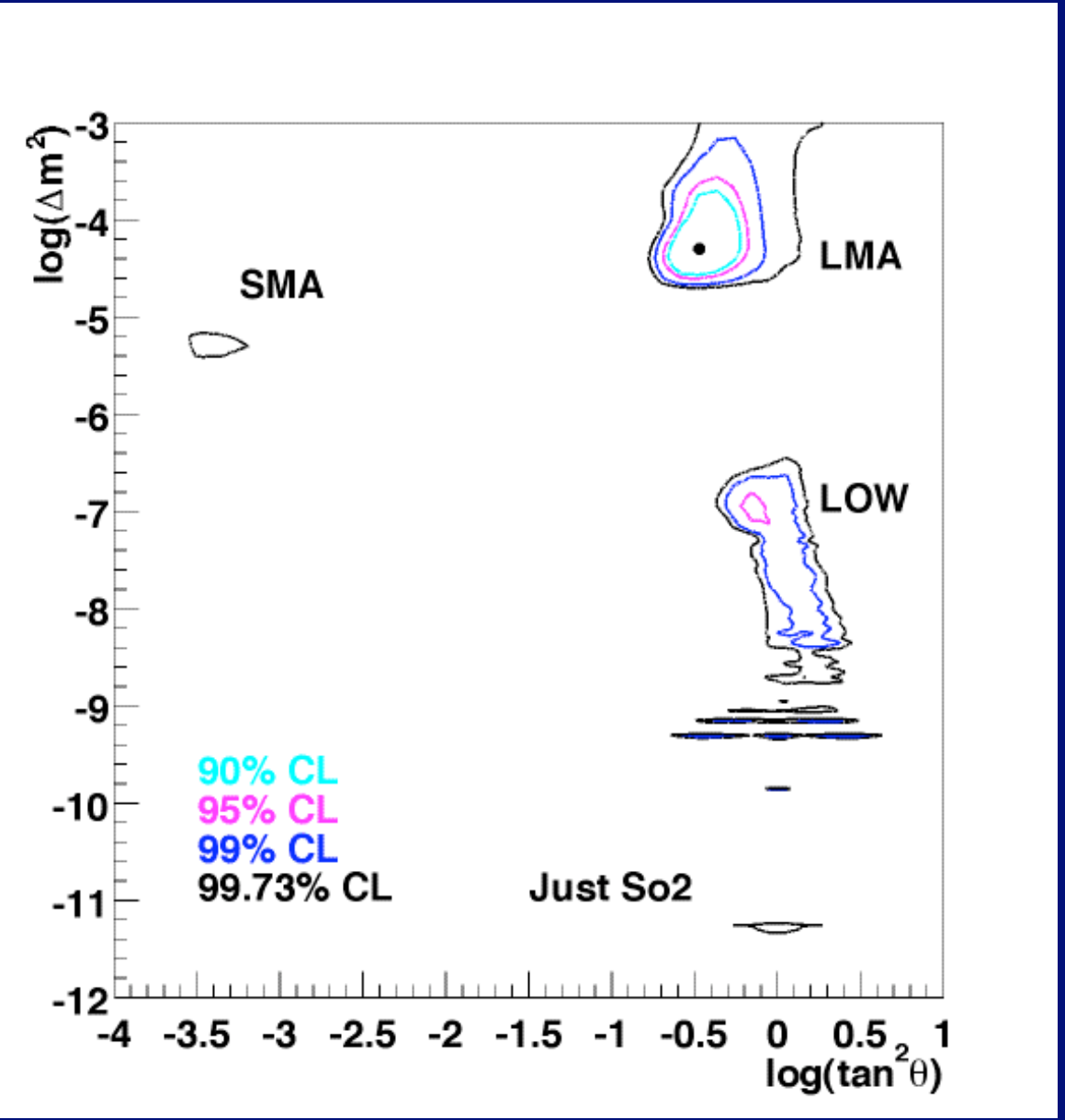
$A_e(SNO) = 7.0 \pm 4.9 \pm 1.3$

$A_e(SK) = 5.3 \pm 3.7 \pm 2.0$

MSW interpretation after SNO's CC Measurement

SNO CC
Super-K flux & day/night
Ga
Cl

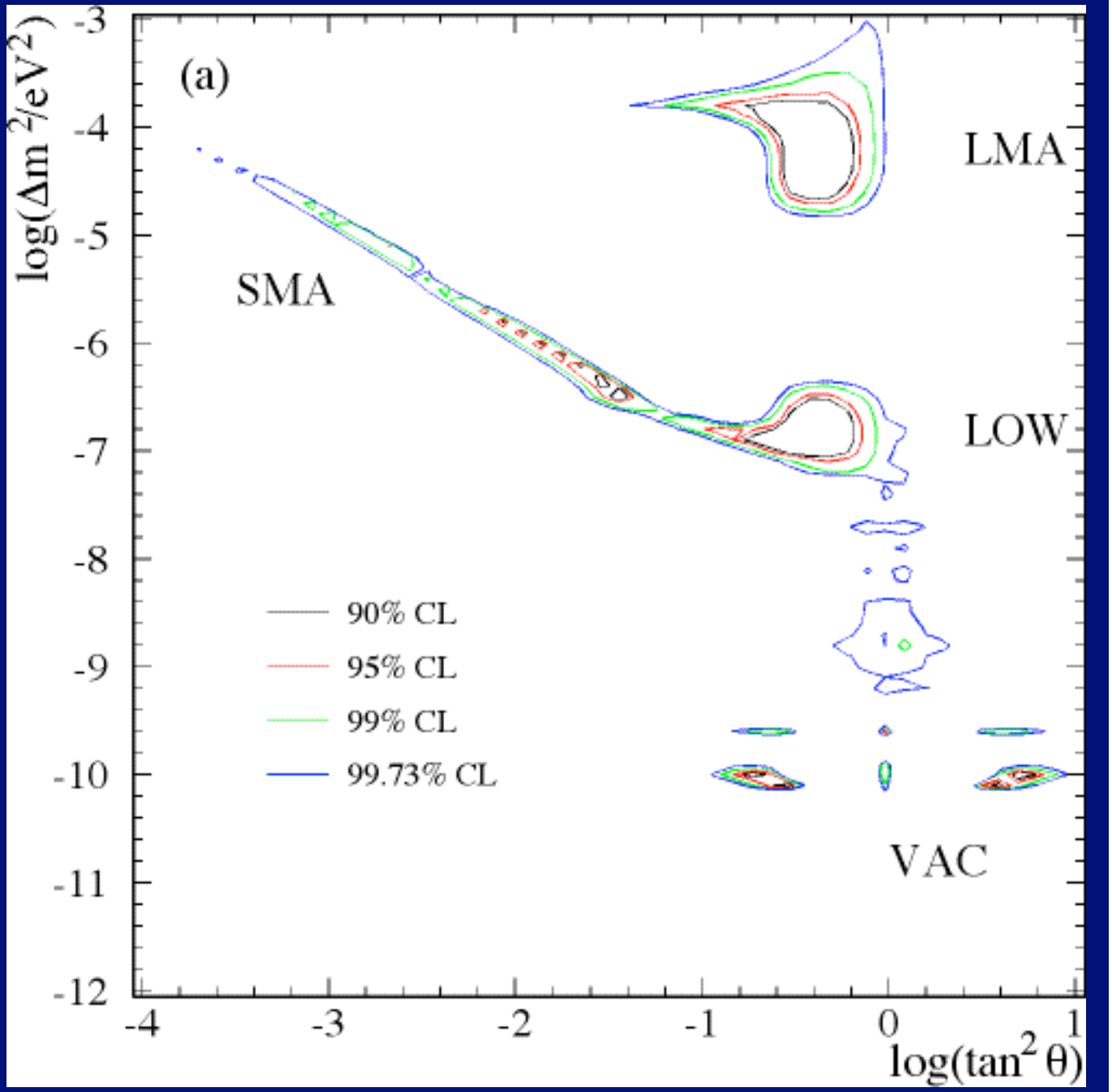
LMA, LOW favored
SMA, others disfavored
or ruled out



Physics Interpretation

SNO
Day/Night
Energy Spectra:

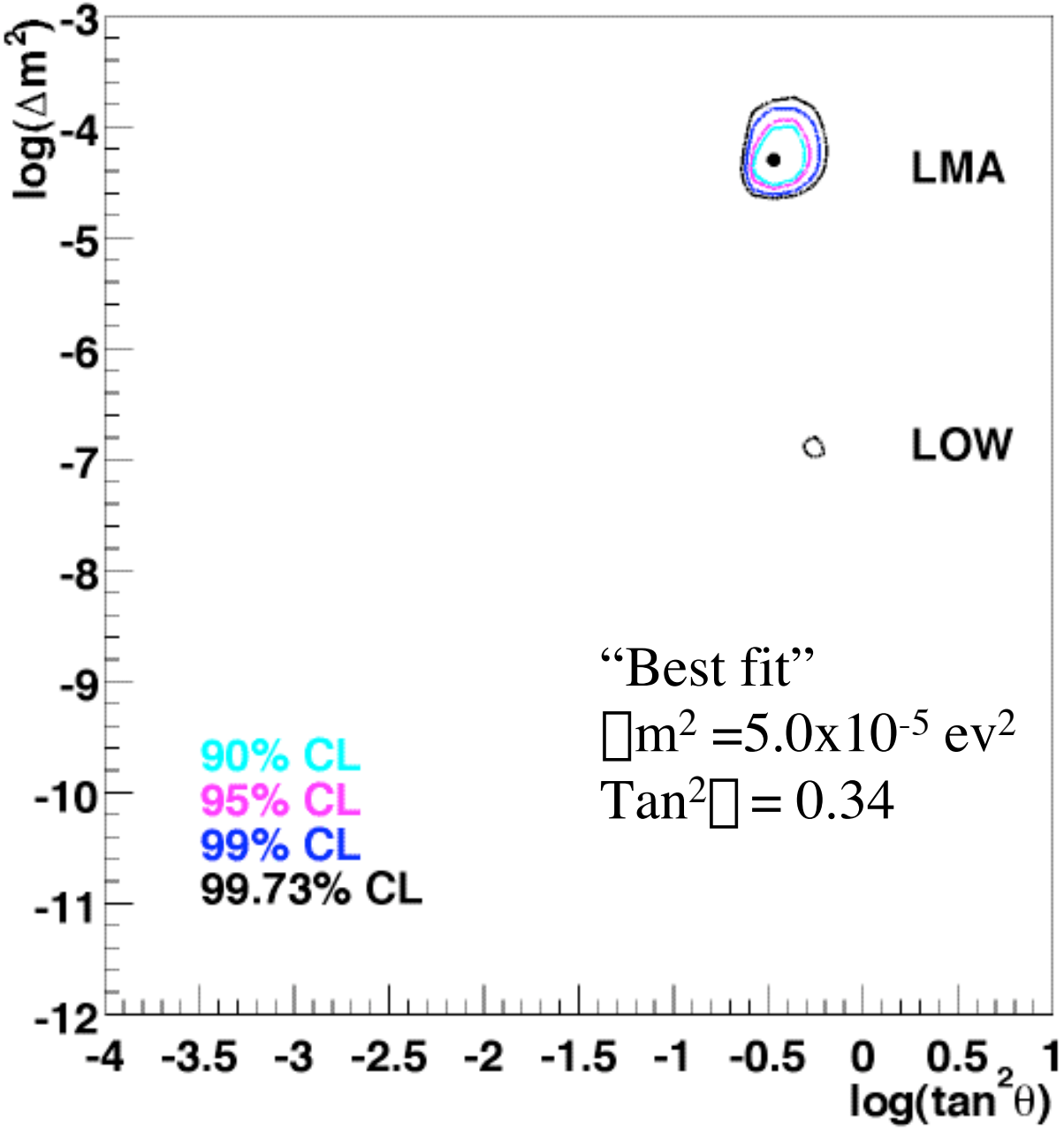
^{8}B free to float



Physics Interpretation

Including:
SNO CC,
Day/Night
Ga
Abdurashitov *et al.*,
PRC **60**, 055801 (1999)
Cl
B.T. Cleveland *et al.*
Astrophs. J **496**, 505
(1998)
Super-K
S. Fukuda *et al.*, PRL
86, 5651 (2001)

hep fixed
9.3 x 10 cm^{-2} s^{-1}

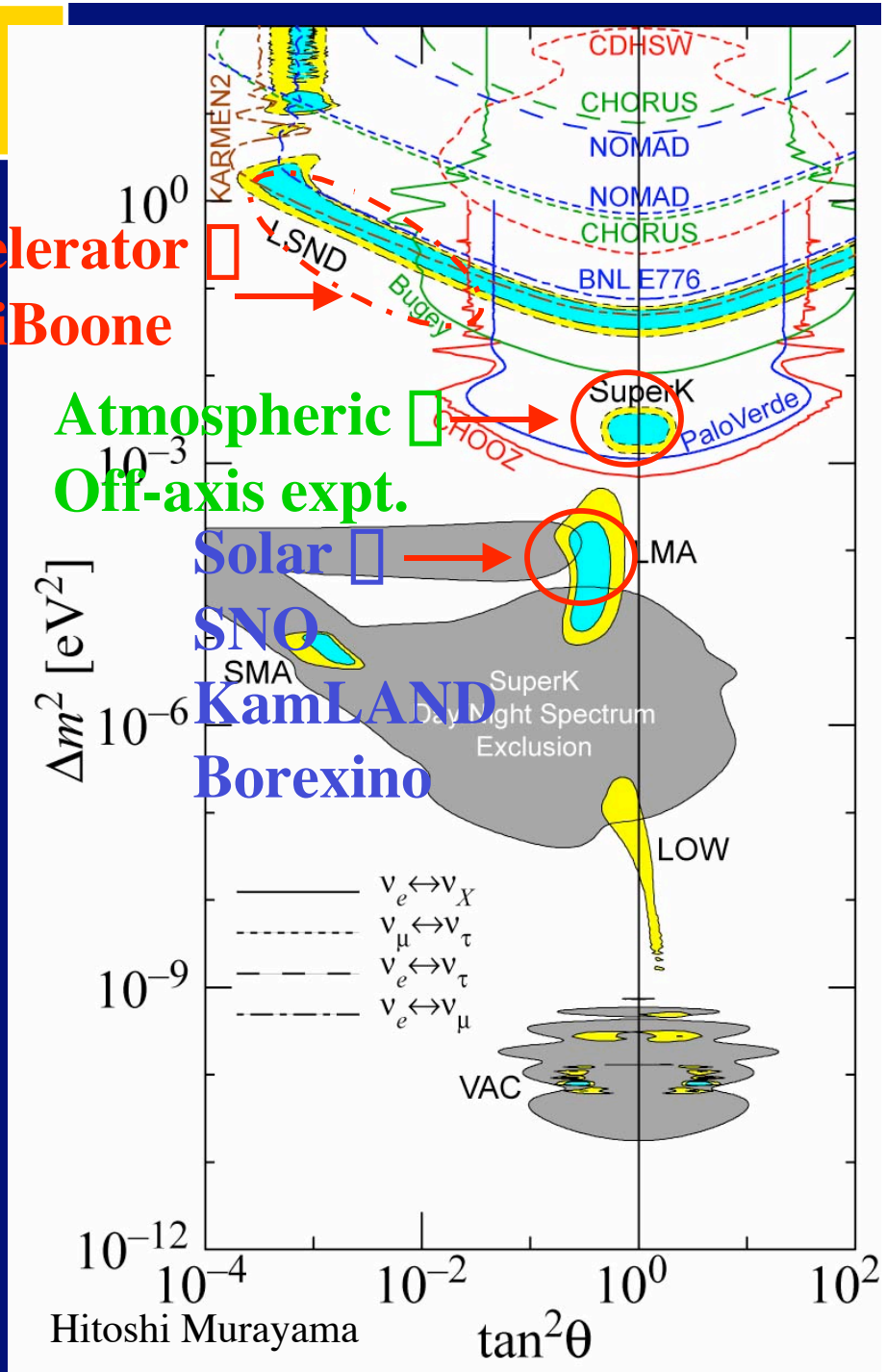


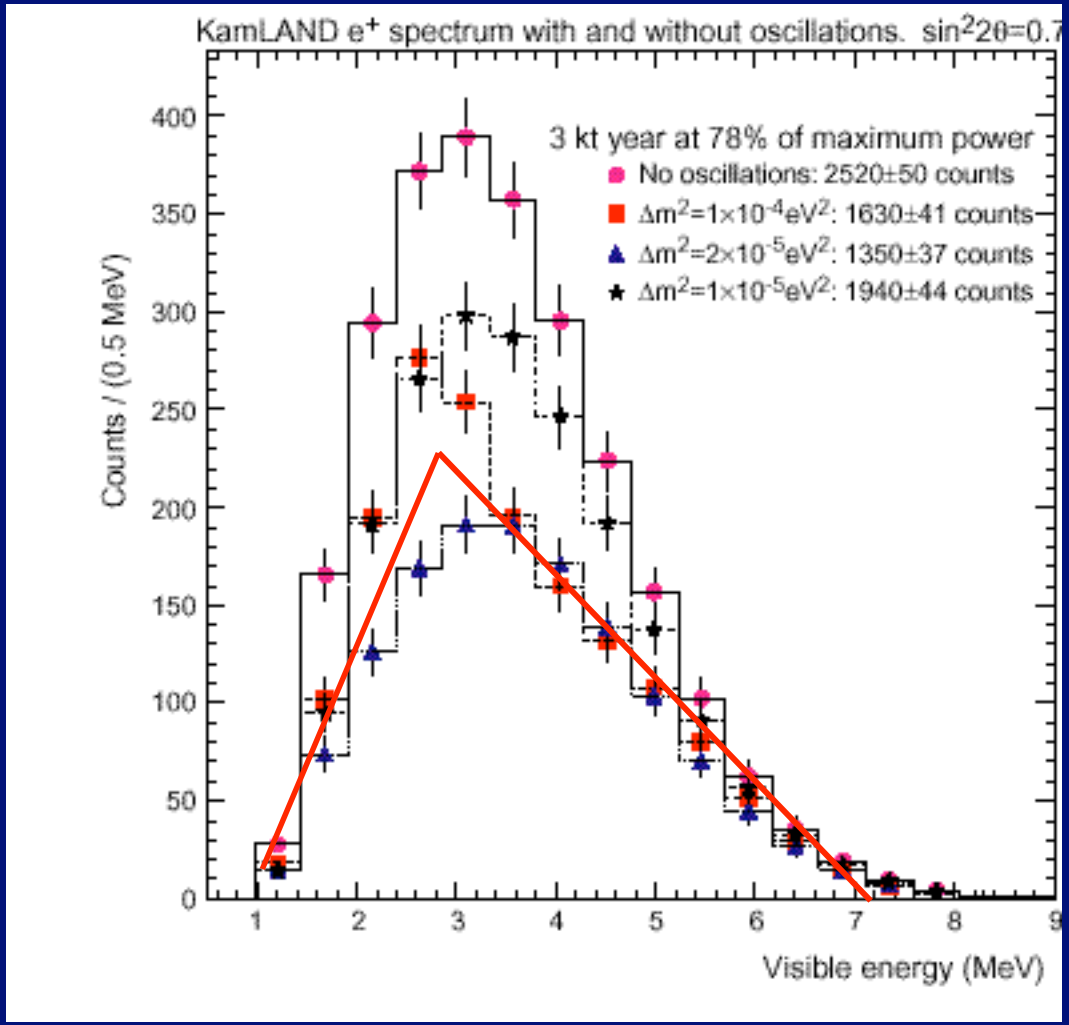
Neutrinos after SNO -2002

- Single expt. appearance >5 □ □$_e$□> □□ or □□
- Day Night for CC observed
- NC □ seen down to 2.2 MeV
- LMA highly favored
- □m^2 ~ 5.0 x 10^{-5} eV^2
- No dark side (tan^2(□)<1)
- Predictions for Borexino & KamLAND

Outstanding Issues

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




KamLAND e+ spectrum with and without oscillations. sin²2θ=0.7
3 kt year at 78% of maximum power
No oscillations: 2520±50 counts
Δm²=1×10⁻⁴eV²: 1630±41 counts
Δm²=2×10⁻⁵eV²: 1350±37 counts
Δm²=1×10⁻⁵eV²: 1940±44 counts
Counts / (0.5 MeV)
Visible energy (MeV)
0
50
100
150
200
250
300
350
400
1
2
3
4
5
6
7
8

NERSC Support

Month	CPU Days	NERSC's PDSF Usage
Feb-01	2027.39	First PRL MC (Calib. Source MC - R1)
Mar-01	342.01	
Apr-01	2214.03	First PRL MC (Calib. Source MC - R2)
May-01	1702.26	First PRL MC (Q spect, Calib. Source MC -R3)
Jun-01	110.09	
Jul-01	445.60	Superhot Th Source
Aug-01	874.79	Acrylic Source + LE Fitter Study
Sep-01	275.35	
Oct-01	795.71	
Nov-01	1286.70	Calibration Source MC
Dec-01	2186.75	Low energy background MC
Total	12260.69	

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Sarah Rosendahl Colin Okada

Kathy Opachich
Noah Oblath

website
SNOHP1.lbl.gov

NC paper: nucl-ex/ 0204008
D/N paper: nucl-ex/ 0204009

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