A Place in the Sun for Neutrinos

- Experimental inputs:
  - Rates from 7 experiments
  - Shape, D/N from Super-Kamiokande
  - The SNO experiment
- What we know from Solar Neutrinos
- The next steps
- Low-energy solar neutrinos
  - Physics goals
  - Experiments

Some other Solar Neutrino Talks at WIN'02

Thursday

11:30 Colin Okada "What else can SNO do?"

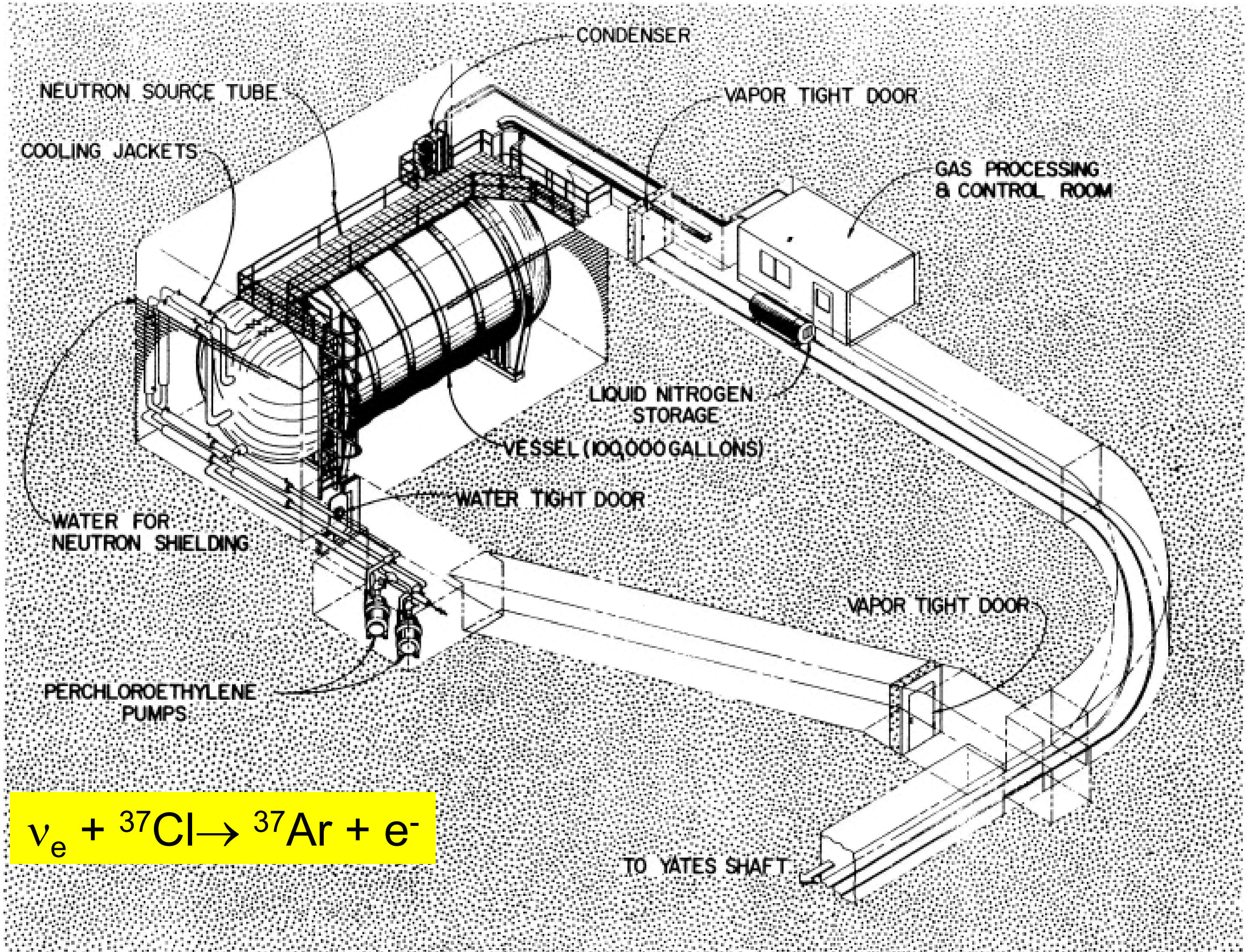
2:00 Junpai Shirai "KamLAND"

2:40 Till Kirsten "Aims and Status of Borexino"

Friday

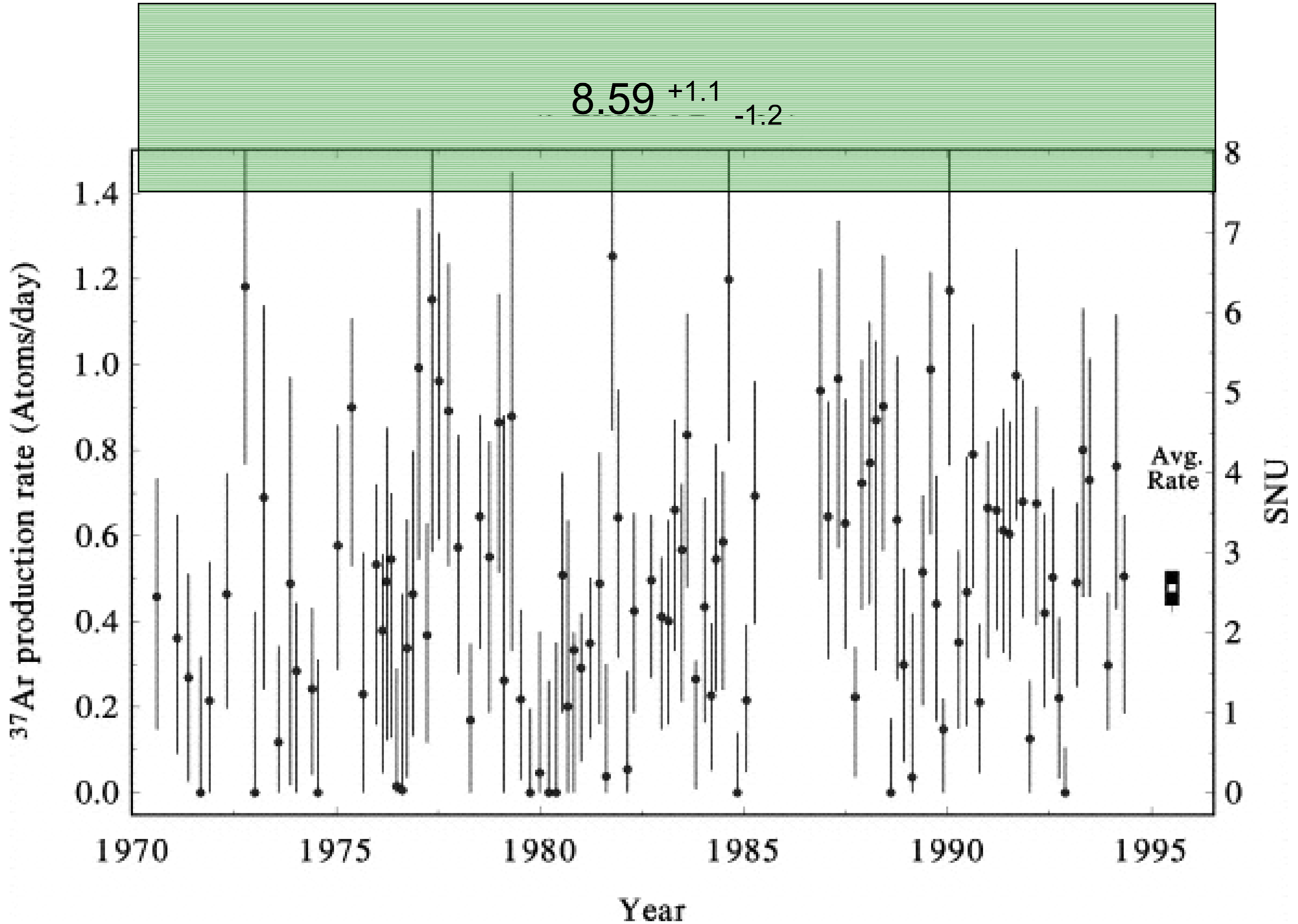
6:45 Tom Bowles "Low Energy Neutrino Spectroscopy □(LENS)"

Cl-Ar at Homestake



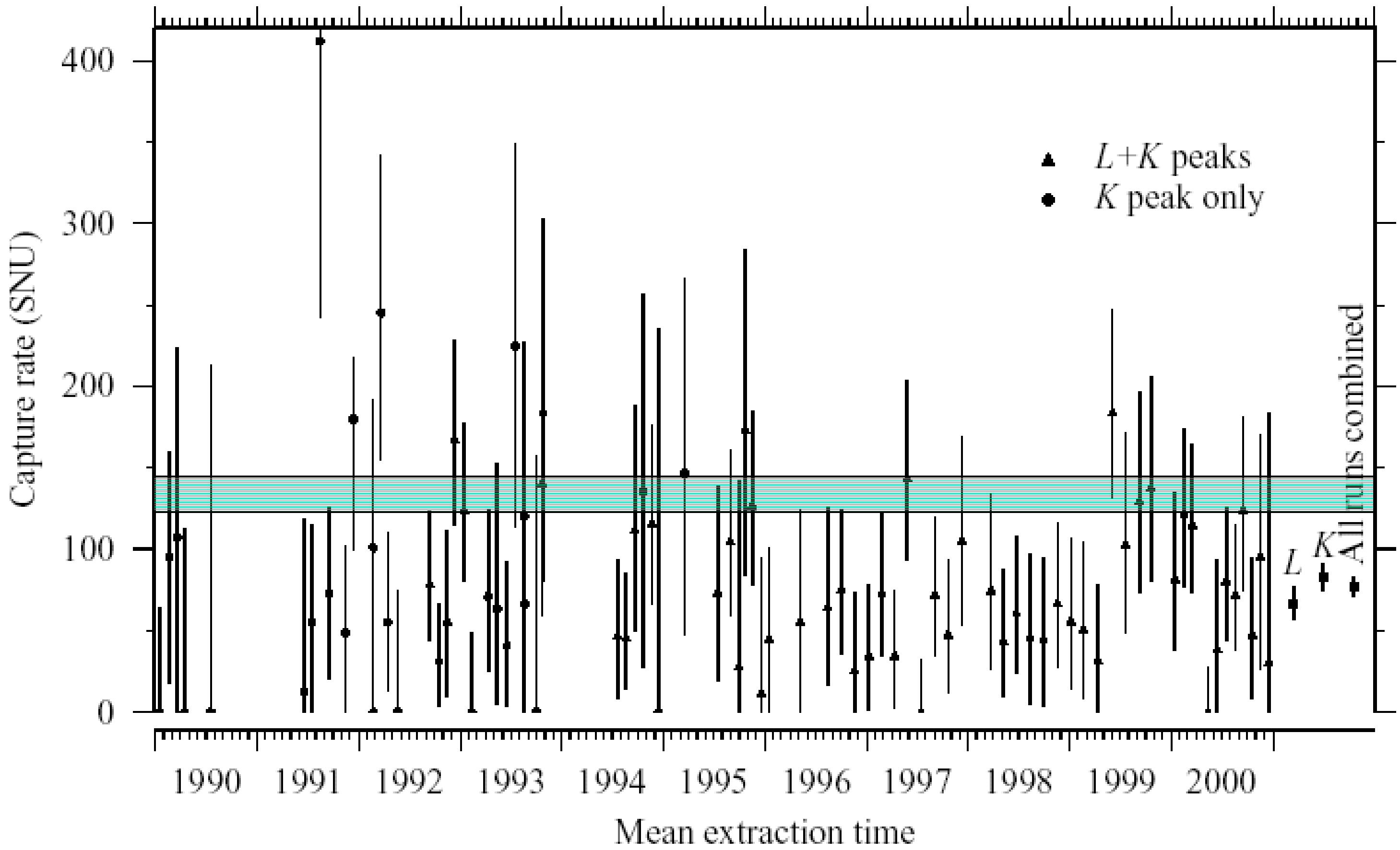
$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

Cl - Ar Results 1970 - 1994



The SAGE Experiment

V. Gavrin et al. NP (B)91, 36, 2001



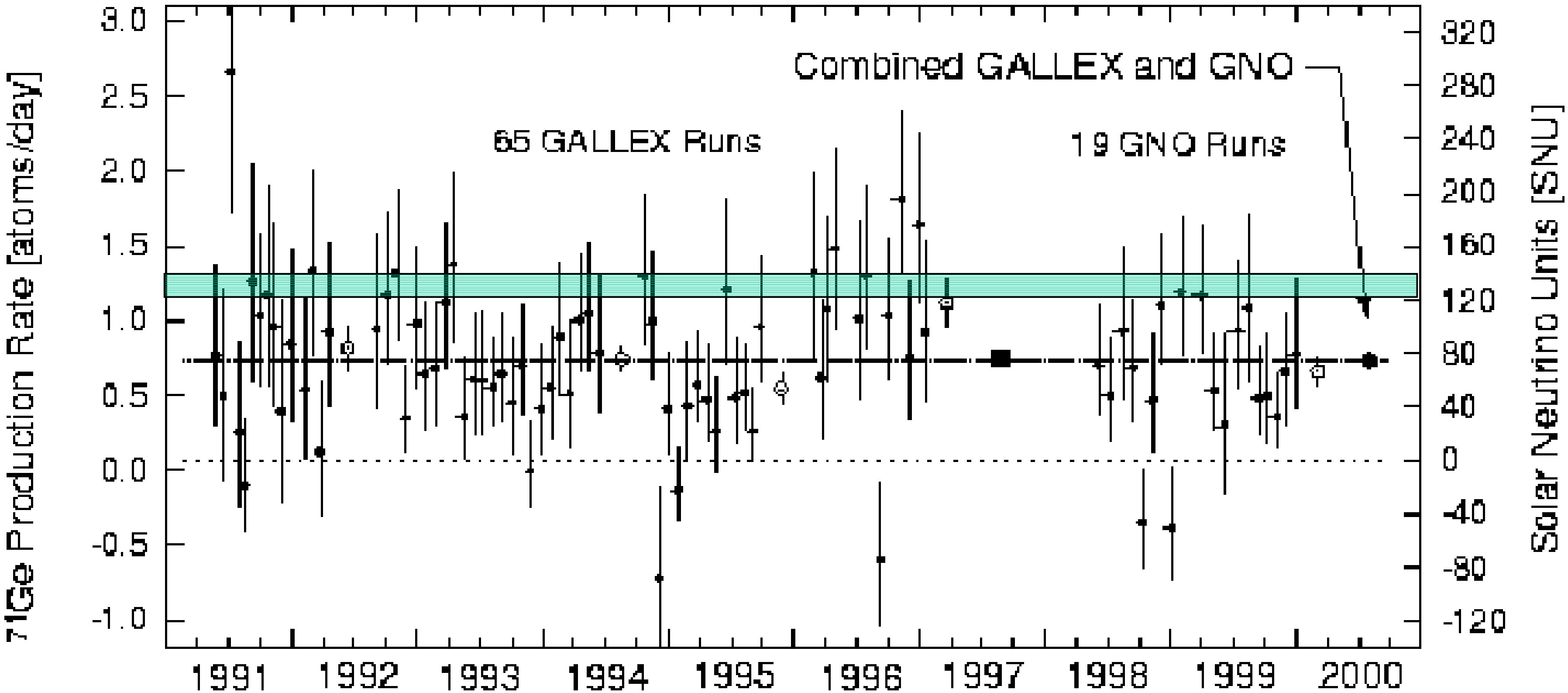
130±9

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ga + e^-$

Combined L and K data
$75.4\ _{-6.8}^{+7.0}\ _{-3.0}^{+3.5}$ SNU

The GNO and Gallex Experiments

M. Altmann et al. hep-ex/0006034



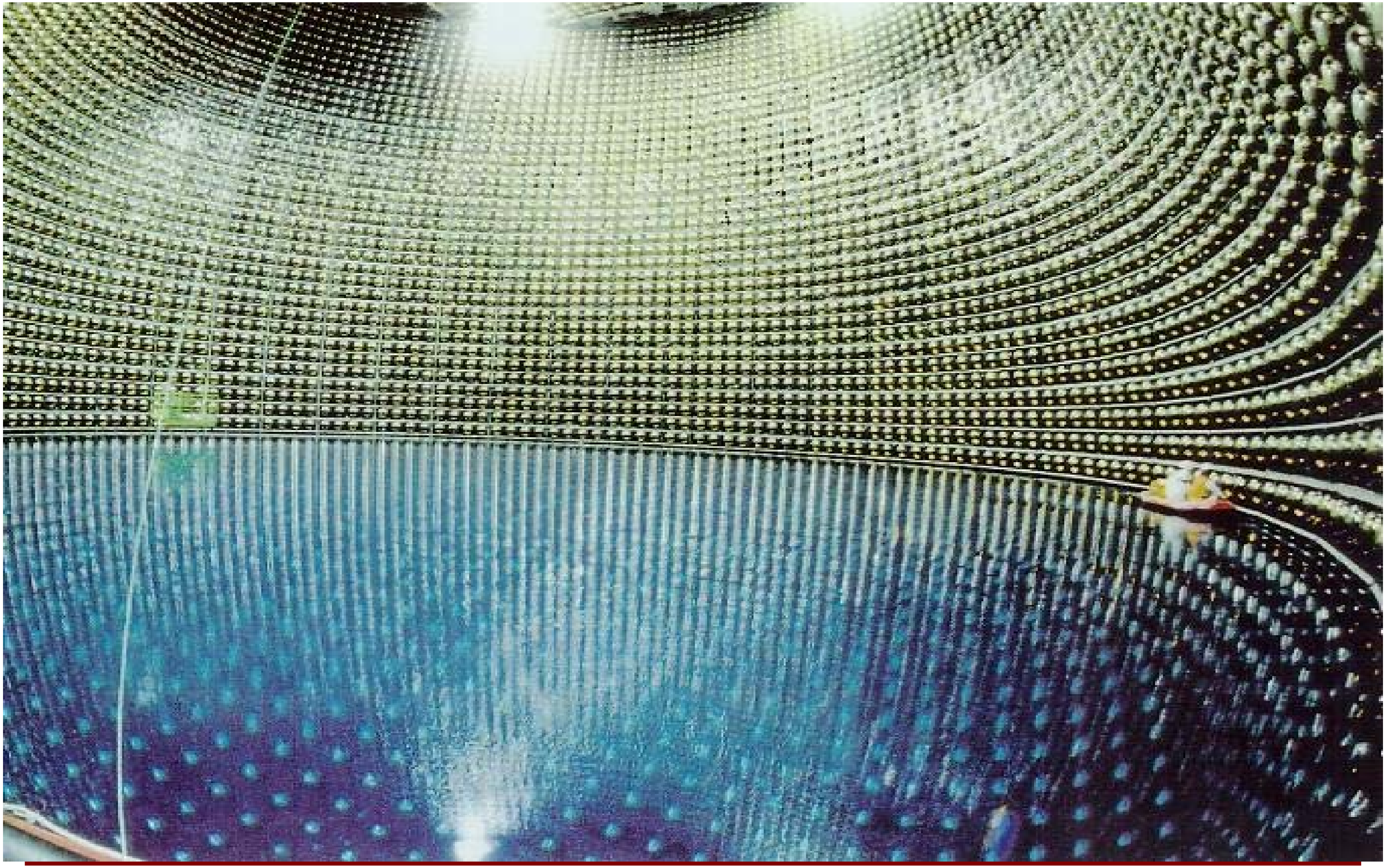
$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ga + e^-$

Combined Gallex+ GNO
74.1(68) SNU

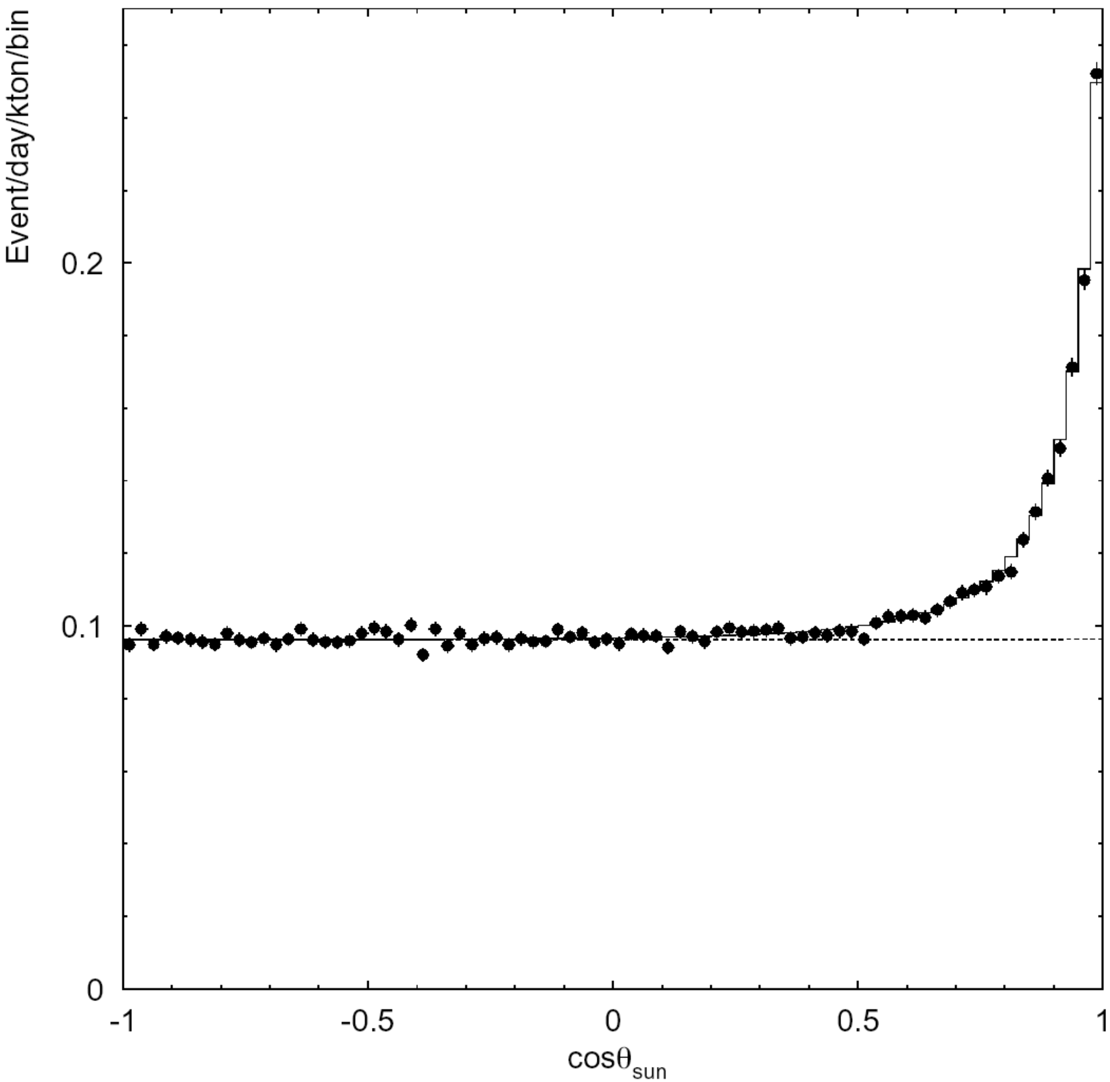
If your experiment needs better statistics, you need a better experiment.

Lord Rutherford

The Super-Kamiokande Light-Water Cherenkov Detector



Super-Kamiokande



May 31, 1996 -
July 1, 2001

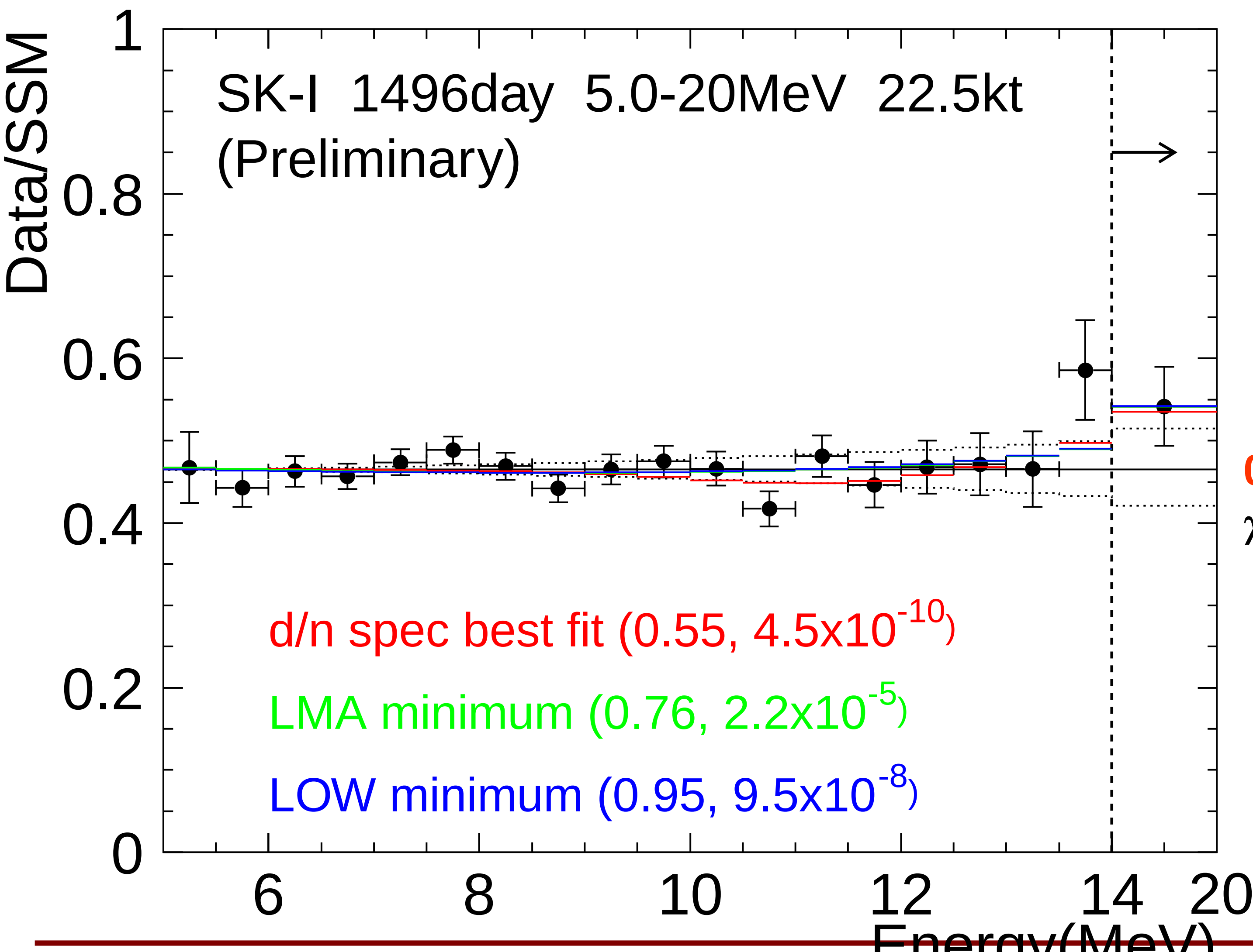
1496 live days

E ≥6.5 MeV (361 d)
E ≥5.5 MeV (756 d)
E ≥5.0 MeV at end

$\Phi_8 = 2.35 \pm 0.02 \pm 0.08$

10^6 cm^{-2} s^{-1}

Energy spectrum



0.465

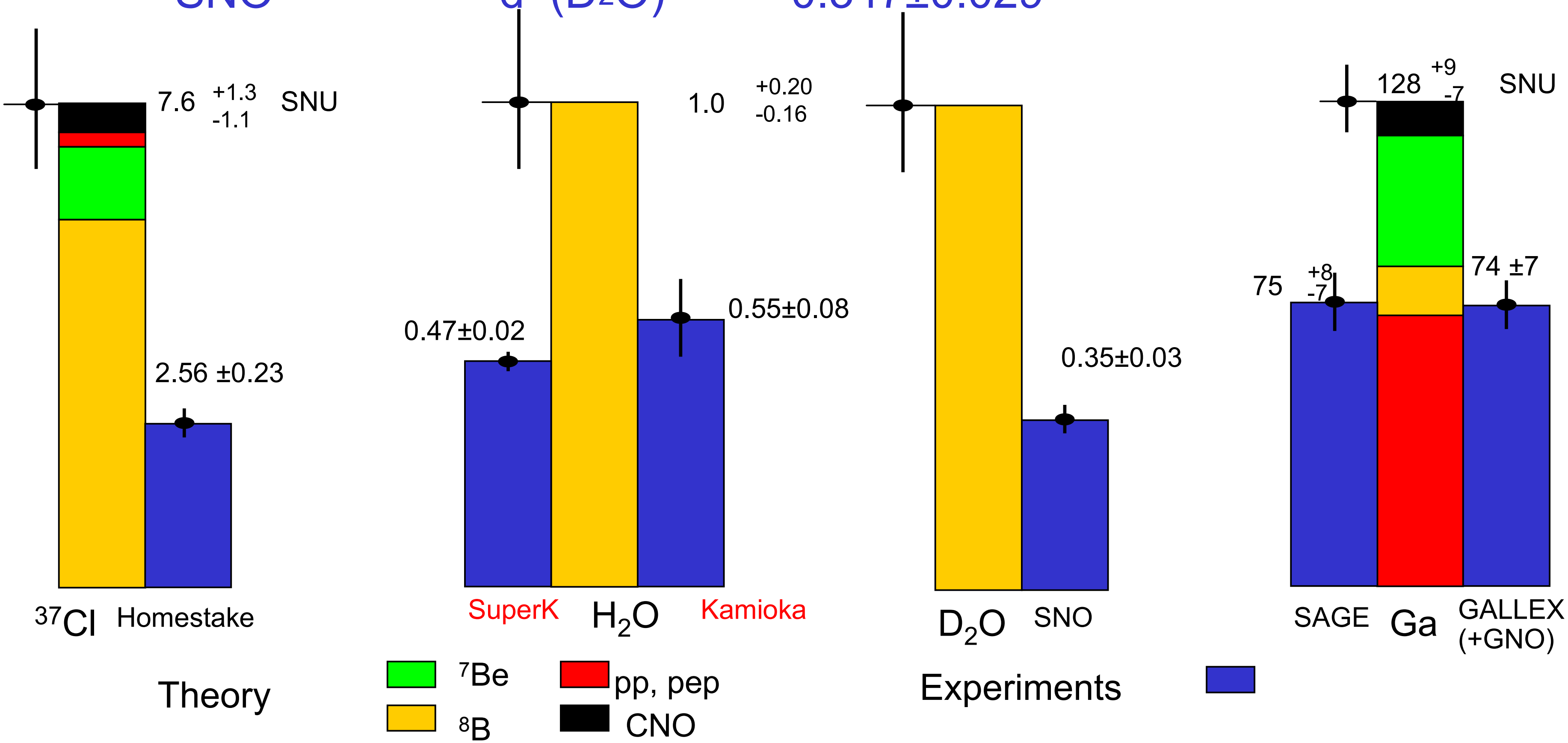
χ^2(flat)=17.40 (50%)

Rate measurements

(BP2000.2) Totsuka

- Homestake ^{37}Cl 0.34±0.03
- SAGE ^{71}Ga 0.59±0.06
- GALLEX+GNO ^{71}Ga 0.58±0.05
- Super-K e^- (water) 0.465±0.016*
- SNO d (D_2O) 0.347±0.029

*** 0.451 for BP2000_old**



ν Reactions in Heavy Water

CC

$$\nu_e + d \Rightarrow p + p + e^-$$

- "Charged Current"
- ν_e only.

NC

$$\nu_x + d \Rightarrow p + n + \nu_x$$

-"Neutral Current"
- Equal cross section for all active ν types

ES

$$\nu_x + e^- \Rightarrow \nu_x + e^-$$

-"Elastic Scattering"
-Mainly sensitive to ν_e, some sensitivity to ν_μ and ν_τ

ν Reactions in SNO

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

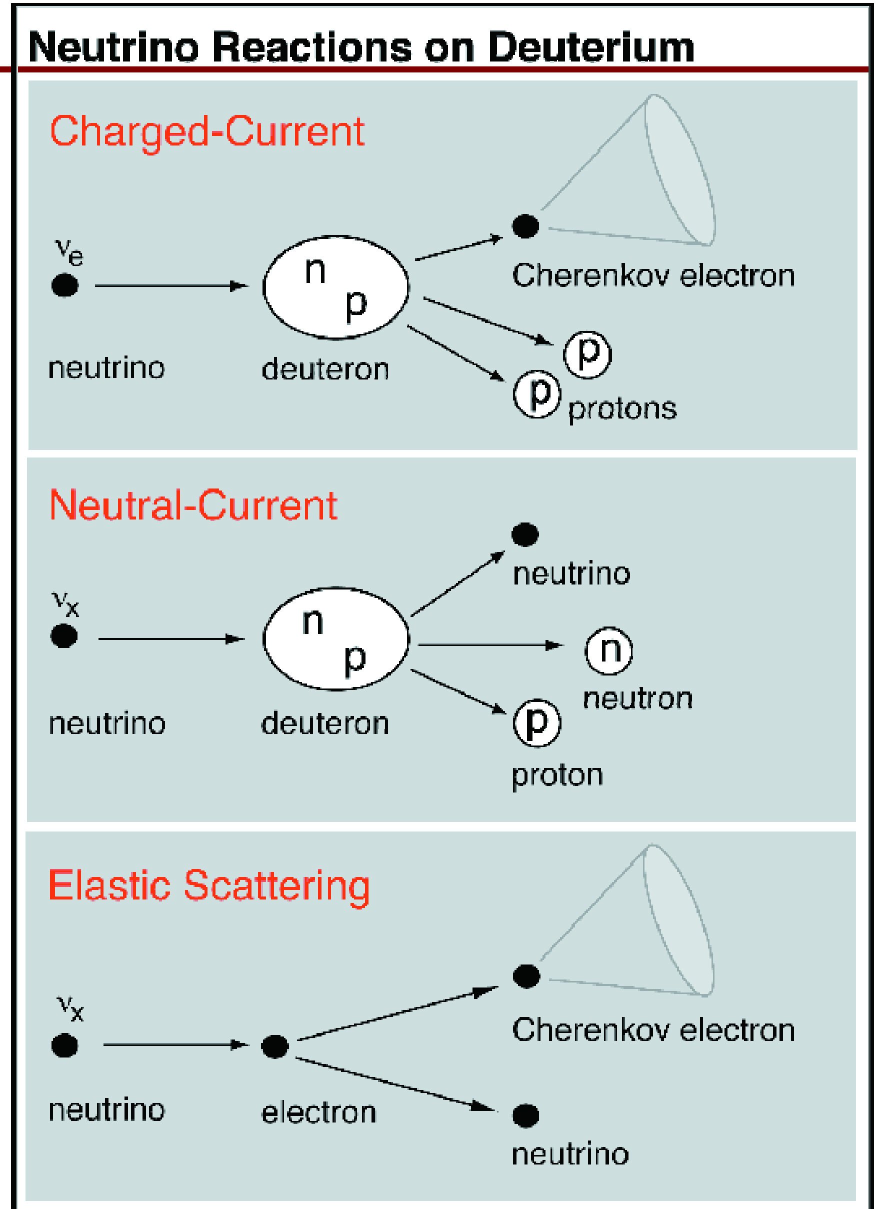
-Gives ν_e energy spectrum well
-Weak direction sensitivity $\propto$ 1-1/3cos(θ)
- ν_e only.

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

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

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

-Low Statistics
-Mainly sensitive to $\nu_{e,}$, some
-sensitivity to ν_μ and ν_τ
-Strong direction sensitivity



SNO

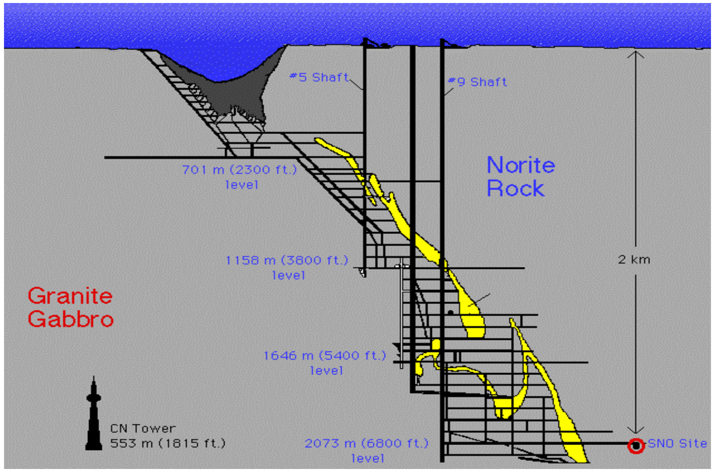
First results from the Sudbury Neutrino Observatory, and their Implications

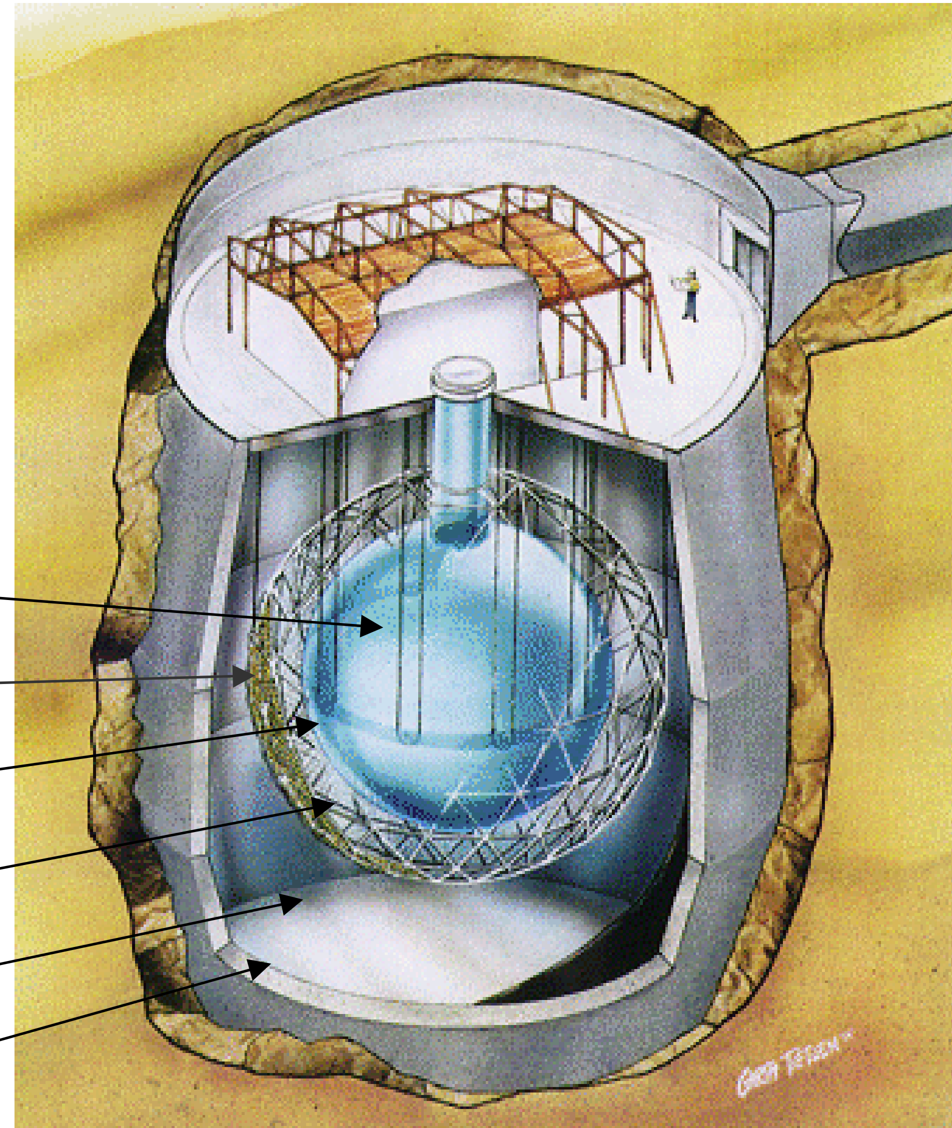
nucl-ex/0106015 v2

J. Farine

Aurora Australis

Sudbury Neutrino Observatory





1000 tonnes D_2O

Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal

SNO Collaboration

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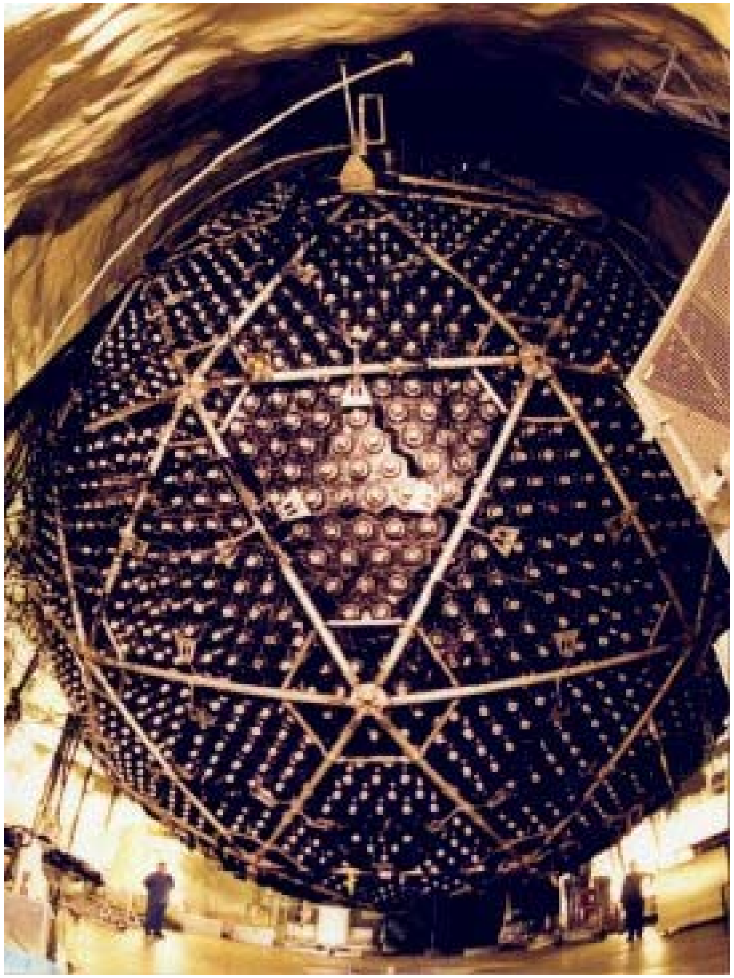
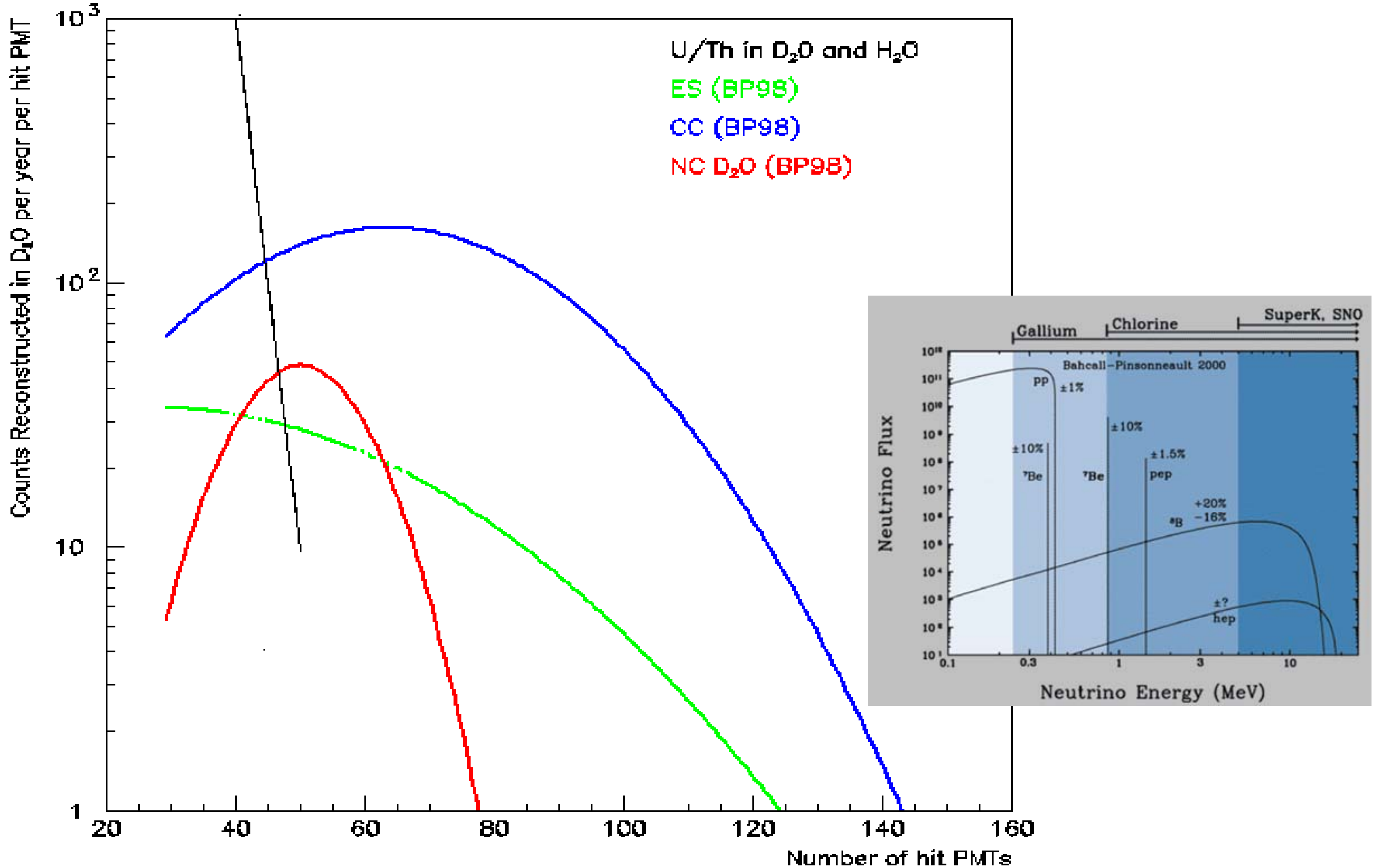
The SNO Detector during Construction



Heavy Water from Bruce Plant

Signals in SNO



Looking for unexpected Neutrino Flavors

Measure total flux of solar neutrinos vs. the pure ν_e flux

Charged-Current to Neutral Current ratio is a direct signature for oscillations

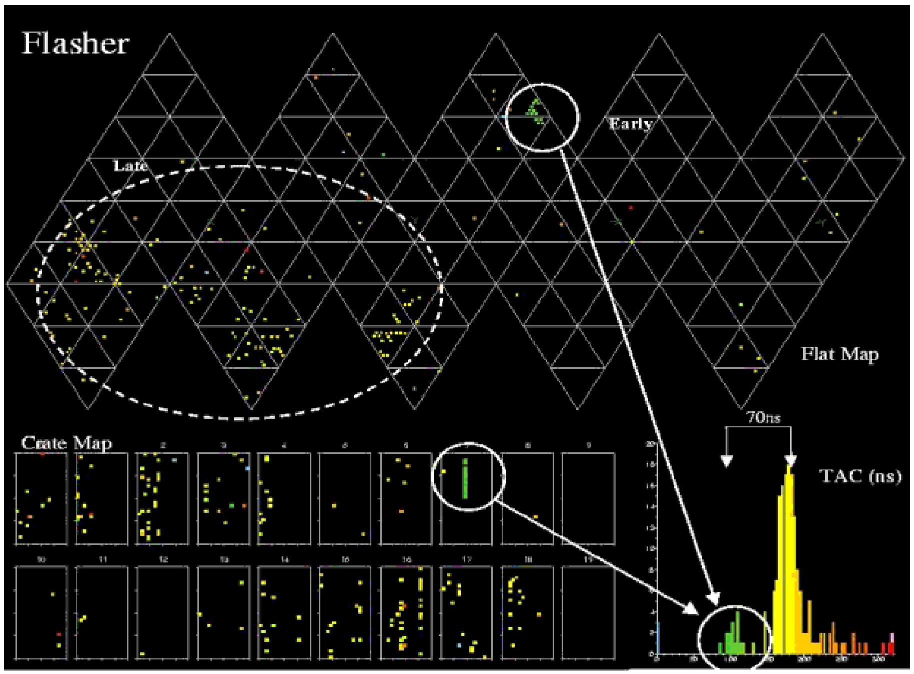
$$\frac{CC}{NC} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

CC/ES Could also show significant effects

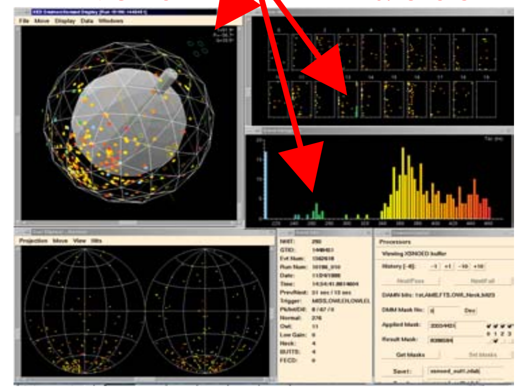
$$\frac{CC}{ES} = \frac{\nu_e}{\nu_e + 0.15(\nu_\mu + \nu_\tau)}$$

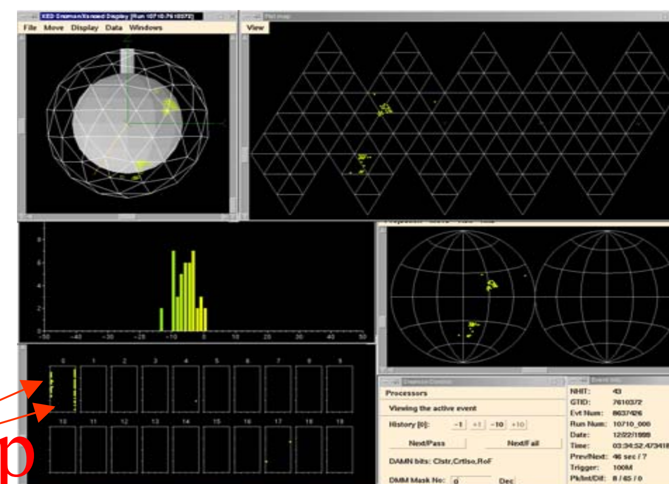
Smoking Guns for Neutrino Oscillations

Instrumental backgrounds



Note Neck Tubes Fired





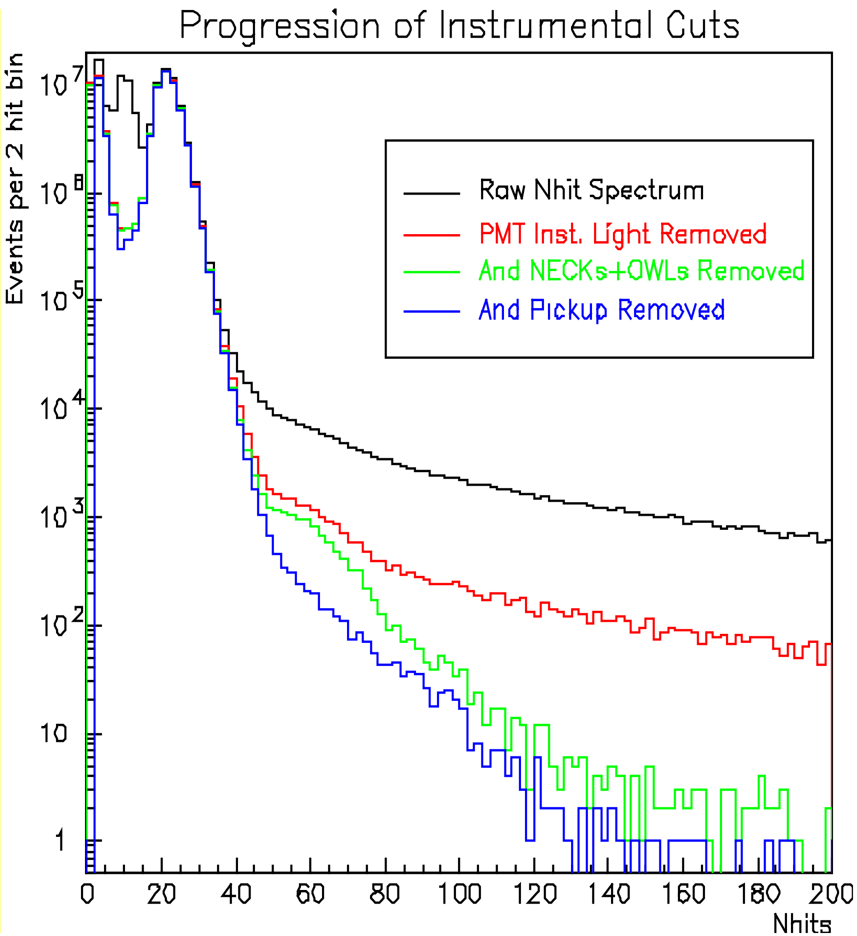
Electronic Pickup

Application of Instrumental Background Cuts

Data Period: **Nov 2, 1999 → Jan 15, 2001**
Live Time: **240.9 days**

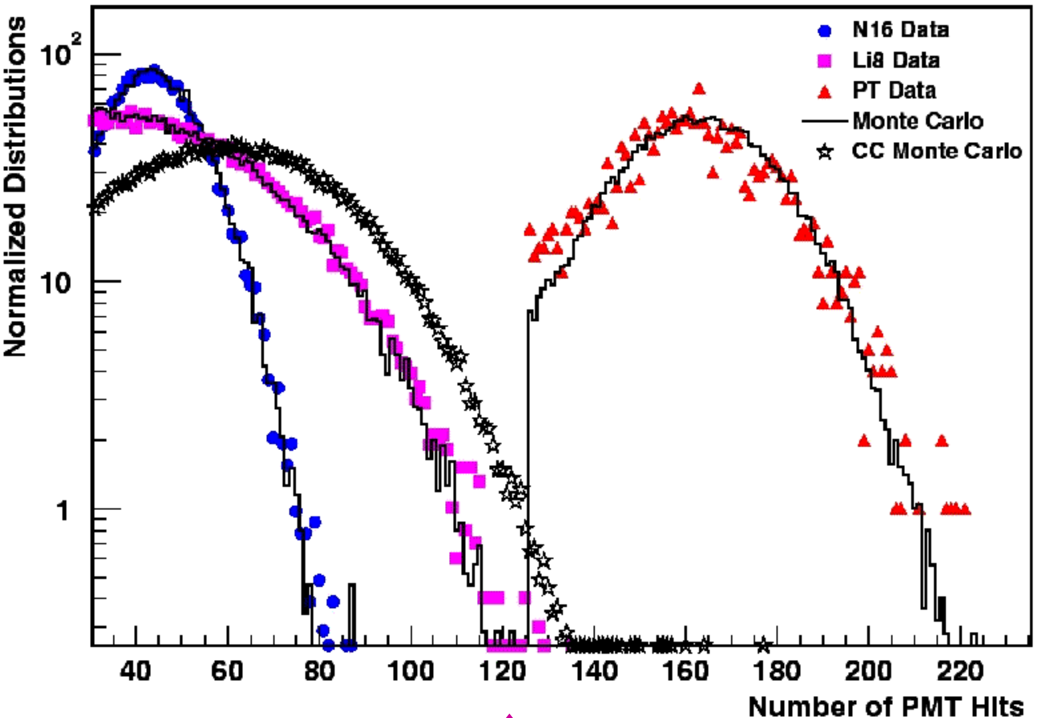
Analysis Step	Events
Total Event Triggers	355,320,964
Neutrino Data Triggers	143,756,178
Nhit≥30	6,372,899
Instrumental Background	1,842,491
Muon Followers	1,809,979
High Level Cuts	956,535
Fiducial Volume Cut	18,783
Threshold Cut, $T_{eff} \geq 6.75$ MeV	1169

Total Events
In Final Data Set **1169**

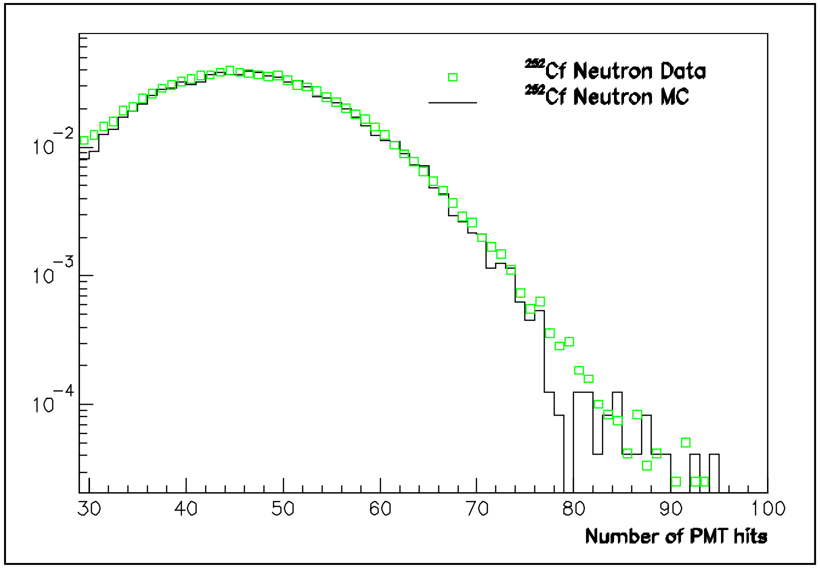


High Level Cuts: Reconstruction figures of merit
In-time light
Event isotropy (θ_{ij})

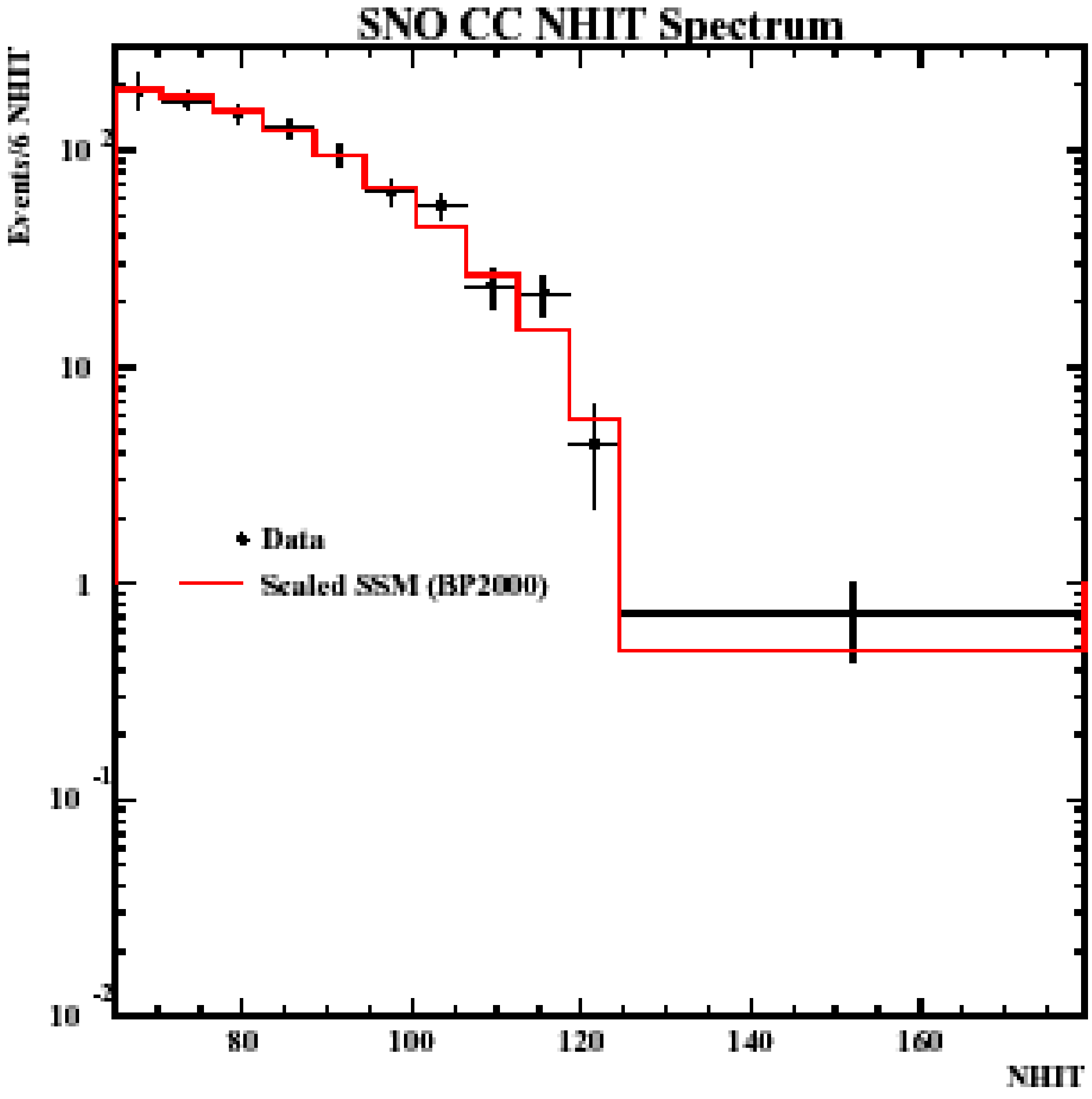
SNO Energy Calibrations



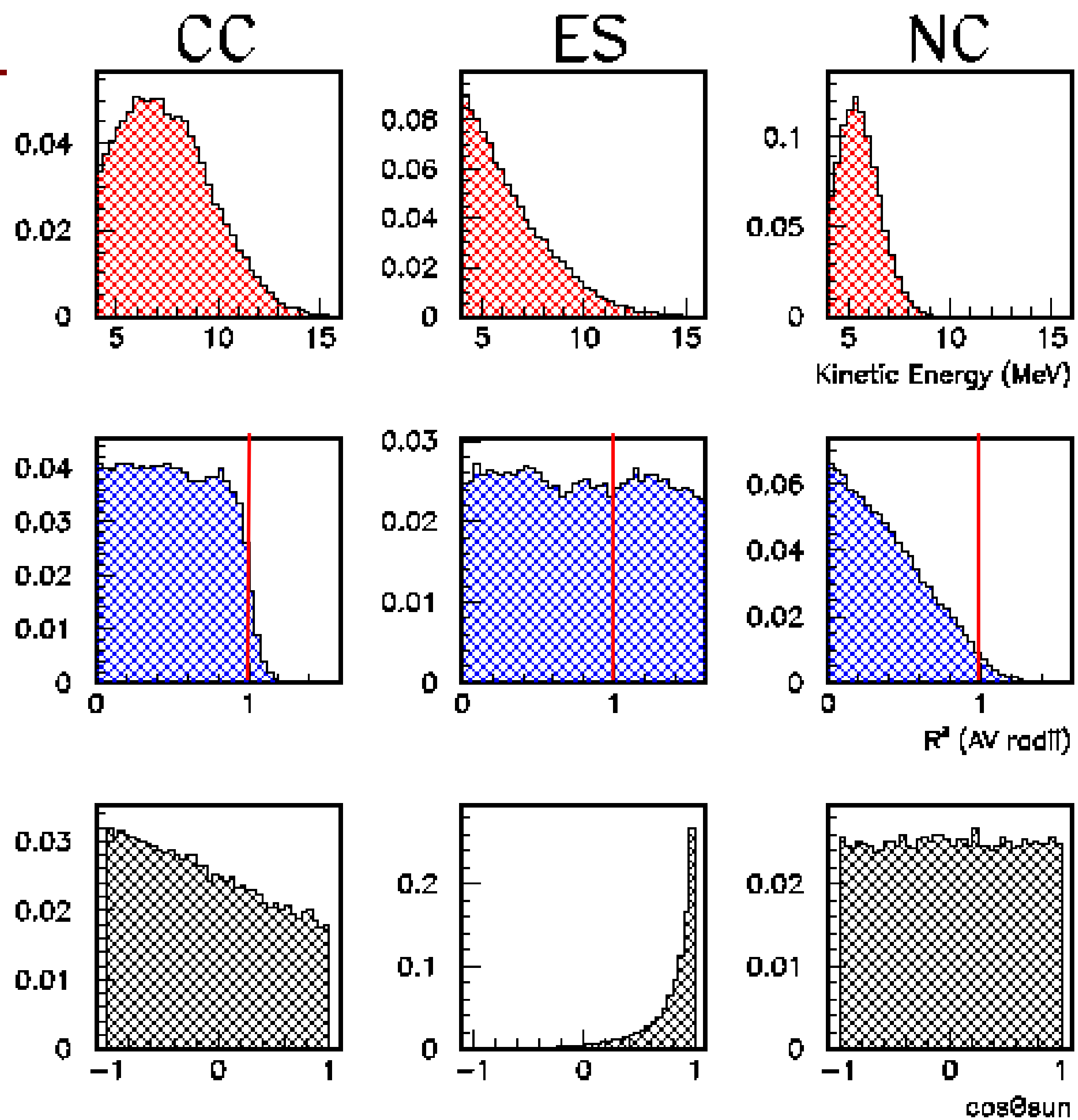
^{252}Cf neutrons



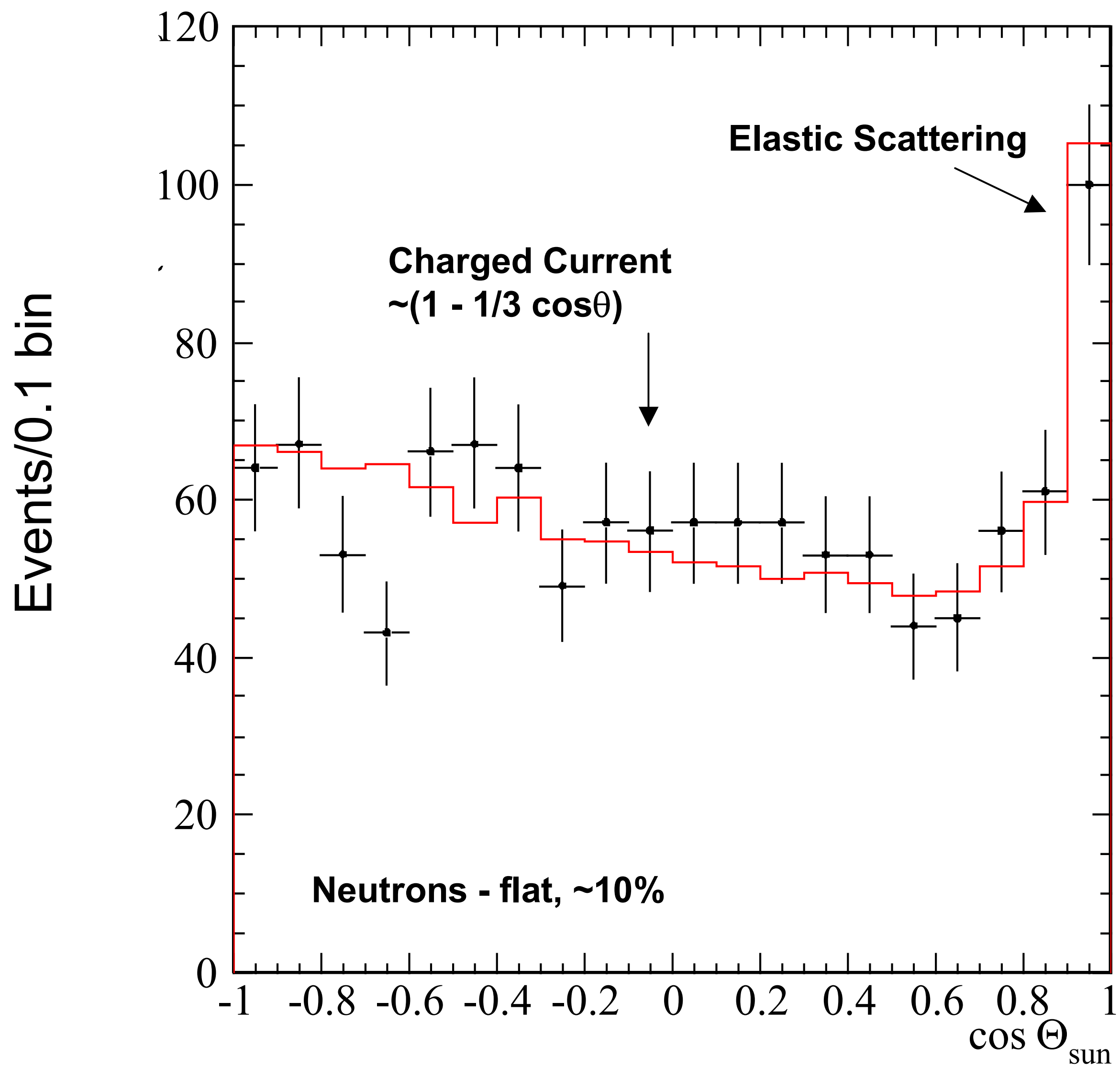
β's from ^{8}Li
γ's from ^{16}N and t(p,γ)^{4}He



SNO CC NHIT Spectrum
Events/6 NHIT
10^2
10
1
10^{-1}
10^{-2}
80
100
120
140
160
NHIT
Data
Scaled SSM (BP2000)


CC
ES
NC
0.04
0.02
0
5
10
15
0.08
0.06
0.04
0.02
0
0.1
0.05
Kinetic Energy (MeV)
0.03
0.01
0.06
0.04
0.02
0
1
R³ (AV radii)
0.2
0.1
−1
cosΘsun

Direction of Events with respect to the Sun

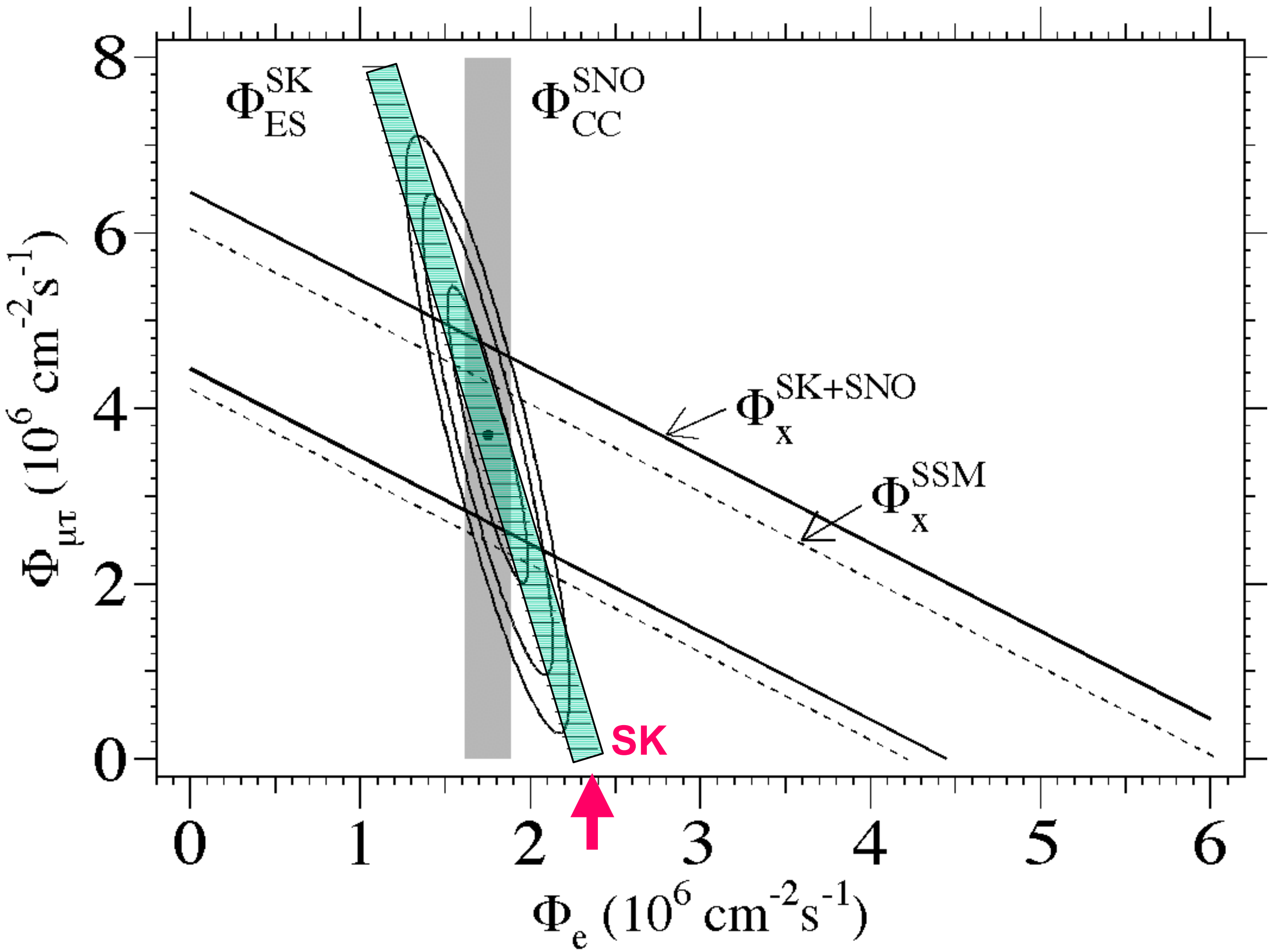


Neutrino Flavor Composition of ^{8}B Flux

Fluxes

(10^6 cm^{-2} s^{-1})

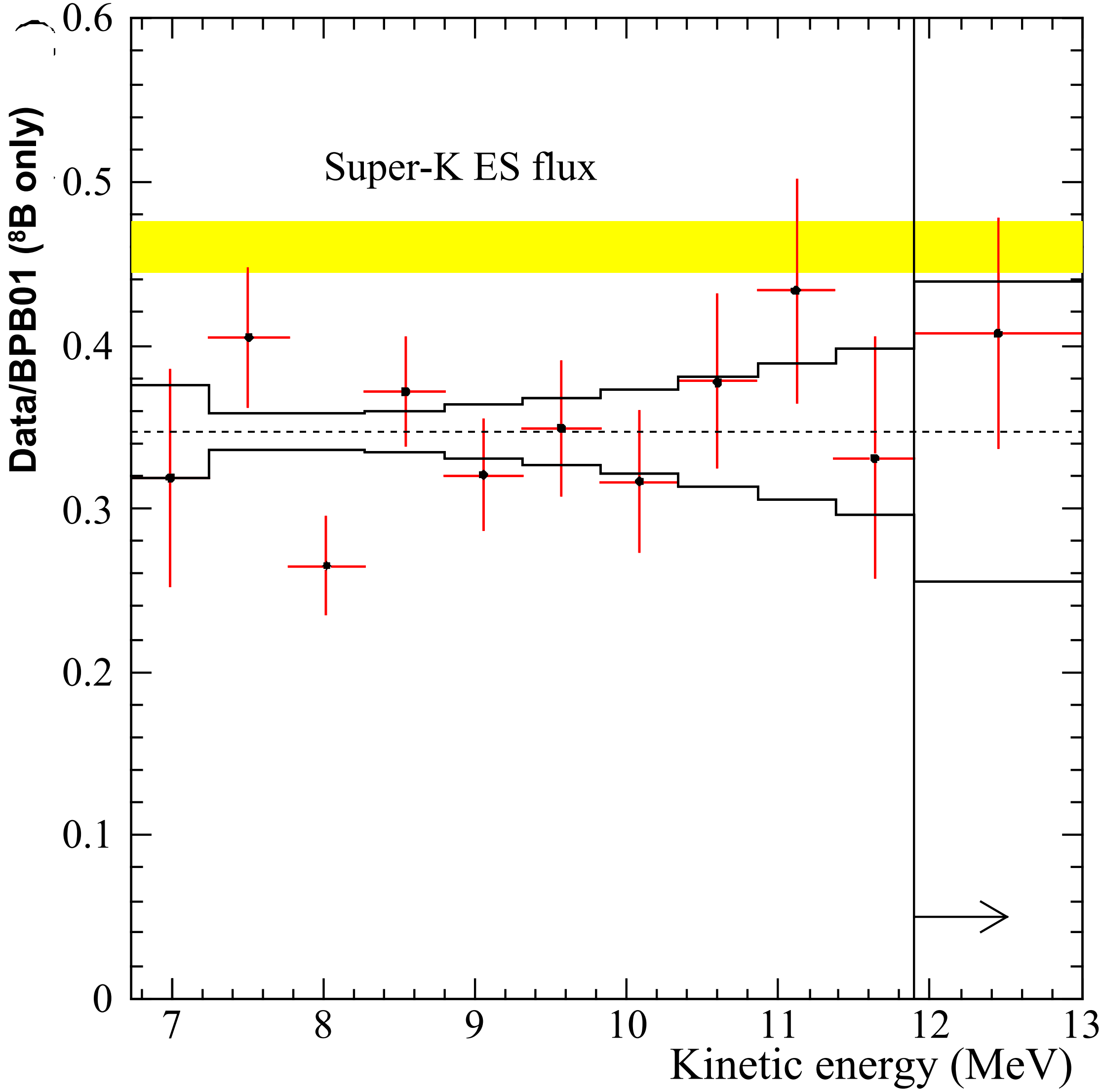
ν_e:	1.75(15)
$\nu_{\mu\tau}$:	3.69(113)
ν_{total}:	5.44(99)
ν_{SSM}:	5.05



$\phi_{CC} = \phi_e$

$\phi_{ES} = \phi_e + 0.154\, \phi_{\mu,\tau}$

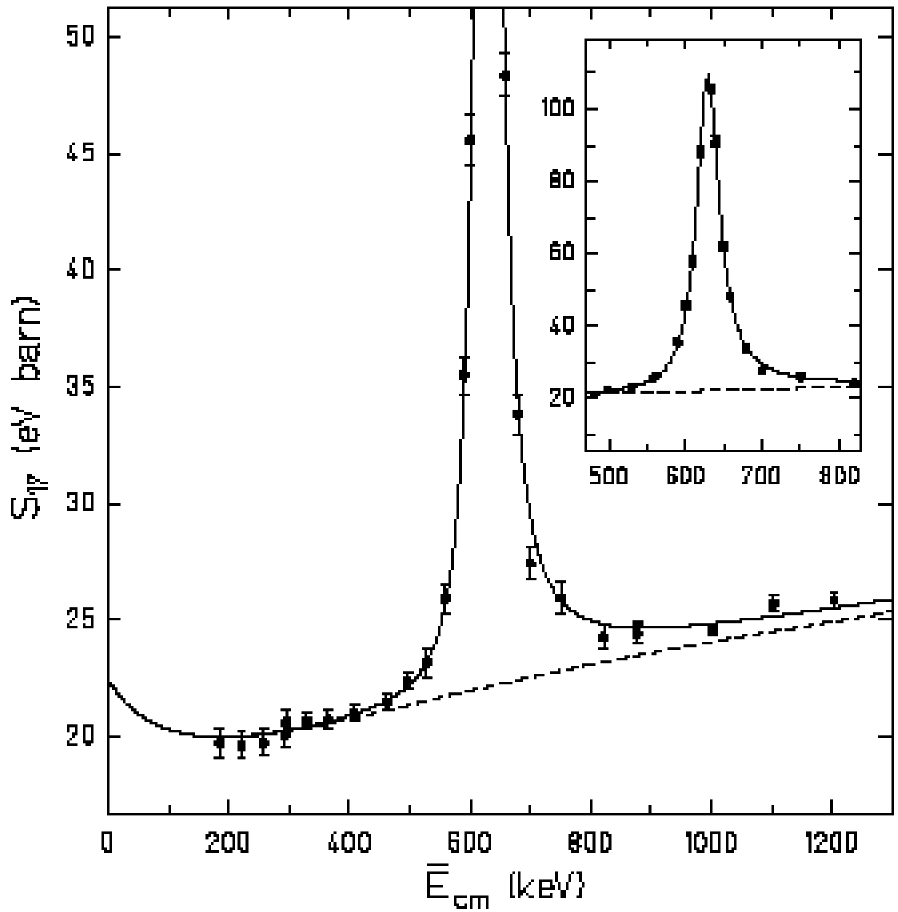
Charged Current Energy Spectrum



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

no evidence for shape distortion.

New Measurement of $^7Be(p,\gamma)^8B$ Junghans et al. nucl-ex/0111014



Φ_8 $(10^6\ cm^{-2}\ s^{-1})$

$$1998 : 5.05\left(1.00^{+0.20}_{-0.16}\right)$$

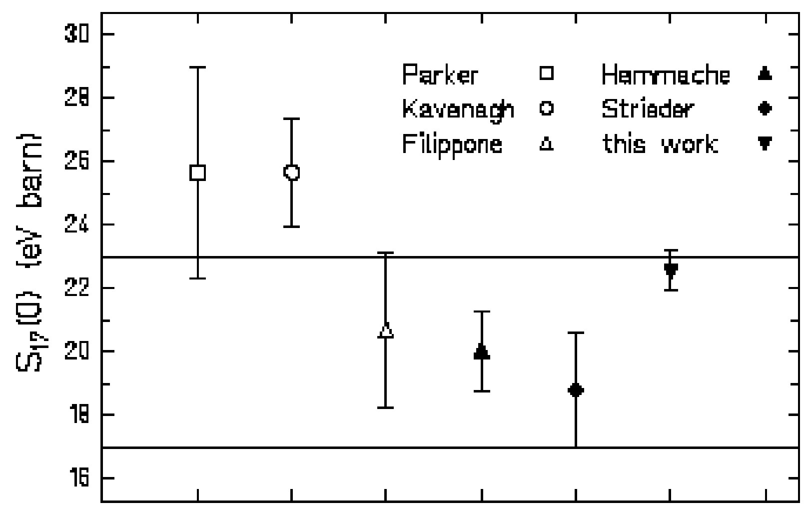
$$2001 : 5.93\left(1.00^{+0.14}_{-0.15}\right)$$

Bahcall et al. hep-ph/0111150

S(0) (keV b)

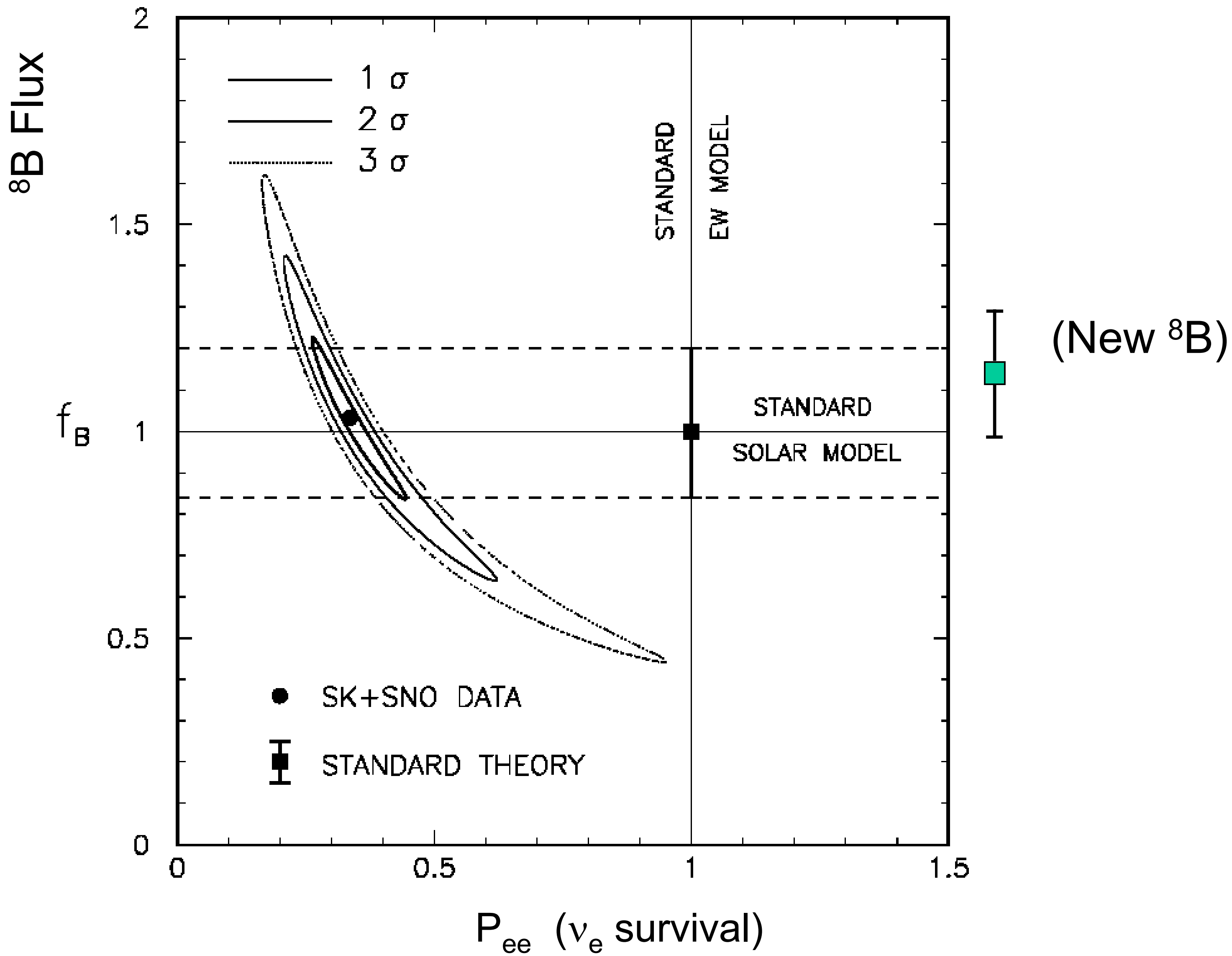
1998: 19^{+4}_{-2}

2001: $22.3 \pm 0.7 \pm 0.5$



Neutrino Oscillations

Fogli et al. hep-ph/0106247



Charged Current and Elastic Scattering Fluxes

– Absolute Fluxes: (Units $10^6\ cm^{-2}\ s^{-1}$)

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

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

– Super-Kamiokande finds (S. Fukuda, et al., hep-ex/0103032)

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

$$\frac{CC}{ES} \neq 1.0$$

$CC - ES = 0.57 \pm 0.17\ \ (3.3\ \sigma)$

Experimental Systematic Errors

Error Source	CC Error (%)	ES Error (%)
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 Shift	±3.1	±3.3
Vertex Resolution	±0.7	±0.4
Angular Resolution	±0.5	±2.2
Live Time	±0.1	±0.1
Trigger Efficiency	0.0	0.0
Cut Acceptance	+0.7/-0.6	+0.7/-0.6
Earth orbit eccentricity	0.0	0.0
^{17}O, ^{18}O	0.0	0.0
Residual Backgrounds ($R_{fit} \leq 550$ cm)		
Instrumental Background	-0.2/+0.0	-0.5/+0.0
High Energy γ's	-0.3/+0.0	-1.8/+0/0
Low Energy Background	0.0	0.0
Experimental Uncertainty	**+7.0/-6.2**	**+6.8/-5.7**
Cross Section	**3.0**	**0.5**

Radiative and other corrections

CC (and NC) cross sections calculated with BCK Effective Field Theory.
Counterterm $L_{1,A}$ obtained by normalizing to NSGK Potential Model
Radiative corrections not made, except for updates to g_A

Calculation	g_A	Ref
NSGK	1.254	Nakamura et al. PR C63 034617,
BCK	1.26	Butler, Chen & Kwong, PR C63 035551
SNO 2001	1.267	Beacom & Parke hep-ph/0106128

New, consistent treatment of radiative corrections by
Kurylov, Ramsey-Musolf, and Vogel (nucl-th/0110051):

Total cross section increases by 3-4%.
Threshold for soft γs in SNO reduces this to 2%

SNO Conclusions

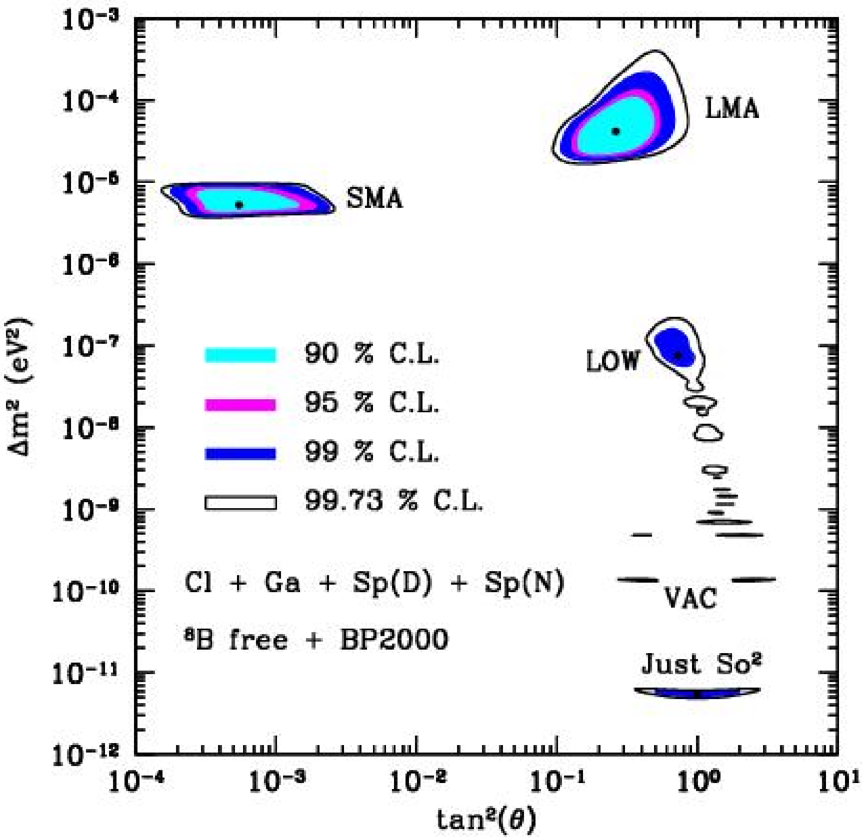
• Evidence that ν_e produced in the Sun are transformed to ν_μ and/or ν_τ -- solar neutrinos having a *flavor other than electron* are being detected on Earth

• First measurement of the total flux of ^{8}B neutrinos:
$\phi_{total}(^8B) = 5.44 \pm 0.99 \times 10^6\ cm^{-2}\ s^{-1}$
Agrees well with solar models:
$\phi_{SSMl}(^8B) = 5.05 \pm 0.80 \times 10^6\ cm^{-2}\ s^{-1}$ (BPB01)

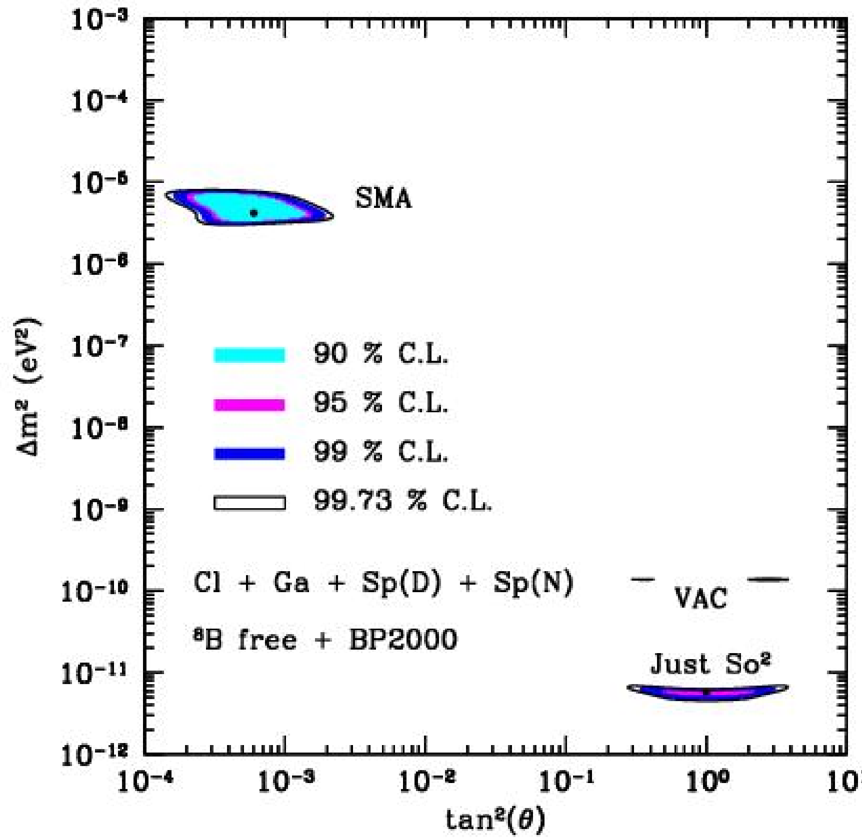
• Neutrino models with mixing solely to a sterile neutrino are not compatible with these data, but small *additional* sterile oscillation channel possible

Allowed Solutions for 2-Neutrino Oscillations (Before)

Fogli et al. hep-ph/0106247; Bahcall et al. hep-ph/0106258

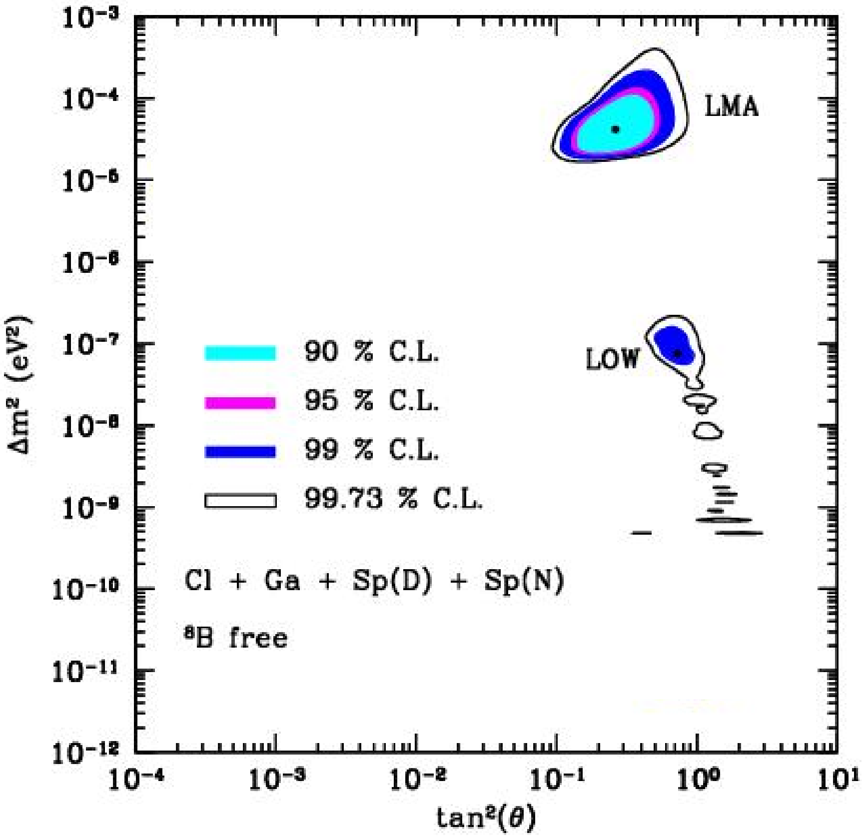


To Active Neutrinos

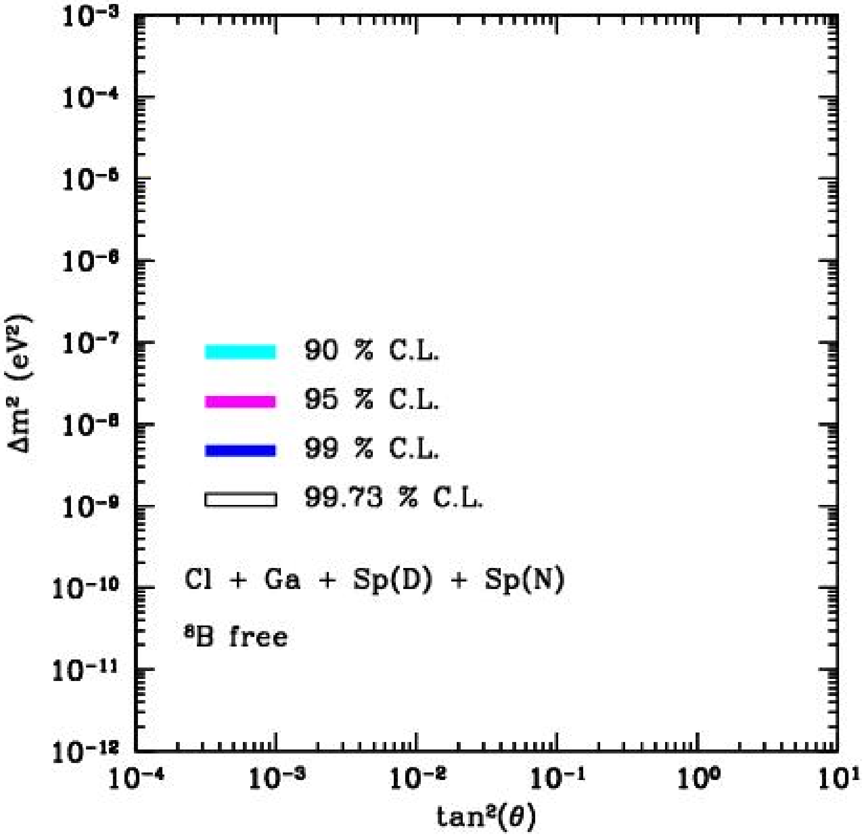


To Sterile Neutrinos

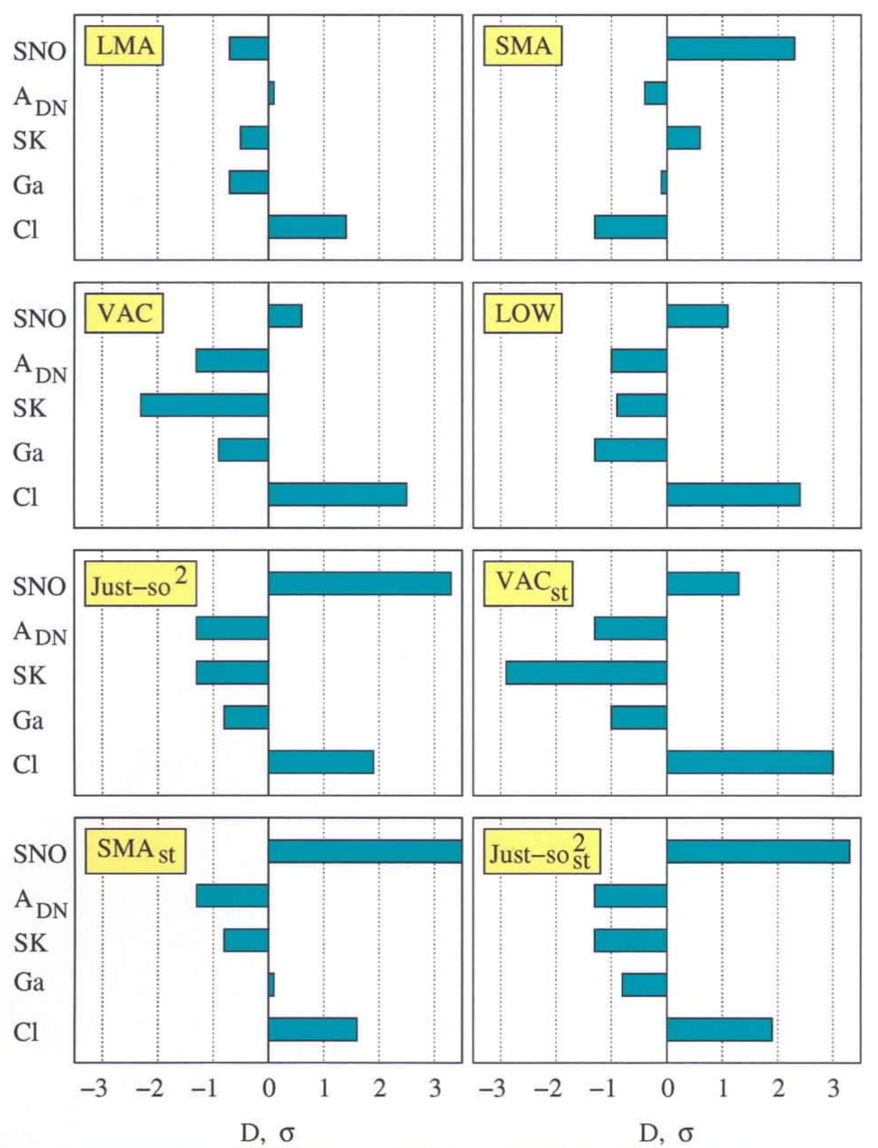
SNO Allowed Solutions for 2-Neutrino Oscillations



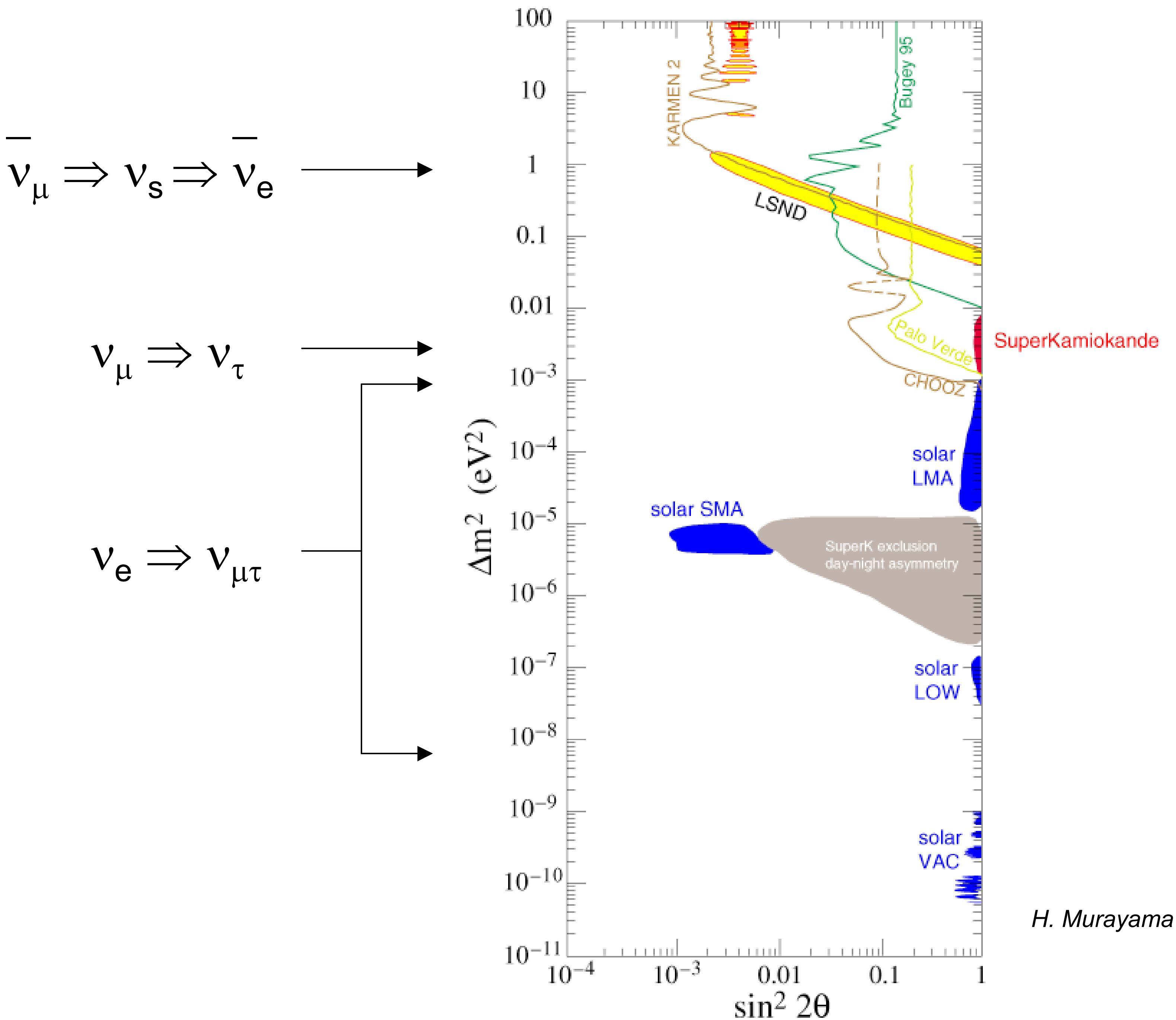
To Active Neutrinos



To Sterile Neutrinos



Krastev & Smirnov
hep-ph/0108177
Aug.22, 2001



$\bar{\nu}_\mu \Rightarrow \nu_s \Rightarrow \bar{\nu}_e$
$\nu_\mu \Rightarrow \nu_\tau$
$\nu_e \Rightarrow \nu_{\mu\tau}$
KARMEN 2
Bugey 95
LSND
Palo Verde
SuperKamiokande
CHOOZ
solar LMA
solar SMA
SuperK exclusion day-night asymmetry
solar LOW
solar VAC
Δm^2 (eV^2)
$\sin^2 2\theta$
H. Murayama

Best bet for MNSP Matrix:

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

Atmospheric

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 0 & -1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix} \times$$

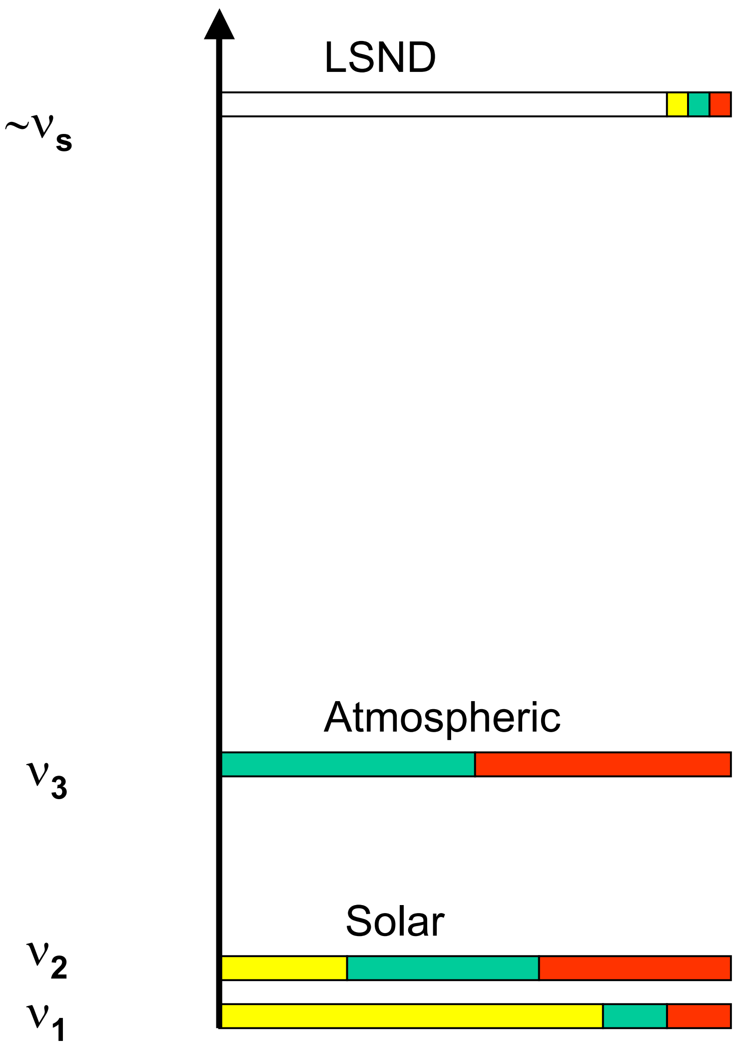
Chooz

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

LMA

$$\times \begin{pmatrix} 0.85 & 0.51 & 0 \\ -0.51 & 0.85 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

A viable mass spectrum



	Mass (eV)	e	mu	tau
$\sim\nu_s$	~1	5	5	
ν_3	0.05		50	50
ν_2	0.003	28	36	36
ν_1	=0	72	13	13

Percentages

Mass eigenstate expansion

$$\nu_e = 0.85\nu_1 + 0.51\nu_2$$

$$\nu_\mu = -0.36\nu_1 + 0.60\nu_2 + 0.71\nu_3$$

$$\nu_\tau = 0.36\nu_1 - 0.60\nu_2 + 0.71\nu_3$$

- Solar neutrino oscillations introduce a 50:50 admixture of ν_μ and ν_τ into the originally pure ν_e state.
- All solar solutions matter-enhanced: we now know level order 1,2

Cosmological Implications

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

Limits on ν_e mass:

$$|U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 < (2.8)^2 \text{ eV}^2$$

$\nu_\mu \Rightarrow \nu_\tau$ oscillations in atmospheric neutrinos:

$$|m_2^2 - m_3^2| \approx 2.4 \times 10^{-3} \text{ eV}^2$$

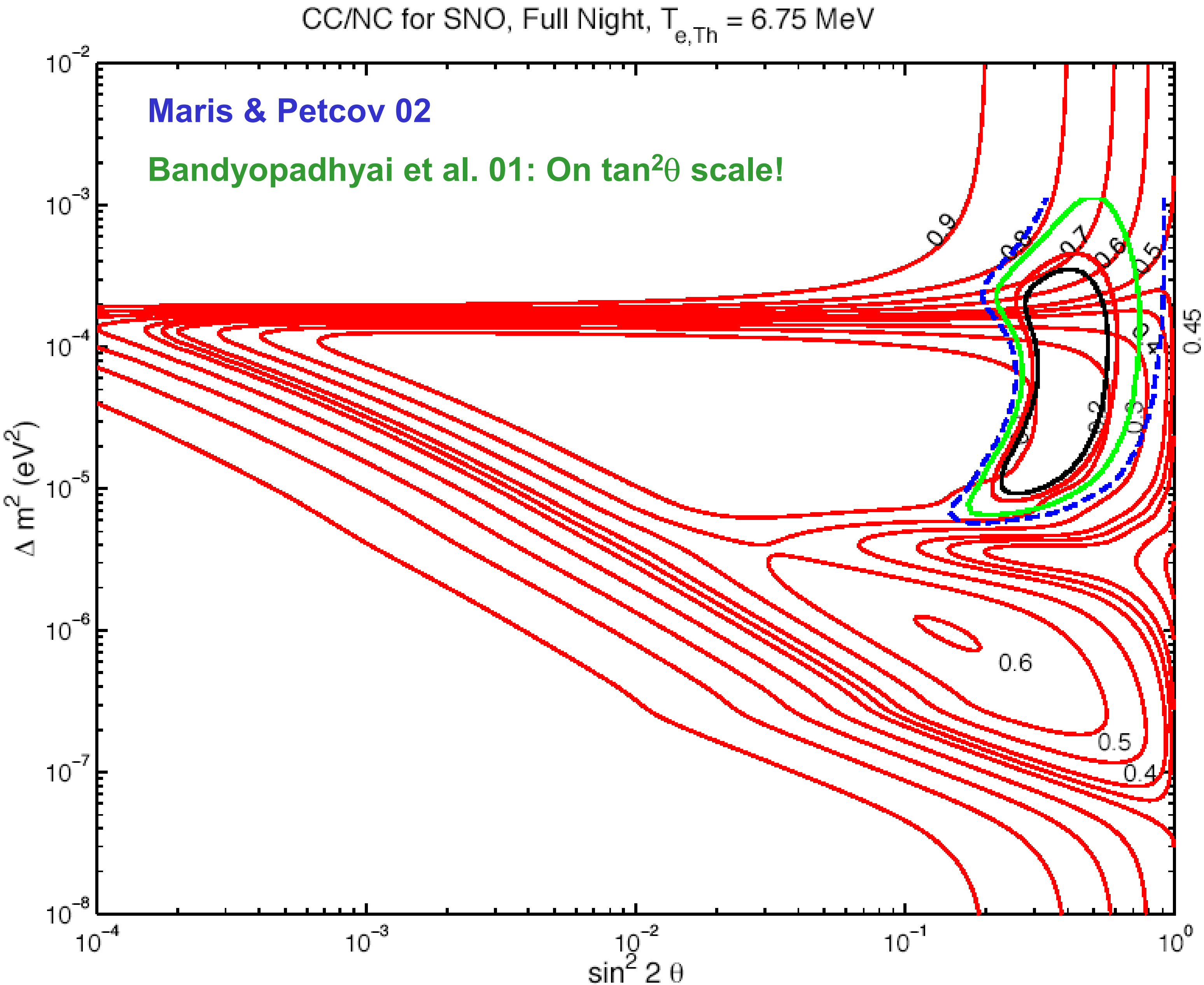
Σ neutrino masses: $0.05 < \sum_{123} m < 8.4$ eV

➥ limit on ν fraction of universe closure density: $0.001 < \Omega_\nu < 0.18$

The next steps...

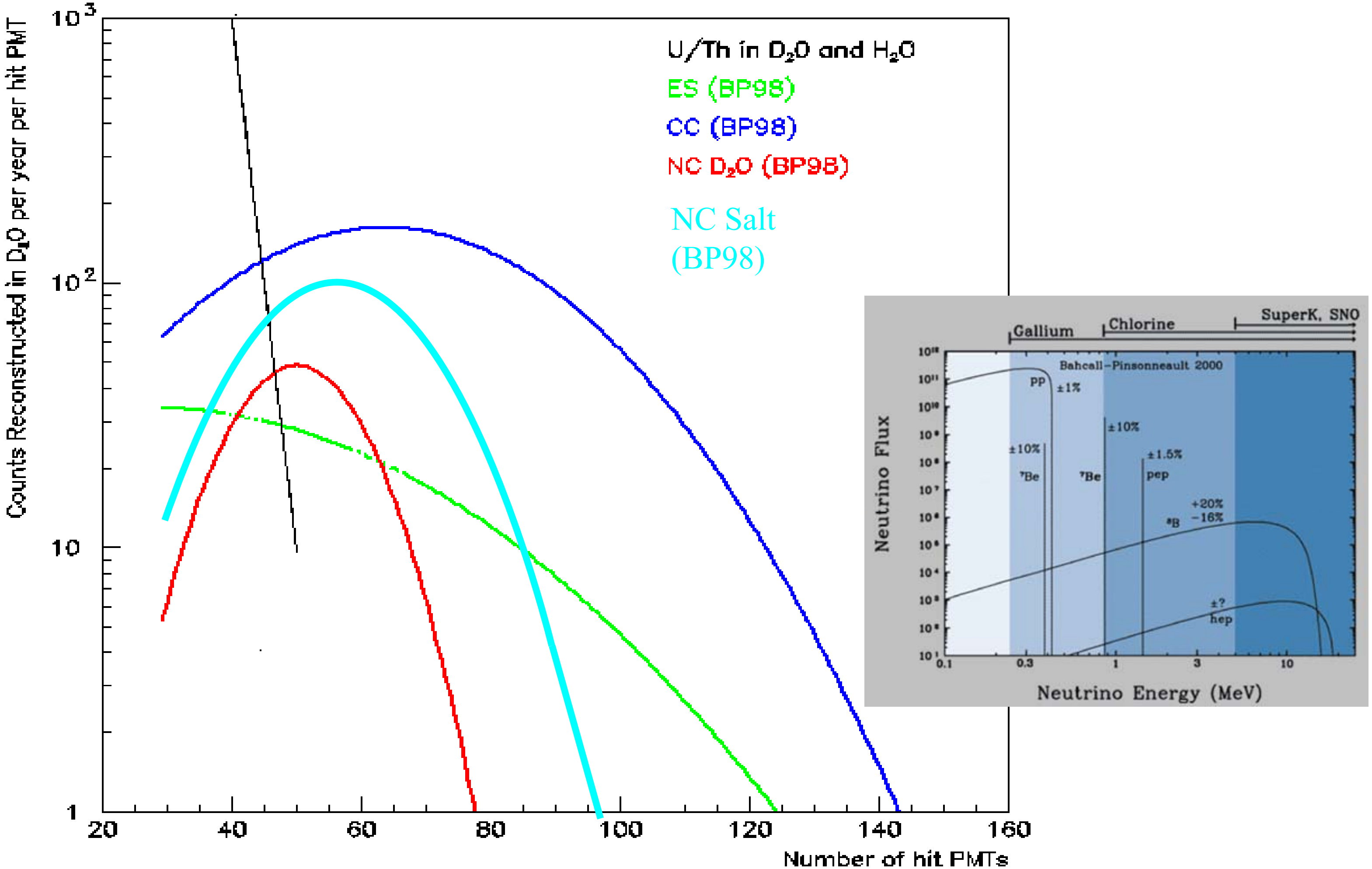
- What are the values of Δm^2, U_{ij}?
- What is the level ordering?
- What are the masses?
- Is $U_{e3} = 0$?
- How big is CP violation for neutrinos?
- Is U 3-dimensional? 4? 6? ∞?

  or, is the 3-D version unitary?
- Do neutrinos and antineutrinos mix?

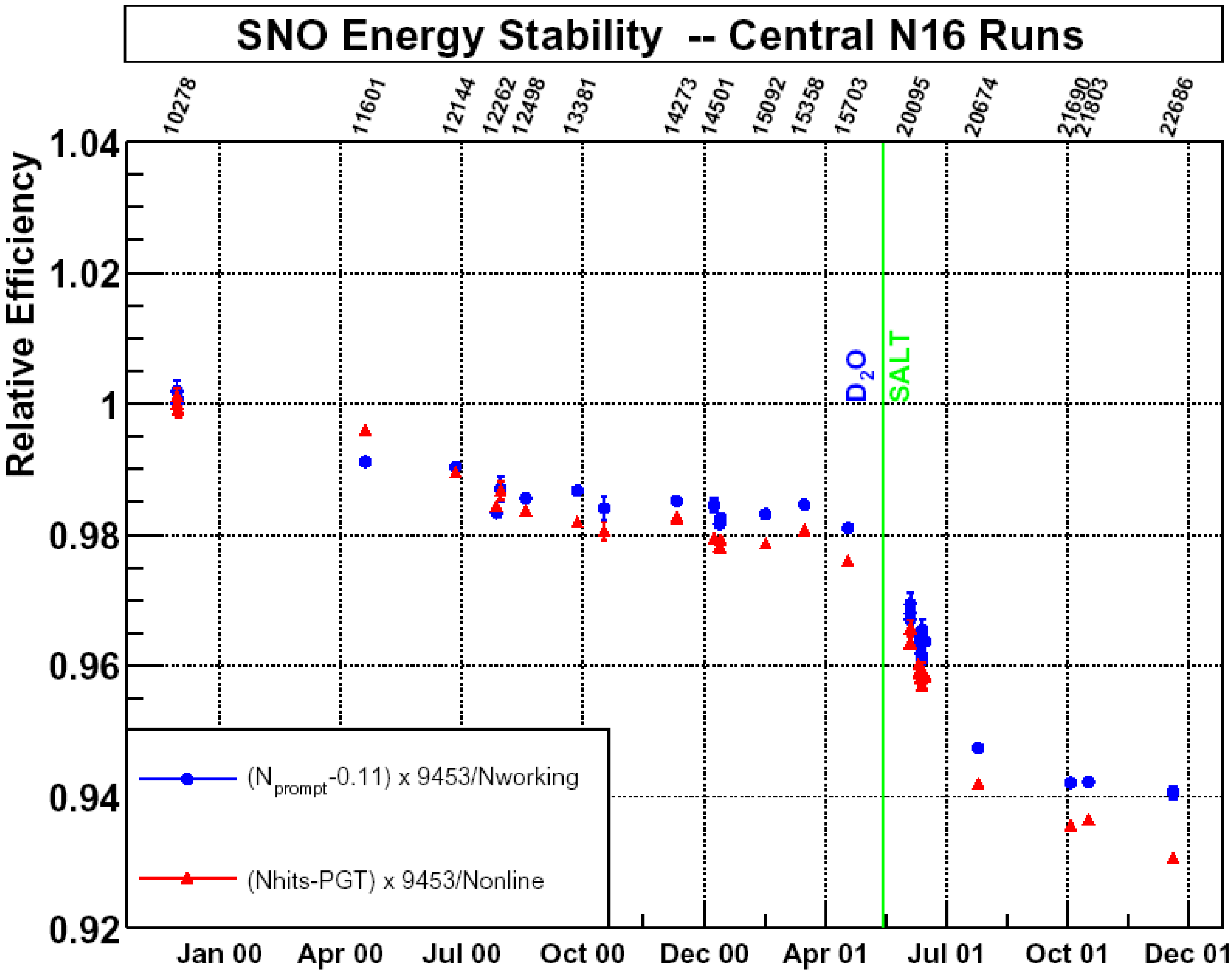


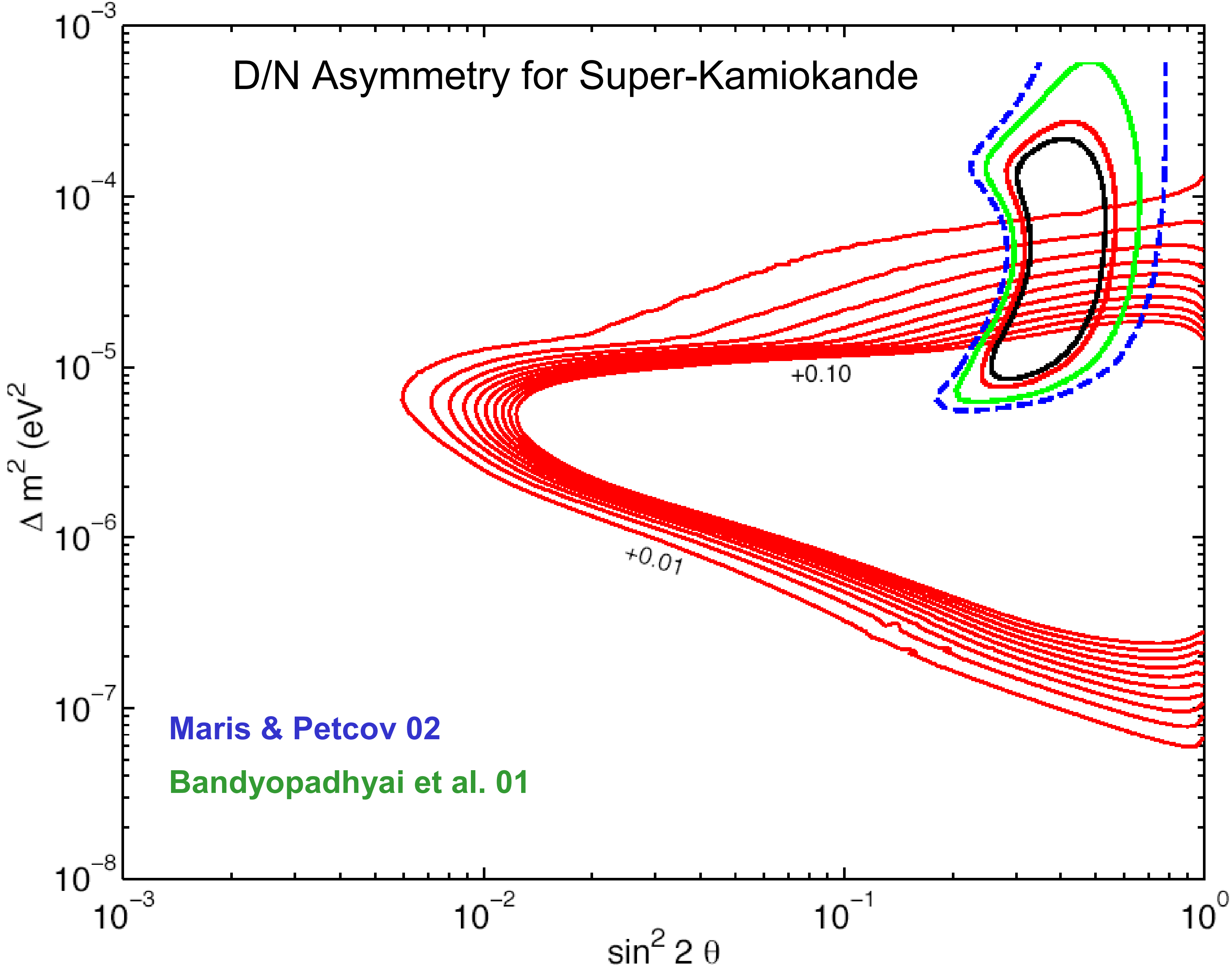
CC/NC for SNO, Full Night, $T_{e,Th}$ = 6.75 MeV
Maris & Petcov 02
Bandyopadhyai et al. 01: On $\tan^2\theta$ scale!
0.9
0.8
0.7
0.6
0.5
0.45
0.6
0.5
0.4
Δm^2 (eV^2)
$\sin^2 2\theta$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}

Signals in SNO



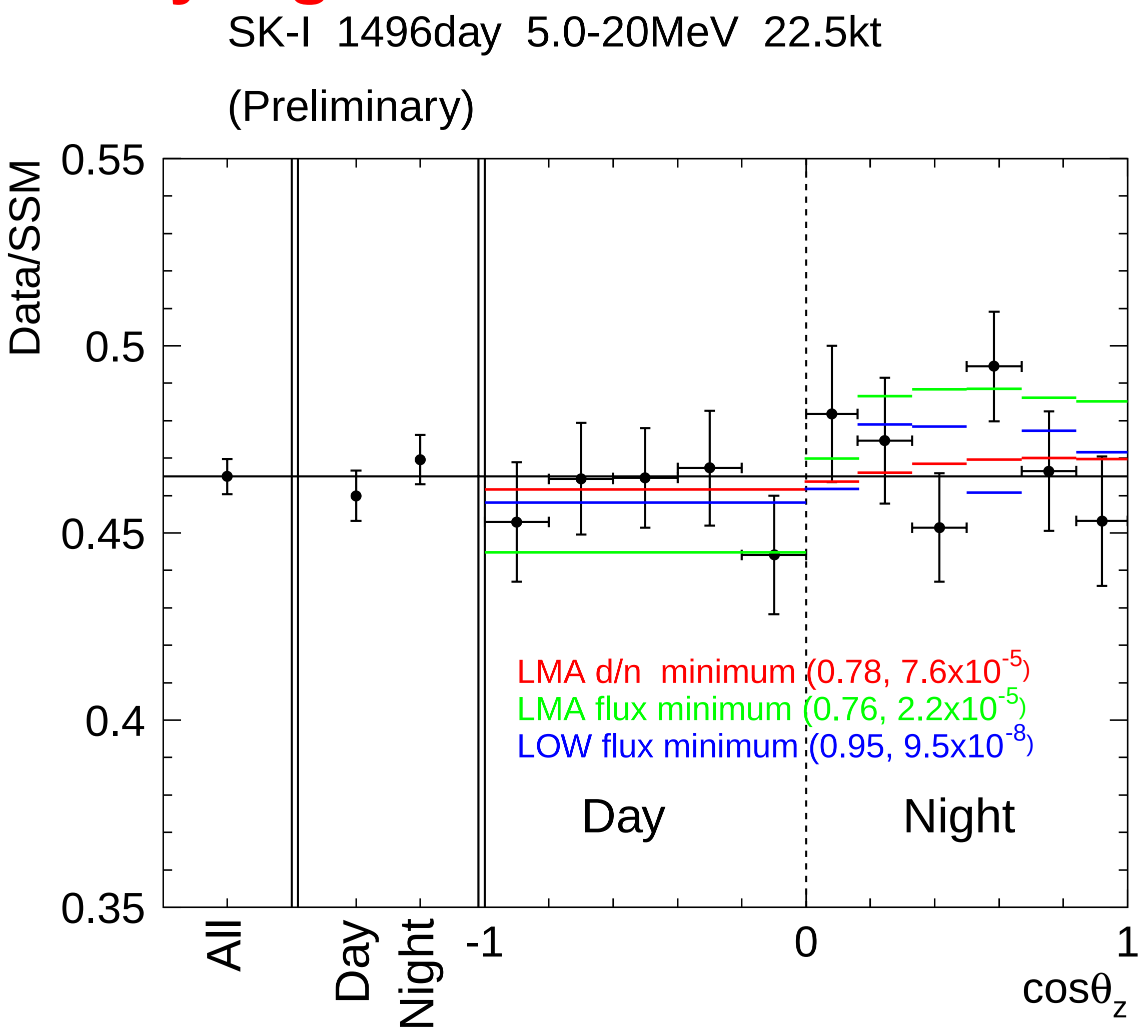
Time dependence of energy calibration

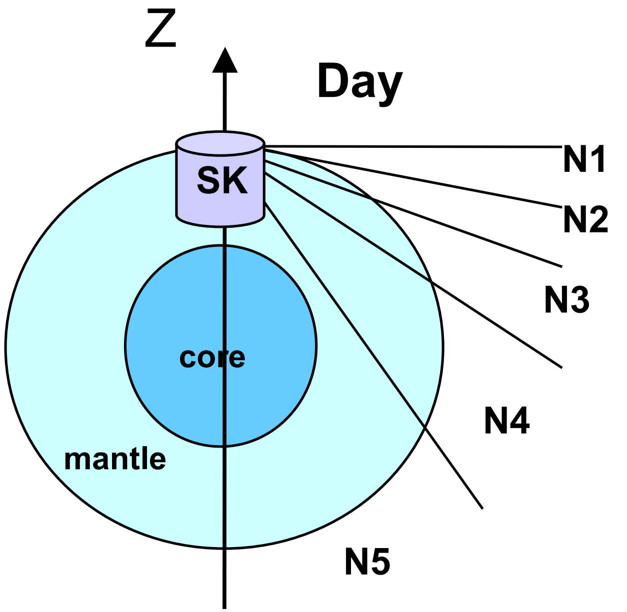




D/N Asymmetry for Super-Kamiokande
Maris & Petcov 02
Bandyopadhyai et al. 01
+0.10
+0.01
Δm^2 (eV^2)
$\sin^2 2\theta$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-3}
10^{-2}
10^{-1}
10^{0}

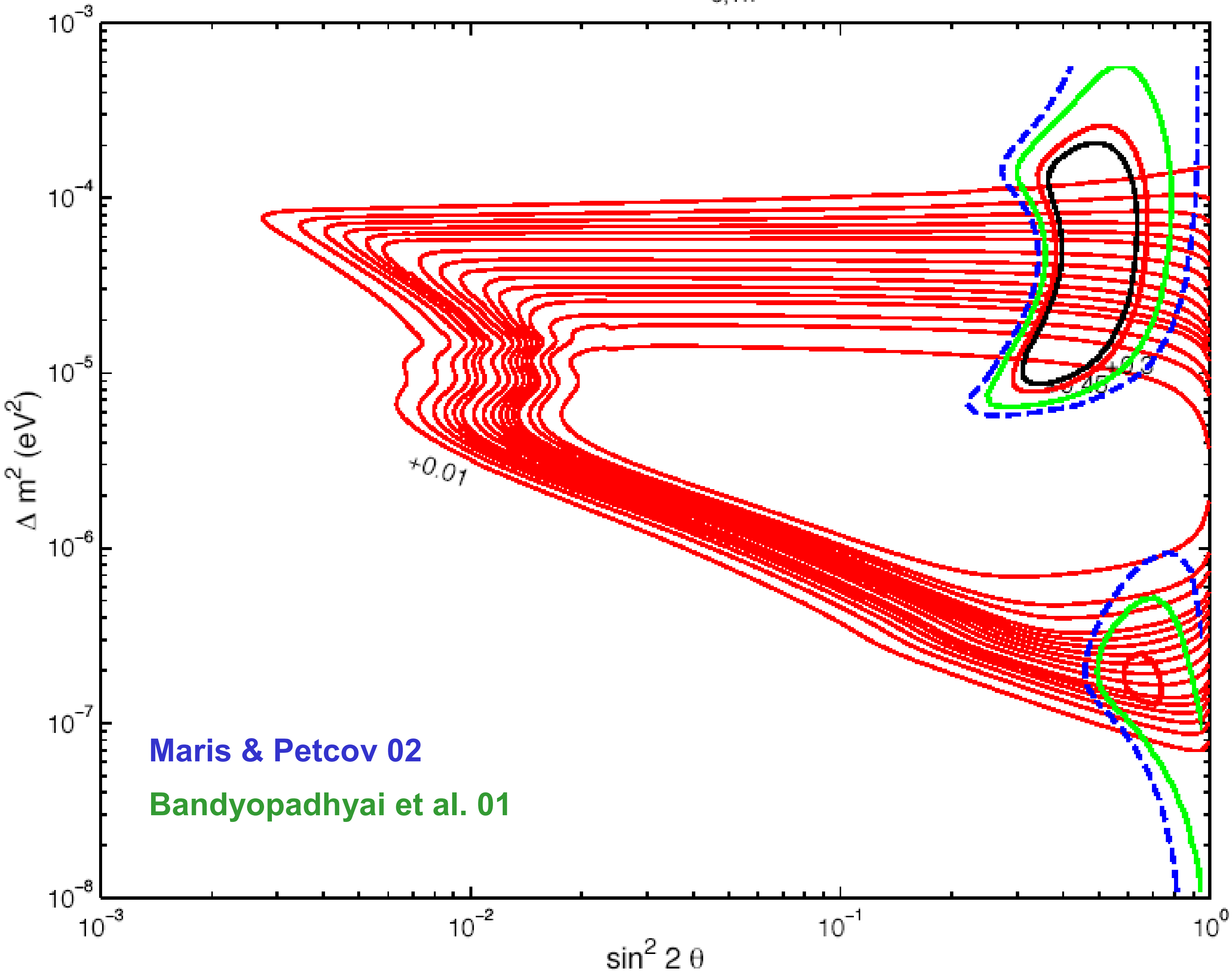
Day/night variation



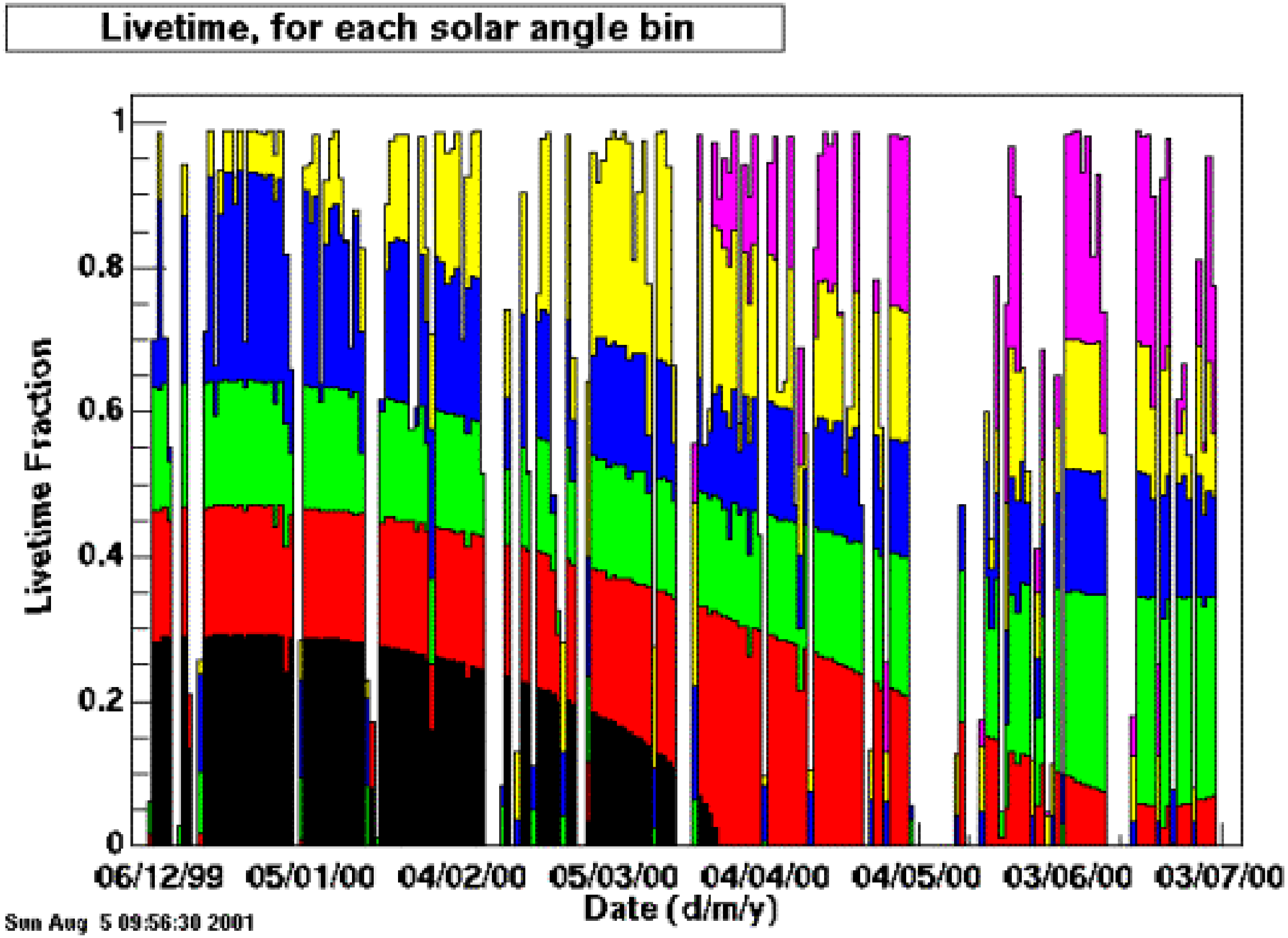


- **Day(733 days): 2.32±0.03+0.08-0.07**
- **Night(763 days): 2.37±0.03±0.08**
- **(N-D)/((N+D)/2): 0.021±0.020+0.013-0.012**

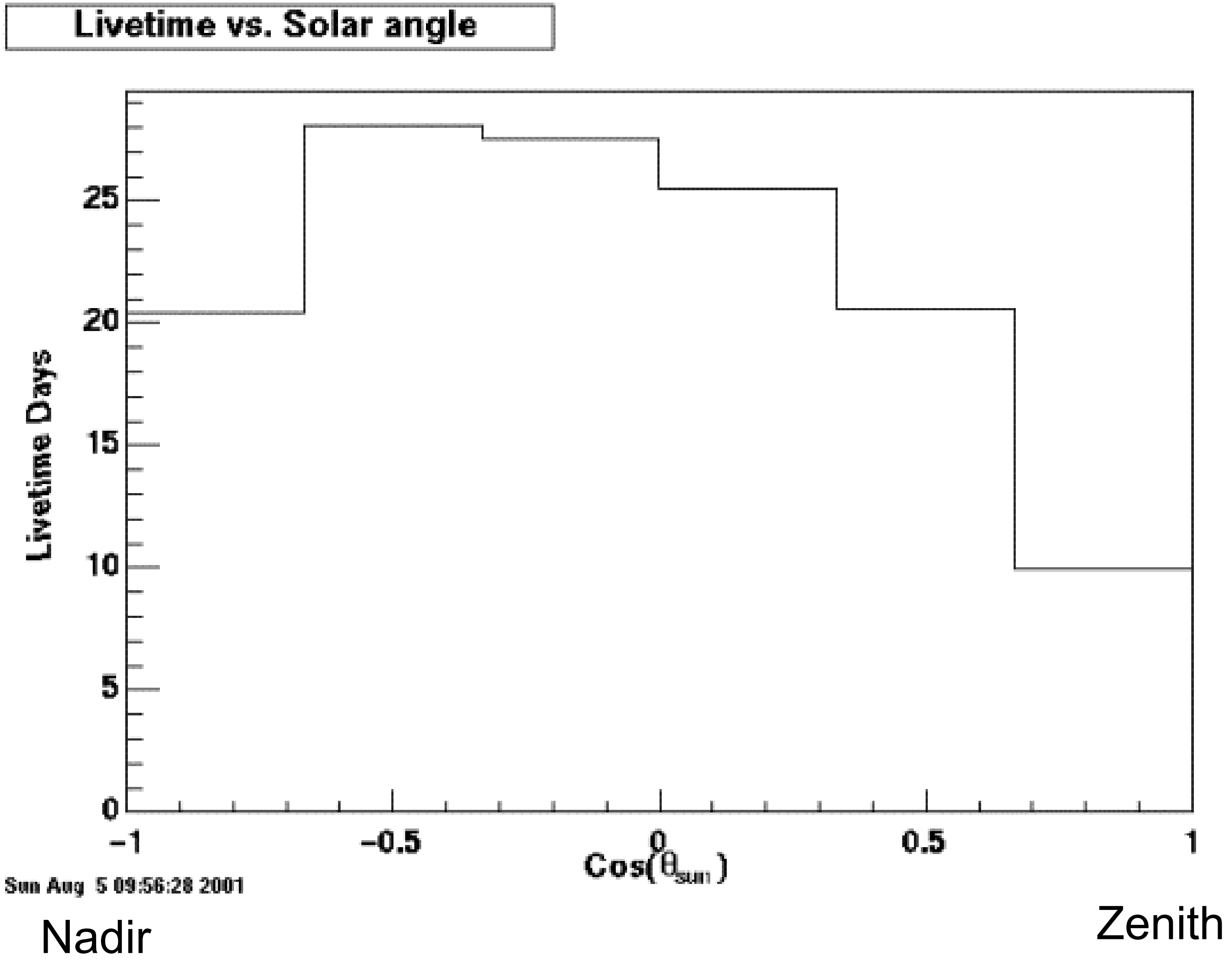
DN Effect for SNO, Full Night, $T_{e,Th}$ = 6.75 MeV



Day-night exposure at SNO



Day-night exposure...

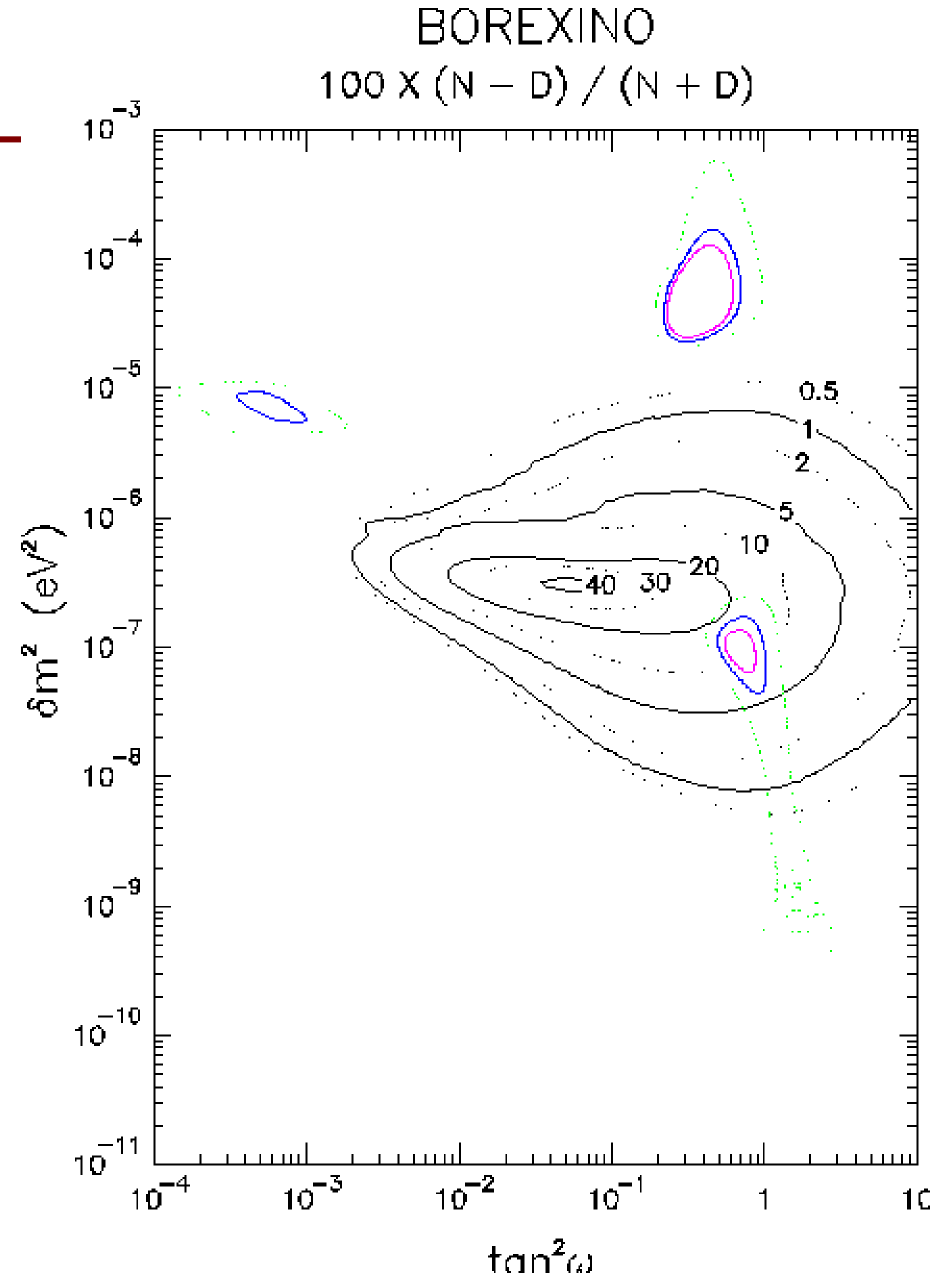


Borexino & KamLAND

Distinguishing LMA and LOW is difficult at present.

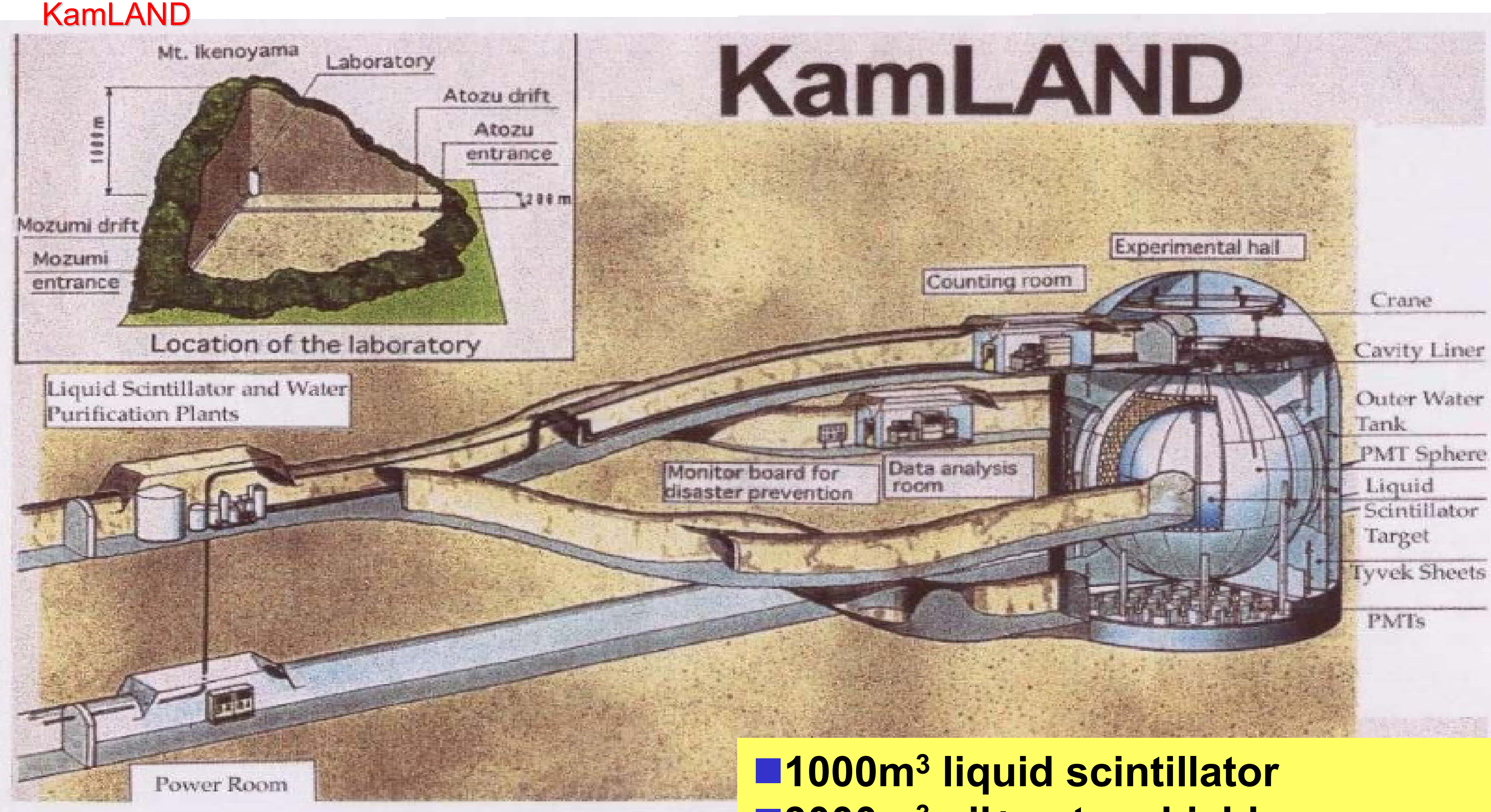
Borexino should see a large D/N asymmetry if it's LOW

KamLAND should have a clear signal from reactor $\bar{\nu}_e$ disappearance if it's LMA



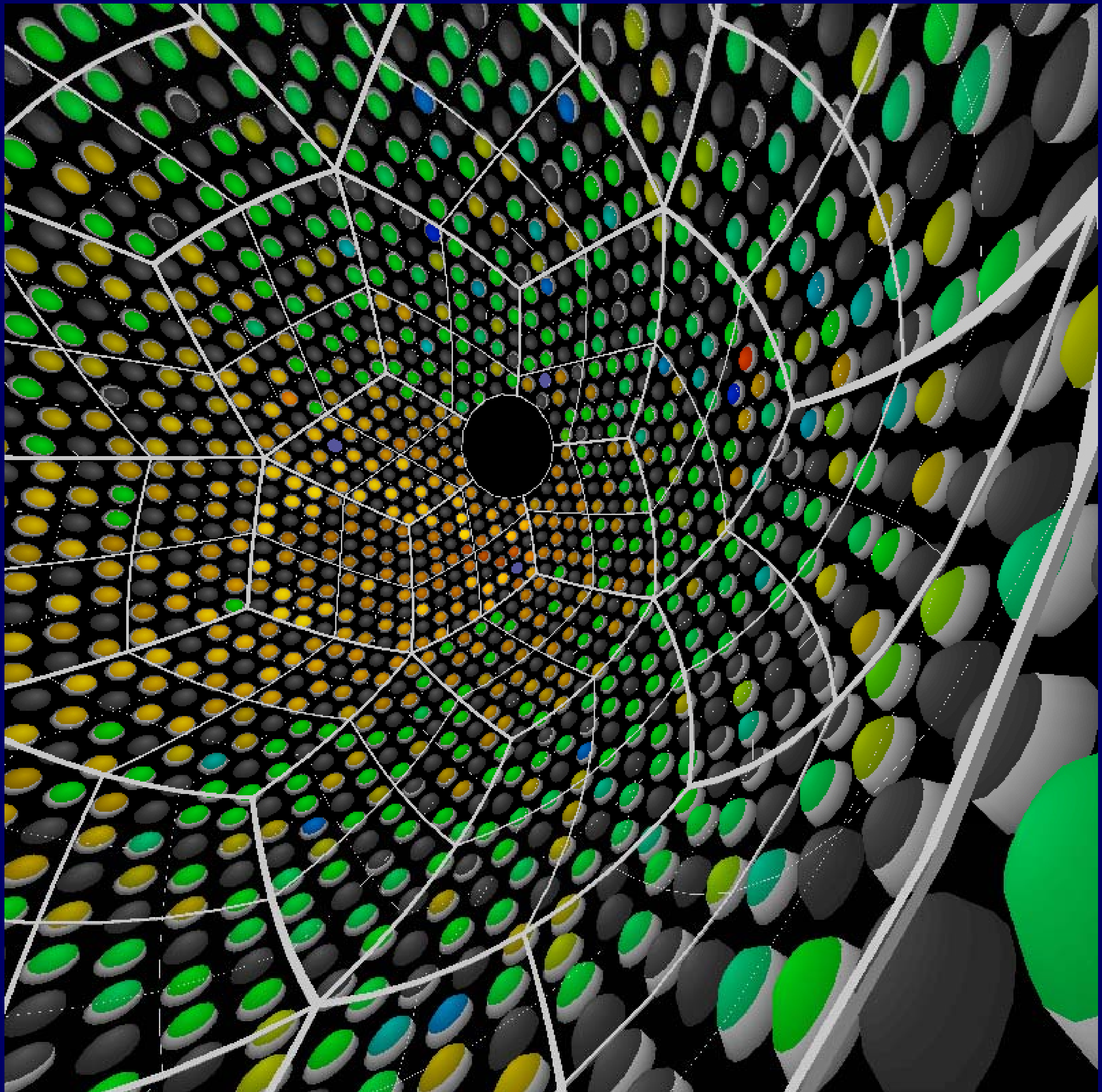
Lisi et al., PRD 61 073009, (2000)

KamLAND



- 1000m^3 liquid scintillator
- 3000m^3 oil+water shield
- 1300 17-inch PMTs +600 20-inch PMTs
- Anti-ν_e from reactors (L~170km)
- Detect e$^+$ from ν_e + p → e$^+$ + n (Eth = 1.8 MeV)

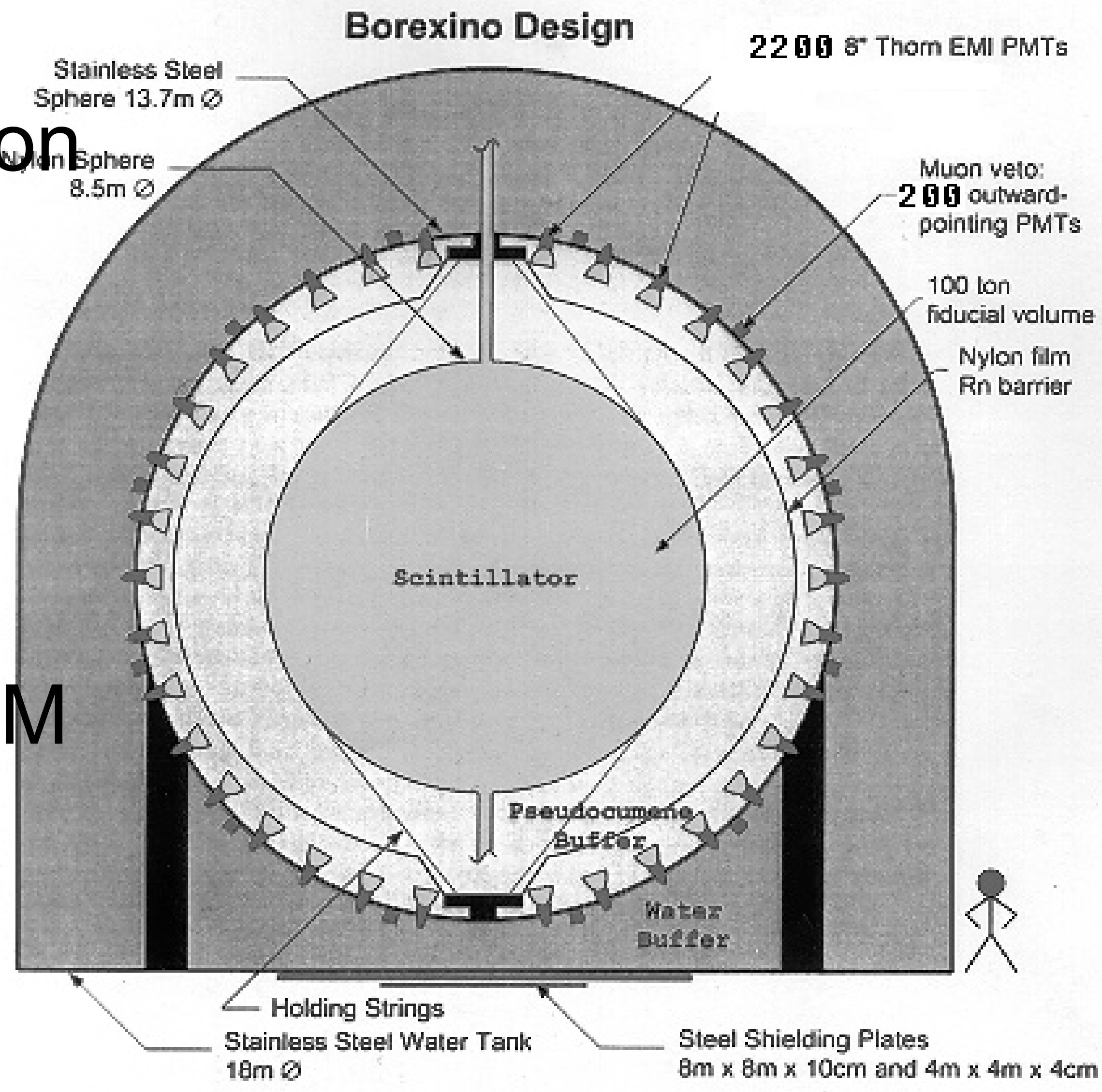
First KamLAND Event -- 27 November, 01



Borexino

http://almine.mi.infn.it/

- 300 ton liquid scintillator (100 ton fid.vol)
- 2200 8-in PMTs
- Ee > 250keV
- $\nu_e + e \rightarrow \nu_e + e$
- 55 ev/day for SSM



Unitarity of MNSP Matrix

Are there sterile neutrinos? What is the dimensionality of U?
Disappearance experiments over long baselines required

Let $U = U_{atm} \bullet U_{e3} \bullet U_{solar}$

MiniBOONE will test whether a sterile component is present at $1eV^2$

SNO ν_μ, K2K, MINOS NC will normalize U_{atm}

Low-energy solar neutrinos can test unitarity for $U_{e3} \bullet U_{solar}$

- *pp* flux now known to ~1%
- very long baseline, small Δm^2
- High precision CC and ES (or NC) required:
  - e.g. LSND in a 3+1 gives ~5% e flavor in a sterile.
  - Active oscillations complicate pp spectrum

Solar Neutrino Experiments

												Solar Neutrino Experiments
		Fiducial Mass		**Threshold, keV**			**BP00 Rates per year**					
Expt.	**Type**	**Tons**	**of**	**ES**	**CC**	**NC**	**pp +pep**	**^{7}Be**	**^{8}B**	**CNO**	**Event Eff. %**	**Start**
Cl-Ar	Radioch.	135	^{37}Cl		814		14	72	363	26	16	1968
Kamioka	Cerenkov	680	water	7000					120		100	1985
SAGE	Radioch.	23	^{71}Ga		233		181	86	31	22	25	1990
Gallex	Radioch.	12	^{71}Ga		233		94	45	16	11		1991
SuperK	Cerenkov	22000	water	5000					10200		100	1996
GNO	Radioch.	12	^{71}Ga		233		94	45	16	11		1998
SNO	Cerenkov	2000	water	5000					1100		100	1999
		200	^{2}H		6400				10000		100	1999
		200	^{2}H			2223			5000		50	1999
KamLAND	Scintillator	1000	scintillator									2001
Borexino	Scintillator	100	scintillator	250				20000				2002
HERON	L He rotons, Scintillator	5	He	100			3025	1500	2	125	80	
TPC	Gas TPC	7	He	180			4000					
CLEAN	Scintillator	12.5	Ne	100			9000					
XMASS	Scintillator		Xe									
LENS	Scintillator	5	^{176}Yb		301,445		570	400	32	136		
MOON	Scintillator	3.3	^{100}Mo		168		409	129	14	34	20	
Cl	Hybrid	2200	^{37}Cl		814		230	1200	5900	420	16	
GaAs	Ionization		^{71}Ga									
LiF	Bolometer	0.9	^{7}Li		862	487	27	29			100	

Solar Neutrino Program