

# *Neutrino Mass and Oscillations*

- *The Neutrinos*
- *The 3 positive indications of oscillations*
- *What does cosmology have to say?*
- *What options do we have?*
- *What is the mass? (direct measurements)*
- *Some key new measurements*

# The Neutrinos

Spin 1/2, Charge 0, Helicity –1, Flavors 3.

		<u>Mass</u>
<b>Electron Family</b>	$\nu_e$	< 15 eV
	$e^-$	510999.06 eV
<b>Mu Family</b>	$\nu_\mu$	< 170 keV
	$\mu^-$	105658.389 keV
<b>Tau Family</b>	$\nu_\tau$	< 18 MeV
	$\tau^-$	1777.1 MeV

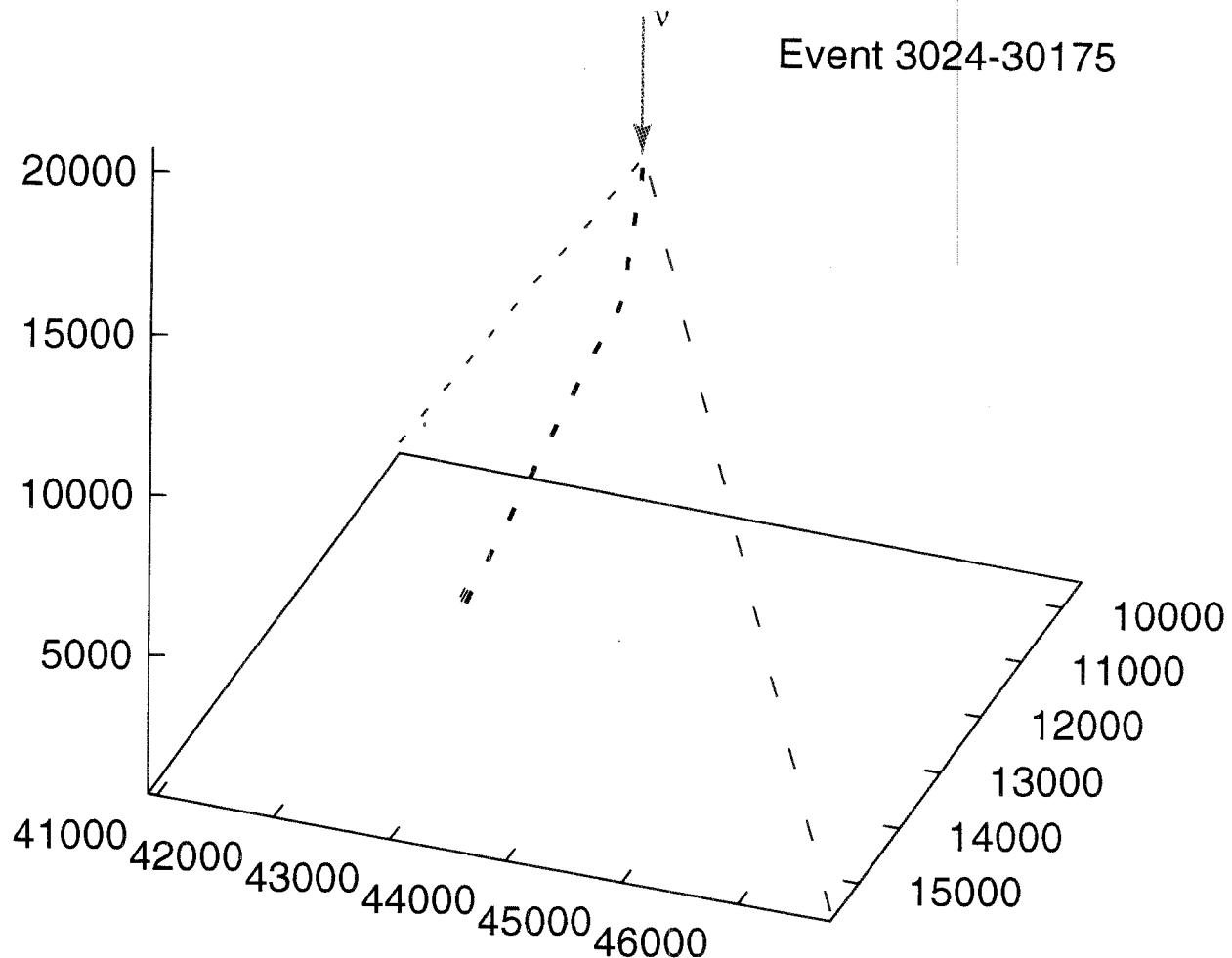
- Are the masses exactly zero, as in the Standard Model ?
- Are the families mixed? Is lepton family number violated ?
- Are there other kinds of neutrino?
- Are neutrinos their own antiparticles?
- Do neutrinos make up a significant part of the mass of the universe?

PDG 1998

# DONUT Experiment (FNAL E872)

July 1:

- 864  $\nu$  events selected electronically
- 361 scanned
- of 97 events, 12 kinks, 3 candidates



Candidate event in ECC1. The three tracks with full emulsion data are shown. The red track shows a 100 mrad kink 4.5mm from the interaction vertex. The scale units are microns.

## Neutrino Mass Matrix

For an electron, the mass term in the Lagrangian would be,

$$L^D = -\frac{m_D}{2} \bar{\psi} \psi + \text{h.c.}$$

Since the fall of parity, we prefer a chiral basis,

$$\begin{aligned}\psi_L &= \frac{1}{2}(1 - \gamma_5)\psi \\ \psi_R &= \frac{1}{2}(1 + \gamma_5)\psi \\ L^D &= -\frac{m_D}{2}(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L) + \text{h.c.}\end{aligned}$$

Then, for a Dirac particle,

$$L_m^D = -\frac{1}{2}[(\bar{\psi}_L)^c, \bar{\psi}_R, \bar{\psi}_L, (\bar{\psi}_R)^c] \begin{pmatrix} 0 & 0 & 0 & m_D \\ 0 & 0 & m_D & 0 \\ 0 & m_D & 0 & 0 \\ m_D & 0 & 0 & 0 \end{pmatrix} \begin{bmatrix} (\psi_L)^c \\ \psi_R \\ \psi_L \\ (\psi_R)^c \end{bmatrix}$$

(Lorentz-invariant mass terms only arise from LR combinations.)

*Haxton and Stephenson Prog. Part. Nucl. Phys. 12, 409 (1984).  
P. Vogel Nucl. Part. Astrophys. Conf. 1997.*

Why is the neutrino mass so small?

Standard Model eliminates the RH fields,

$$L_m^{SM} = -\frac{1}{2}[(\bar{\psi}_L)^c, 0, \bar{\psi}_L, 0] \begin{pmatrix} 0 & 0 & 0 & m_D \\ 0 & 0 & m_D & 0 \\ 0 & m_D & 0 & 0 \\ m_D & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} (\psi_L)^c \\ 0 \\ \psi_L \\ 0 \end{pmatrix}$$

That makes the mass zero.

Gell-Mann, Ramond & Slansky, and Yanagida, suggested a different way,

$$L_m^{ss} = -\frac{1}{2}[(\bar{\psi}_L)^c, \bar{\psi}_R, \bar{\psi}_L, (\bar{\psi}_R)^c] \begin{pmatrix} 0 & 0 & m_L & m_D \\ 0 & 0 & m_D & m_R \\ m_L & m_D & 0 & 0 \\ m_D & m_R & 0 & 0 \end{pmatrix} \begin{pmatrix} (\psi_L)^c \\ \psi_R \\ \psi_L \\ (\psi_R)^c \end{pmatrix}$$

To find fields of definite mass, we have to diagonalize. The charge-conjugate pairs are coupled by the new terms to make Majorana eigenstates,

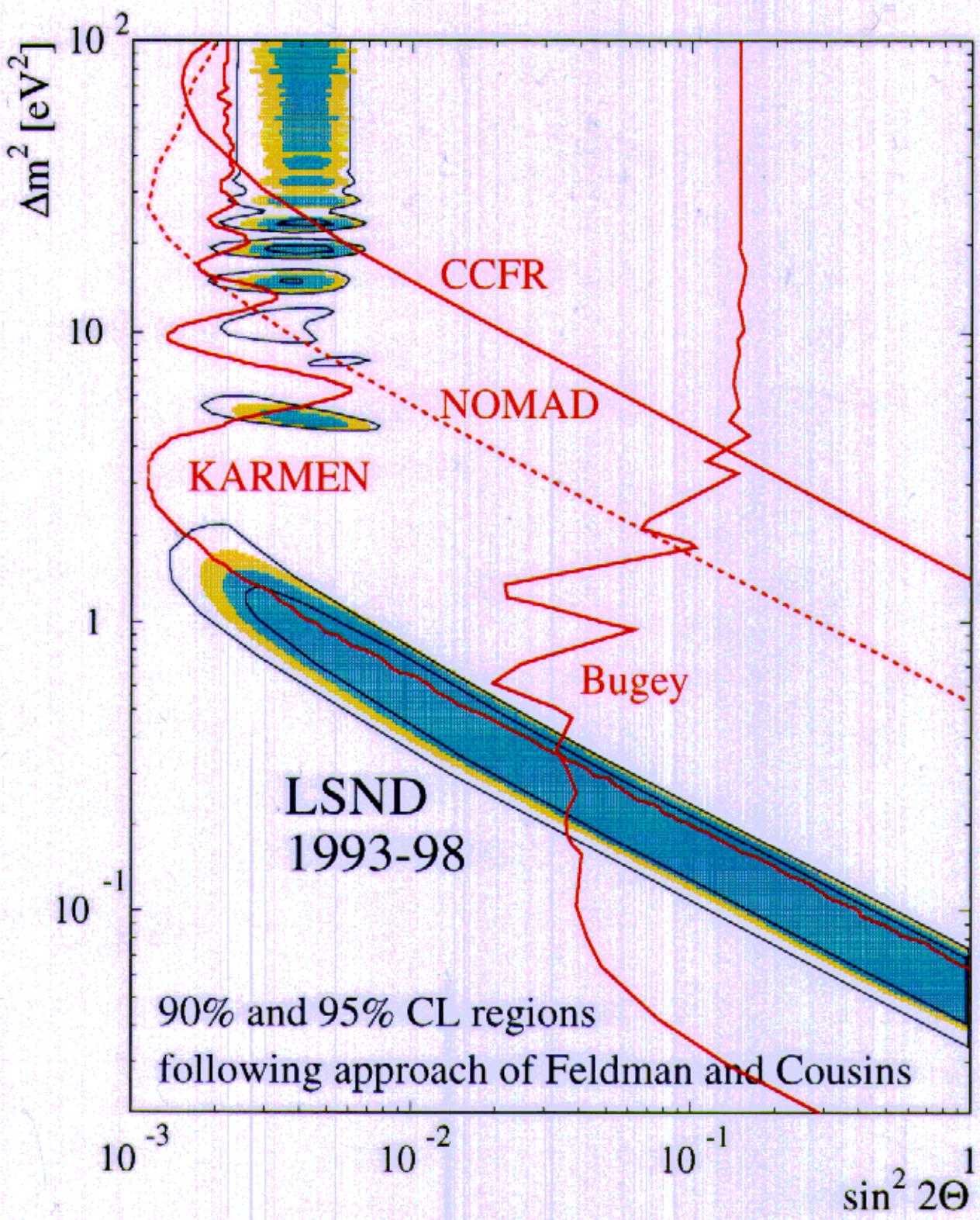
$$\frac{1}{\sqrt{2}} \begin{bmatrix} \psi_L + (\psi_L)^c \\ \psi_R + (\psi_R)^c \\ \psi_L - (\psi_L)^c \\ \psi_R - (\psi_R)^c \end{bmatrix}$$

For  $m_R \simeq M_{\text{GUT}}$  and  $m_L \simeq 0$ , the mass eigenvalues are

$$m_L' \simeq \frac{m_D^2}{M_{\text{GUT}}} \\ m_R' \simeq M_{\text{GUT}}$$

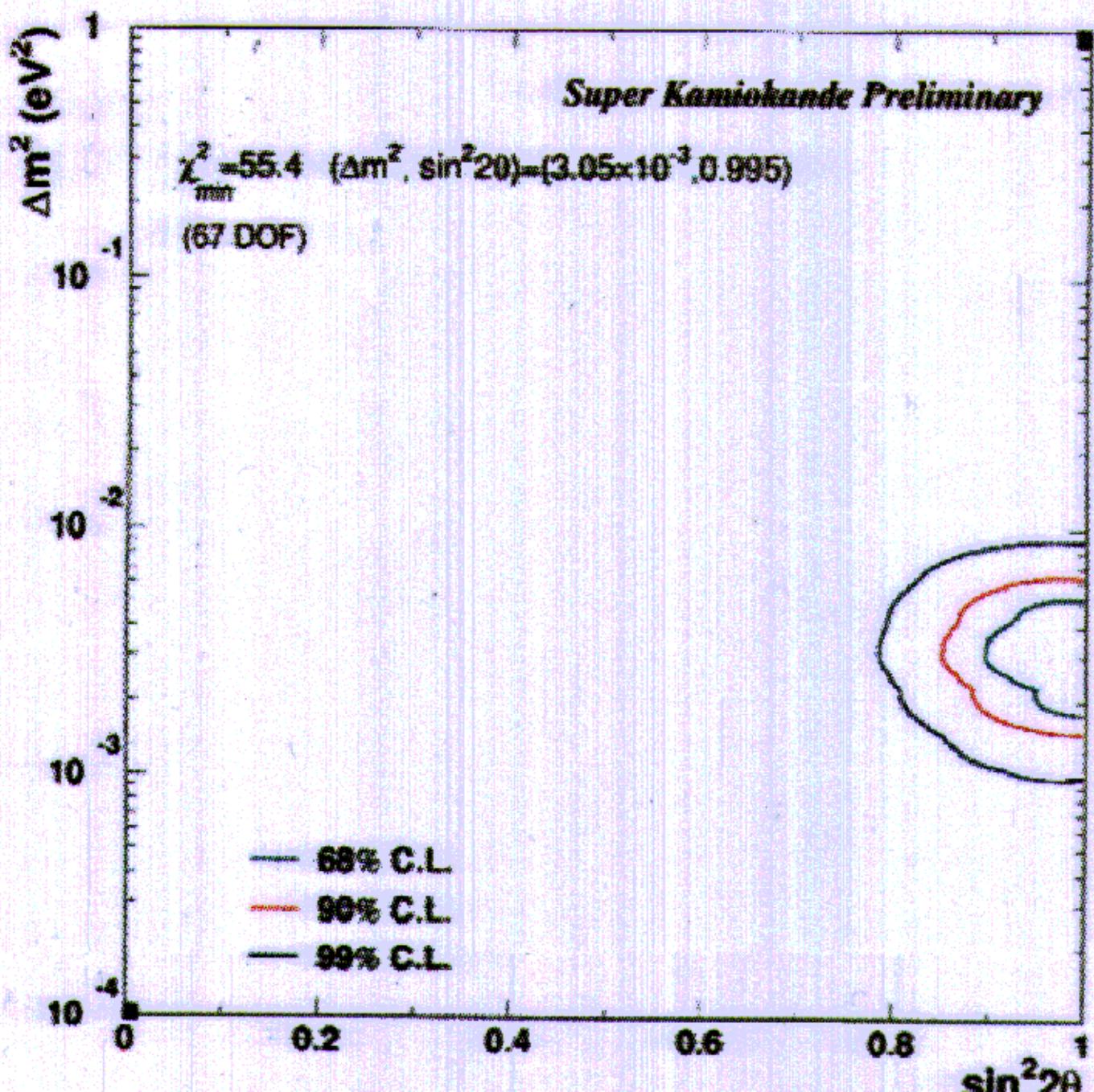
This is the “see-saw” and it predicts,

- Light neutrinos are Majorana,
- The lightness of neutrinos results from the heaviness of  $M_{\text{GUT}}$



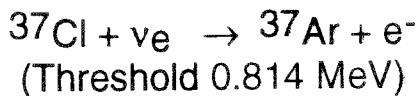
# Allowed region for atmospheric neutrino data

— Fully-contained + partially contained events



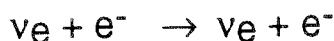
# SOLAR NEUTRINO EXPERIMENTS - 1999

## Chlorine-Argon (Homestake) (127 tonnes $^{37}\text{Cl}$ )



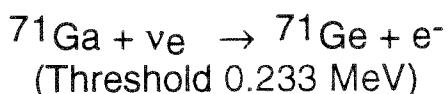
$2.54 \pm 0.16(\text{statistical}) \pm 0.16(\text{systematic})$  SNU \*.

## Water



Kamiokande II + III (680 T) (Threshold 7.0 MeV)	SuperKamiokande (22,000 T) (Threshold 6.5 MeV)
$2.80 \pm 0.19 \pm 0.33$ $\times 10^6 \text{ cm}^{-2}\text{s}^{-1}$ **	$2.44^{+0.05}_{-0.05}{}^{+0.09}_{-0.07}$ $\times 10^6 \text{ cm}^{-2}\text{s}^{-1}$ **

## Gallium



SAGE ( 23 tonnes $^{71}\text{Ga}$ )	Gallex (12 tonnes $^{71}\text{Ga}$ )
$67 \pm 7 \pm 4$ SNU *	$78 \pm 6 \pm 5$ SNU *
$^{51}\text{Cr} : 95 \pm 11 {}^{+5/-8} \%$	$^{51}\text{Cr} : 92 \pm 7 \%$

\*\* PRL 77, 1683 (1996).

\*\* PRL in press.

\* see Bahcall *et al.* PRD 58, 096016-1 (1998). (1 SNU =  $10^{-36}$  captures / atom / s)

## Sources of Neutrinos in the Sun, Flux at Earth

### Flux Contributions

p-p	$^7\text{Be}$	$^8\text{B}$	Data	Experiment
$\mathbf{a_{C1} \Phi_1}$	$+ \mathbf{a_{C7} \Phi_{7+}}$	$+ \mathbf{a_{C8} \Phi_8}$	$= 2.56 \pm 0.22$	Cl-Ar
		$\mathbf{a_{K8} \Phi_8}$	$= 2.44 \pm 0.11$	Kamiokande
$\mathbf{a_{G1} \Phi_1}$	$+ \mathbf{a_{G7} \Phi_{7+}}$	$+ \mathbf{a_{G8} \Phi_8}$	$= 71.1 \pm 7.20$	Gallium
0.979 $\Phi_1$	$+ 0.939 \Phi_{7+} + 0.498 \Phi_8 = 2 \text{ I/Q}$			Luminosity

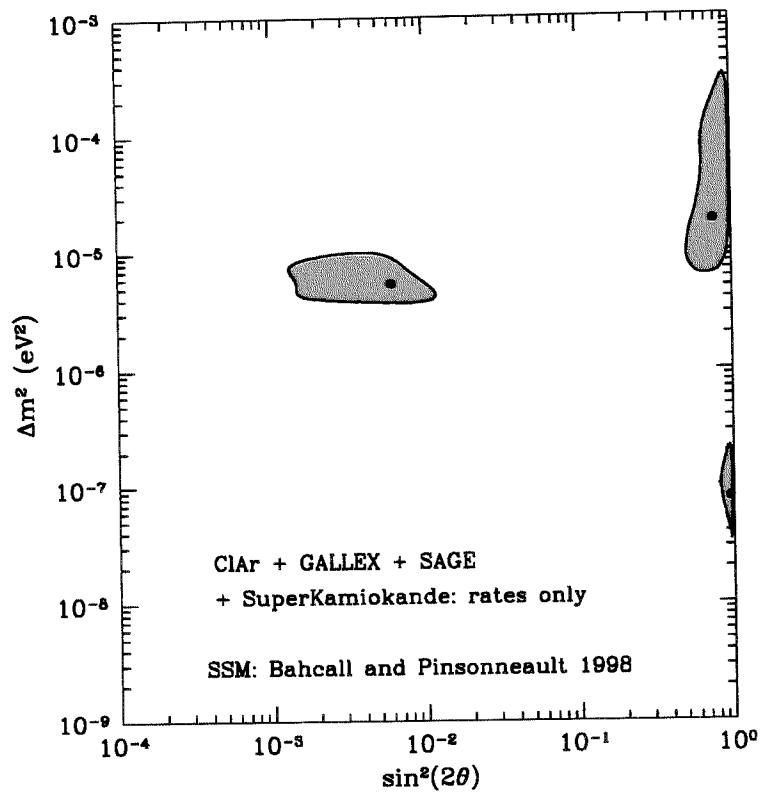
$f_{\text{CNO}} = 0$ ,  $f_{\text{pep}} = 0.0023$   
 fluxes in  $10^{10} \text{ v cm}^{-2} \text{ s}^{-1}$

### Solving for the fluxes

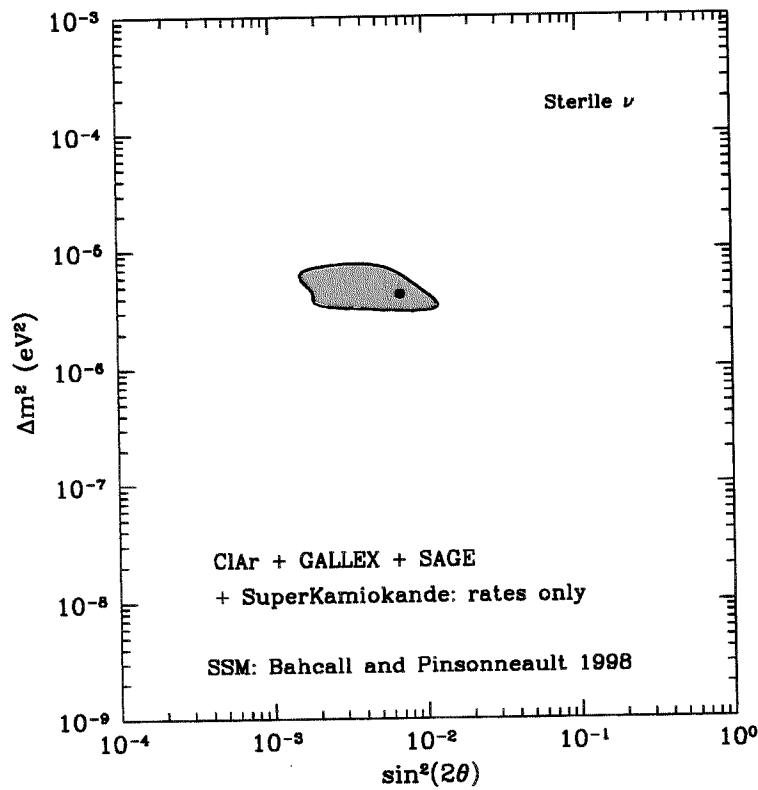
$$\begin{array}{ll}
 \Phi_1 & = \text{pp} + \text{pep} \\
 \Phi_{7+} & = {}^7\text{Be} + \text{CNO} \\
 \Phi_8 & = {}^8\text{B}
 \end{array}
 \quad
 \begin{array}{ll}
 \Phi_1 & = 6.70 \pm 1.10 \\
 \Phi_{7+} & = -0.17 \pm 0.10 \\
 \Phi_8 & = 0.24 \pm 0.22 \times 10^{-3}
 \end{array}$$

- ⇒  ${}^7\text{Be}$  neutrino flux is negative at 93% CL
- ⇒ non-physical solution, inconsistent experimental data

## Solar Neutrinos – Sterile and Active



MSW solutions (rates only, 99% CL) for active neutrinos.  
*Bahcall et al. PRD 58 096016-1 (1998).*

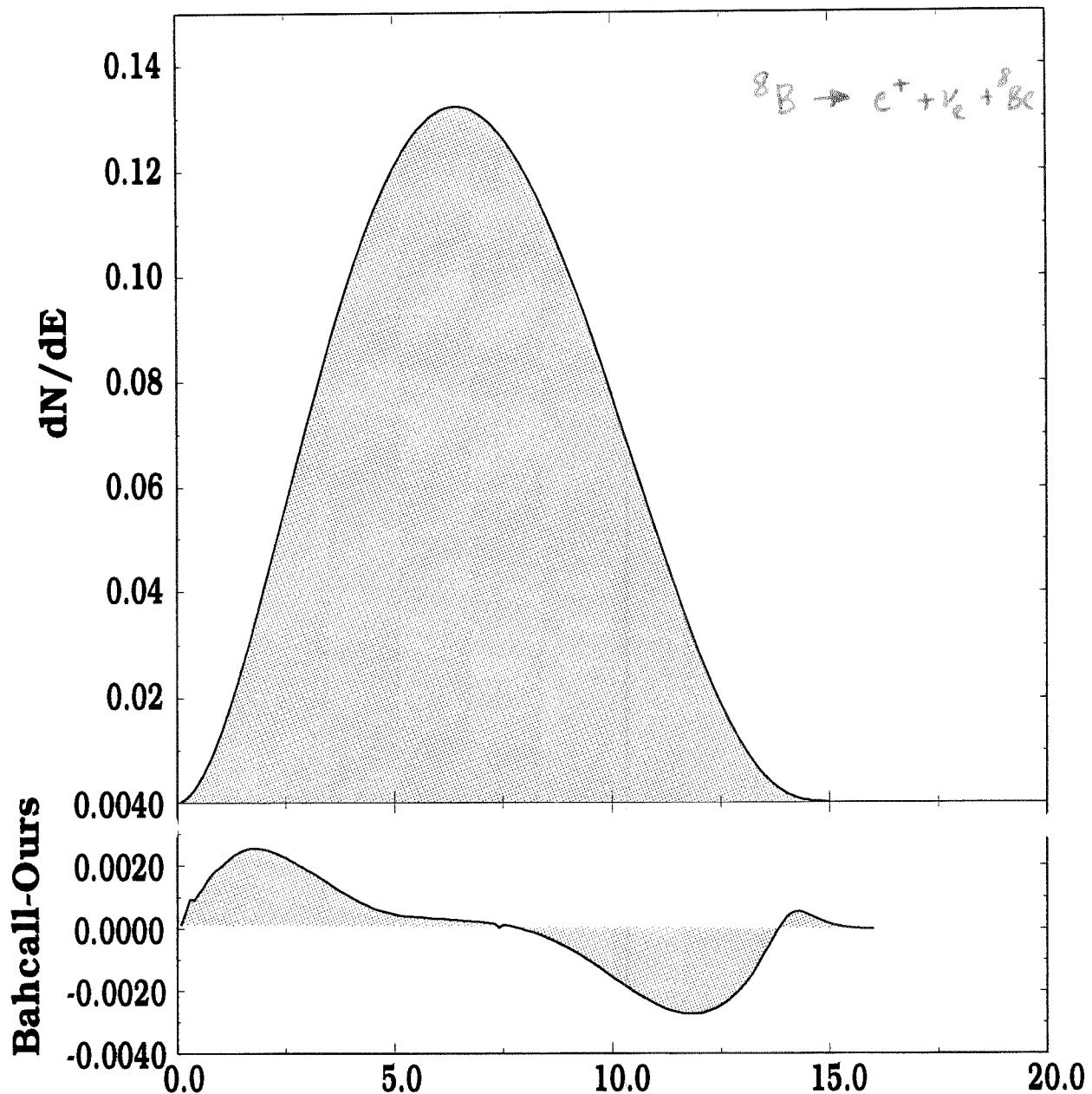


MSW solutions (rates only, 99% CL) for sterile neutrinos.  
*Bahcall et al. PRD 58 096016-1 (1998).*

## *Is There a Spectrum Distortion?*

- *hep neutrinos have a higher energy than  ${}^8B$ , s-wave capture very uncertain*
- *Recent first-principles calculations increase hep by about 2x (Schiavilla and Marcucci)*
- *One of 5 p-wave contributions has been calculated,  
= 70% of the old s-wave*
- *Other 4 will likely be comparable*
- *${}^8B$  may have a ground state transition with a high endpoint energy*
- *Shape of  ${}^8B$  spectrum must be determined in the laboratory (A. Garcia, Notre Dame 99).*

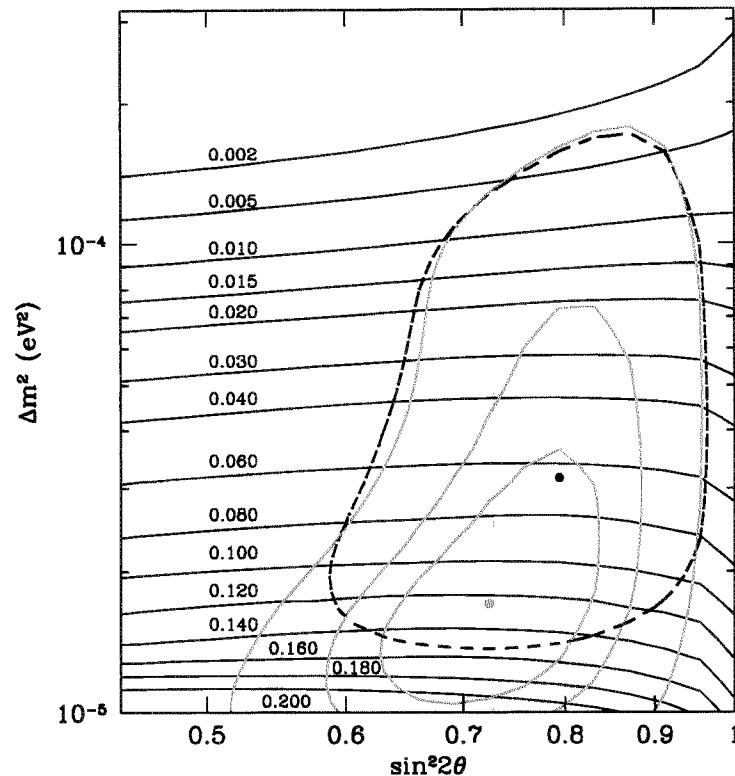
# Neutrino energy spectrum



## The LMA Solution Wars

The upward-going *electron neutrinos* in SuperK have  $E/L \sim 6 \times 10^{-5}$  eV<sup>2</sup>, and so give information about the LMA solar solution.

Bahcall, Krastev, and Smirnov [hep-ph/9905220](https://arxiv.org/abs/hep-ph/9905220) see a slight excess as might be expected for LMA active.

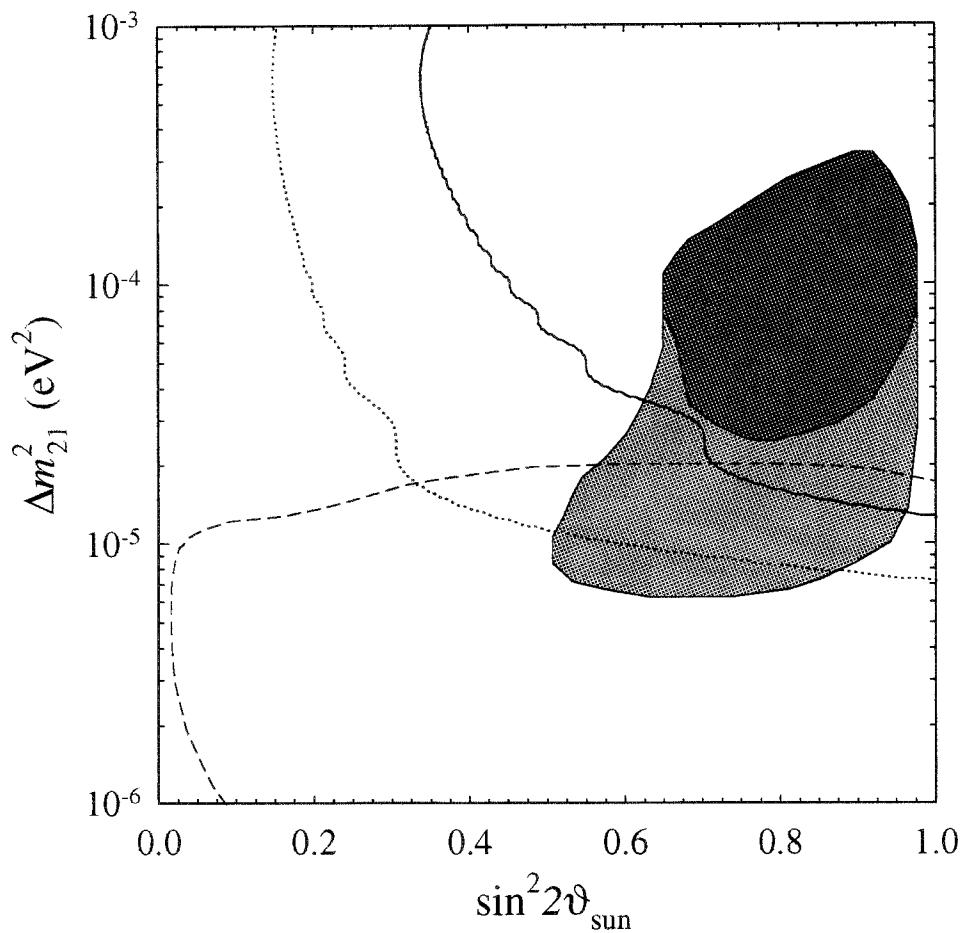


Allowed regions for LMA. Continuous closed contours – rates only (90, 95, 99% CL).

Dashed contour – rates plus day-night (99% CL).

Horizontal contours – Night-Day asymmetries.

Giunti et al. [\*hep-ph/9902261\*](https://arxiv.org/abs/hep-ph/9902261) find the excess rules out the LMA for active. But they left out matter effects. Their result applies to *sterile*, but that is disfavored for LMA.



Allowed regions for LMA (shaded). Solid contour – excluded by SuperK.  
Dotted – excluded by SuperK for  $\sin^2(2\theta) = 1$ ; also approximate reach of KamLAND for  $\bar{\nu}_e$  disappearance.

# "SNO"

## SUDBURY NEUTRINO OBSERVATORY

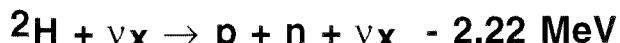
Canada - US - UK

A detector sensitive to  $\nu_\mu$ ,  $\nu_\tau$ , as well as  $\nu_e$ . Also, all the antineutrinos.

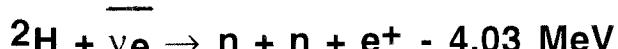
Three distinct reactions on deuterium:



(Charged current: CC)

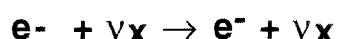


(Neutral current: NC)



(Charged current: CA)

Plus Elastic scattering:

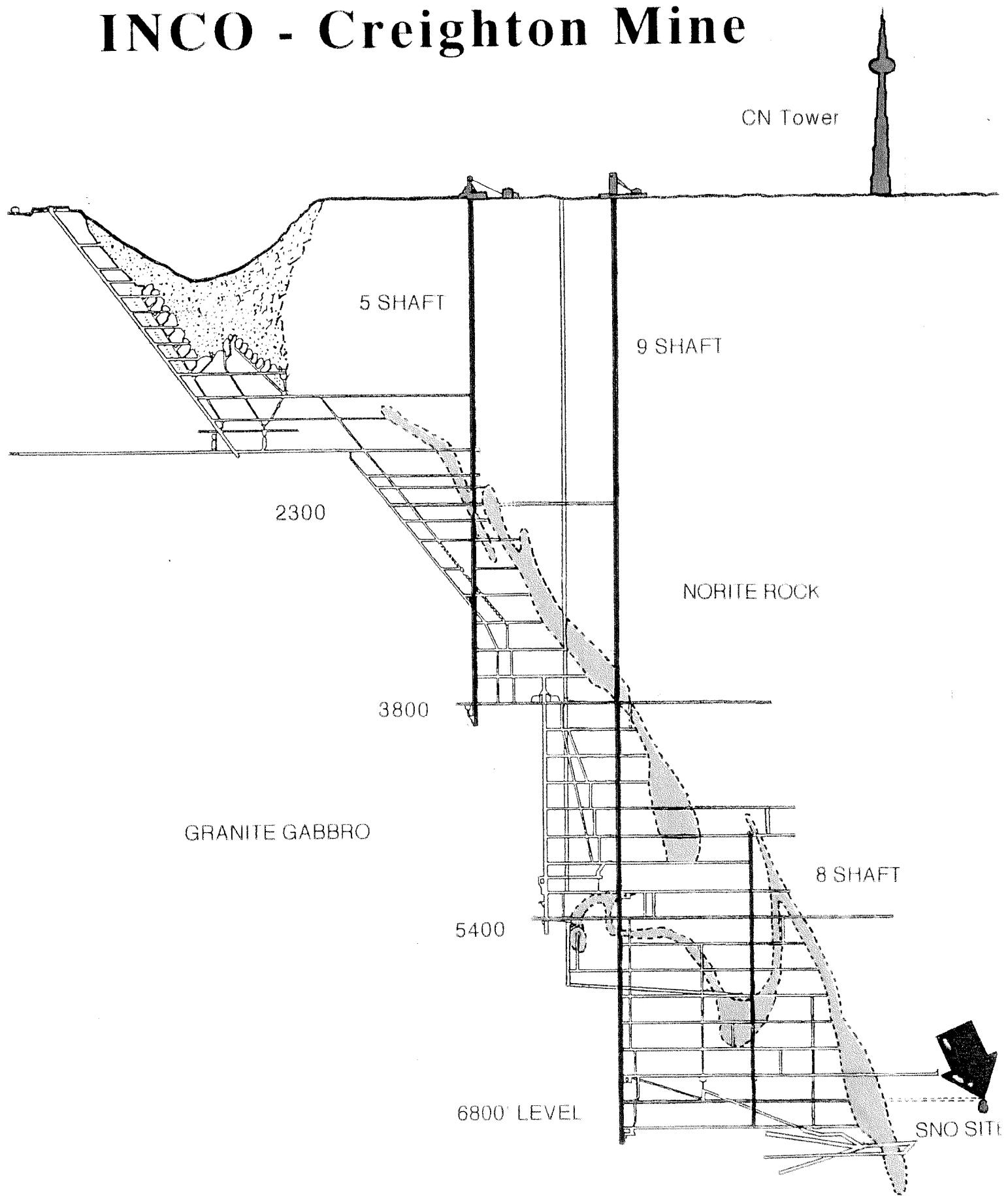


(Elastic scattering: ES)

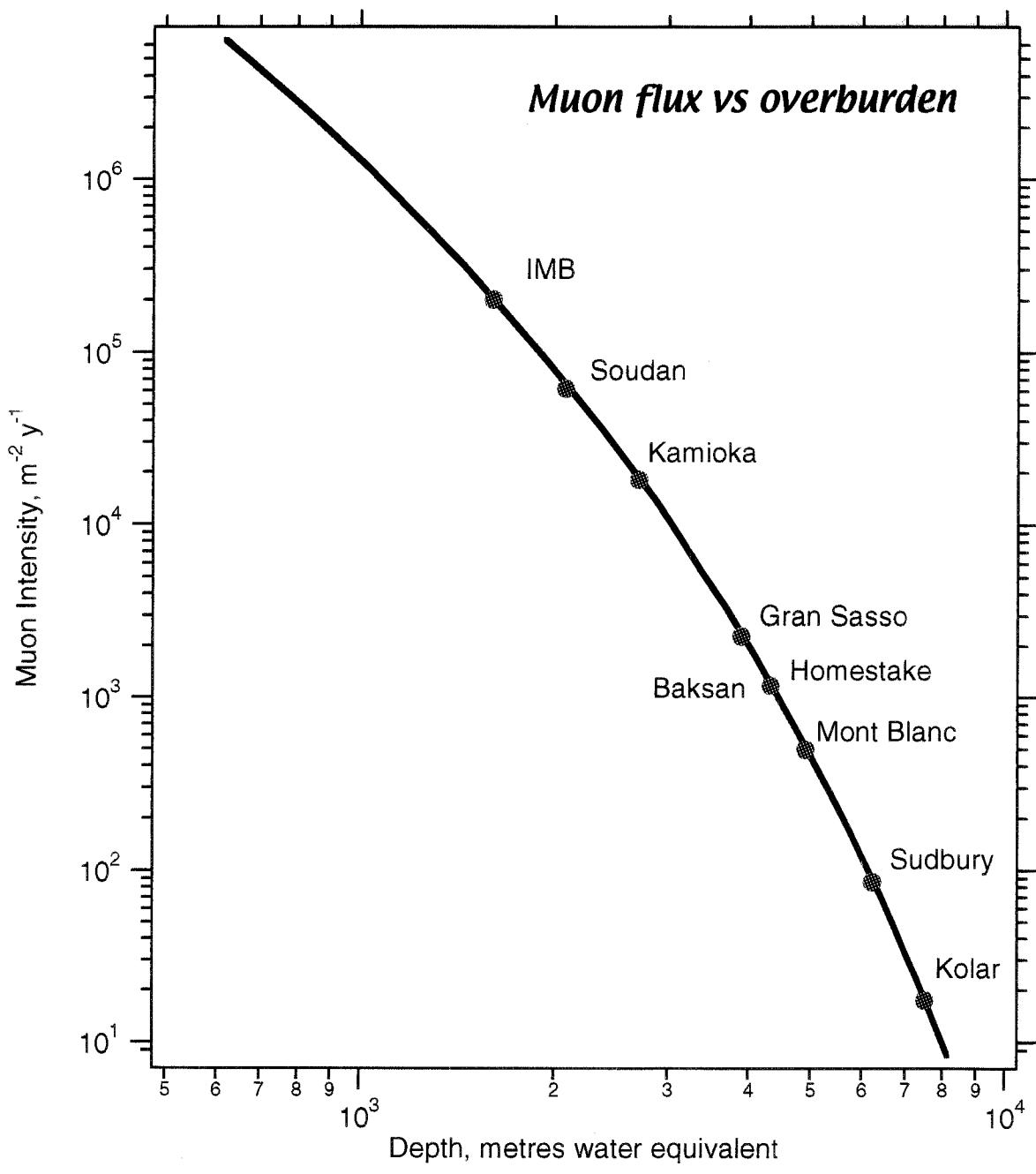
*1000-tonne heavy-water Cerenkov detector.*

*2000 m underground in INCO nickel mine, Sudbury, Ontario.*

# INCO - Creighton Mine







# ***Physics Goals of SNO***

## **Solar Neutrinos**

### **Neutrino Oscillations:**

*SNO can demonstrate neutrino oscillations independent of solar models*

Flavor change? NC/CC  
Spectral distortions? Good spectral response  
Earth regeneration? Active realtime detection  
Yearly modulation? High rates

### **Test of solar models**

Flux of  ${}^8\text{B}$  neutrinos in NC  
Flux of hep neutrinos ( ${}^3\text{He} + \text{p} \rightarrow \text{e}^+ + \nu_e + 19 \text{ MeV}$ )

### **Rates:**

Charged Current :	9 /day
Neutral Current :	6 /day
Elastic scattering from electrons:	1.4 /day

(0.37 SSM Flux, 5 MeV threshold, NC=  ${}^3\text{He}$  option, 45%)

## **Supernova neutrinos**

Relics

If a supernova:

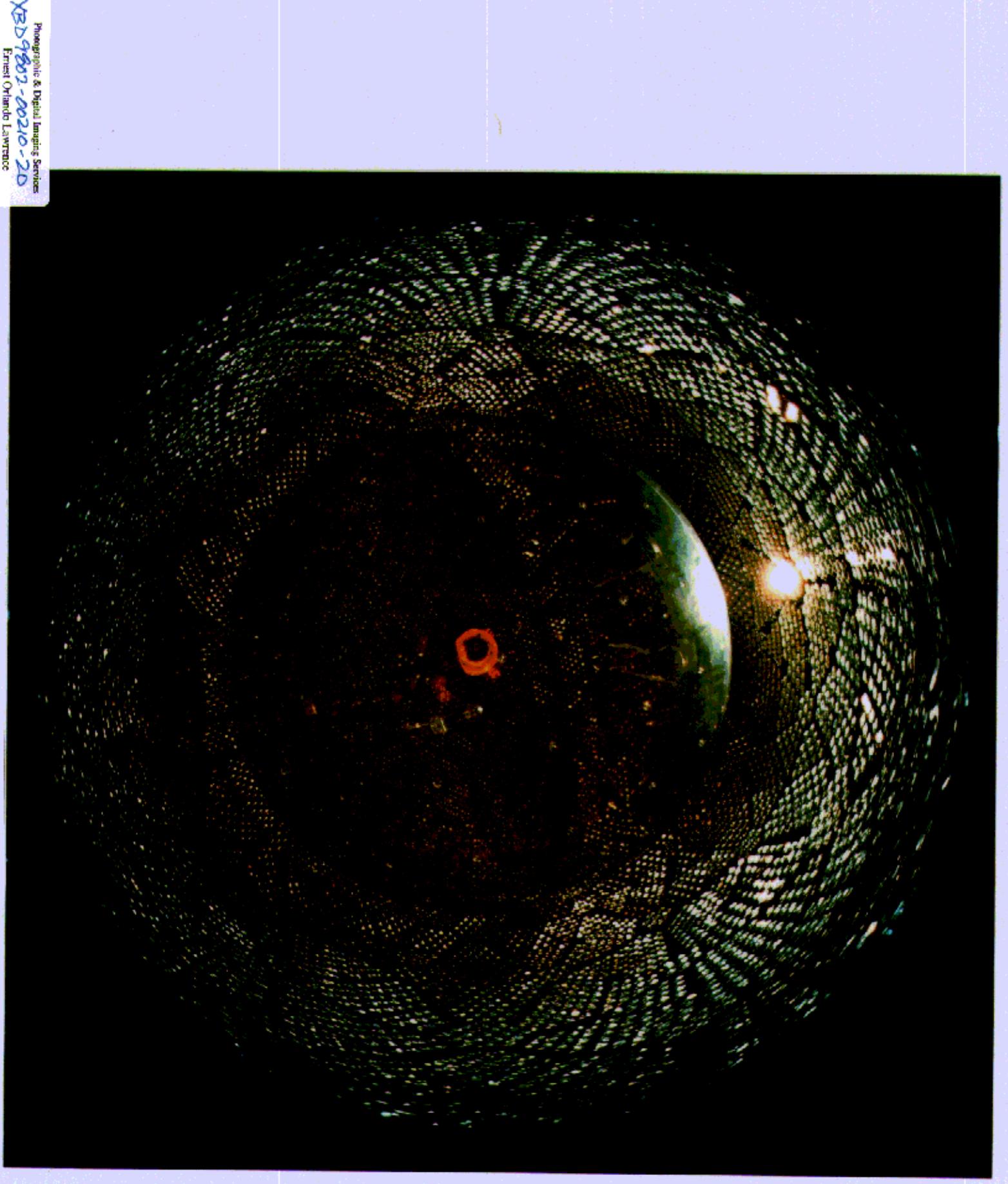
Simultaneous recording of NC total rates, CC spectra

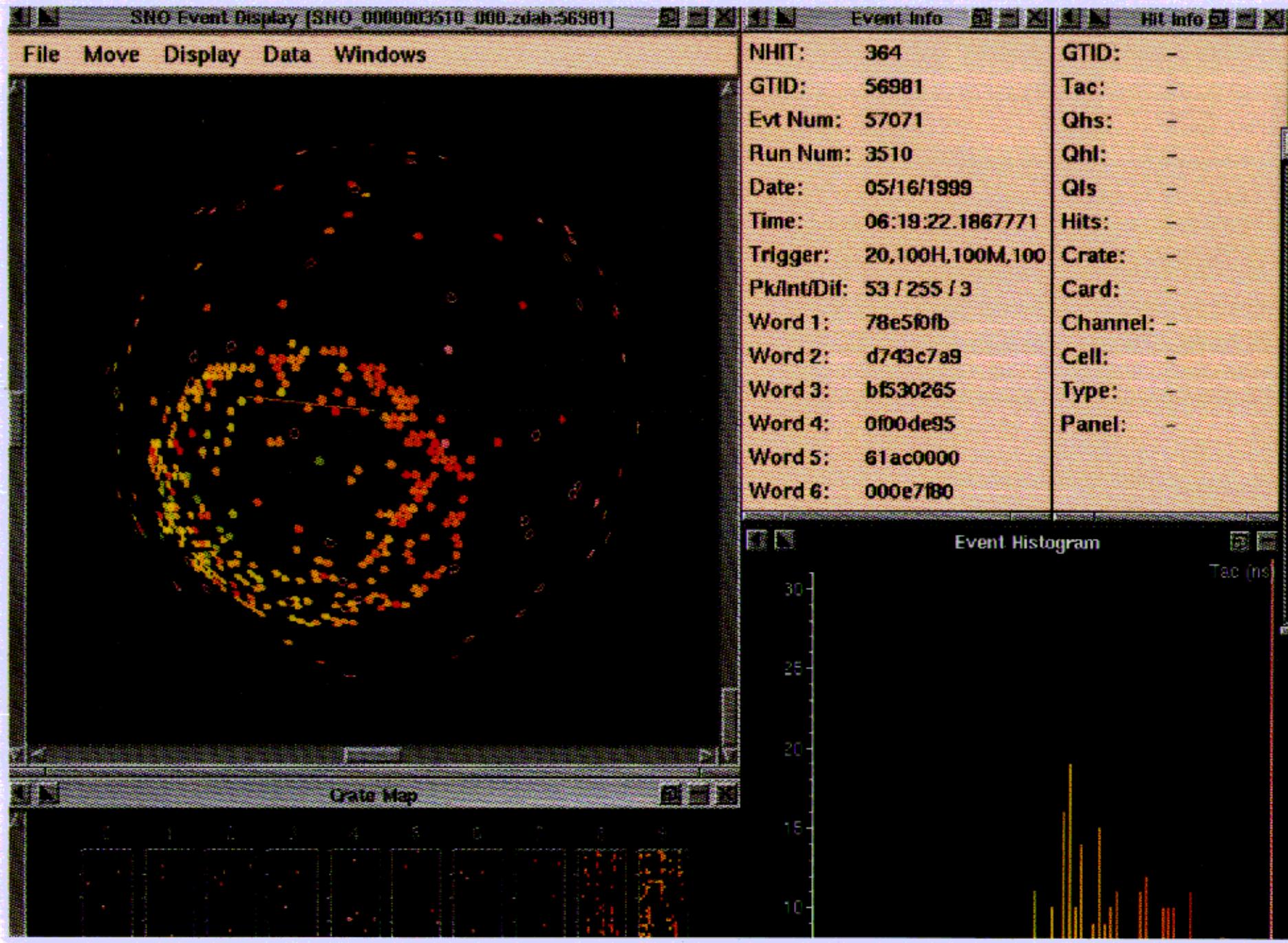
Distinction between neutrinos and antineutrinos

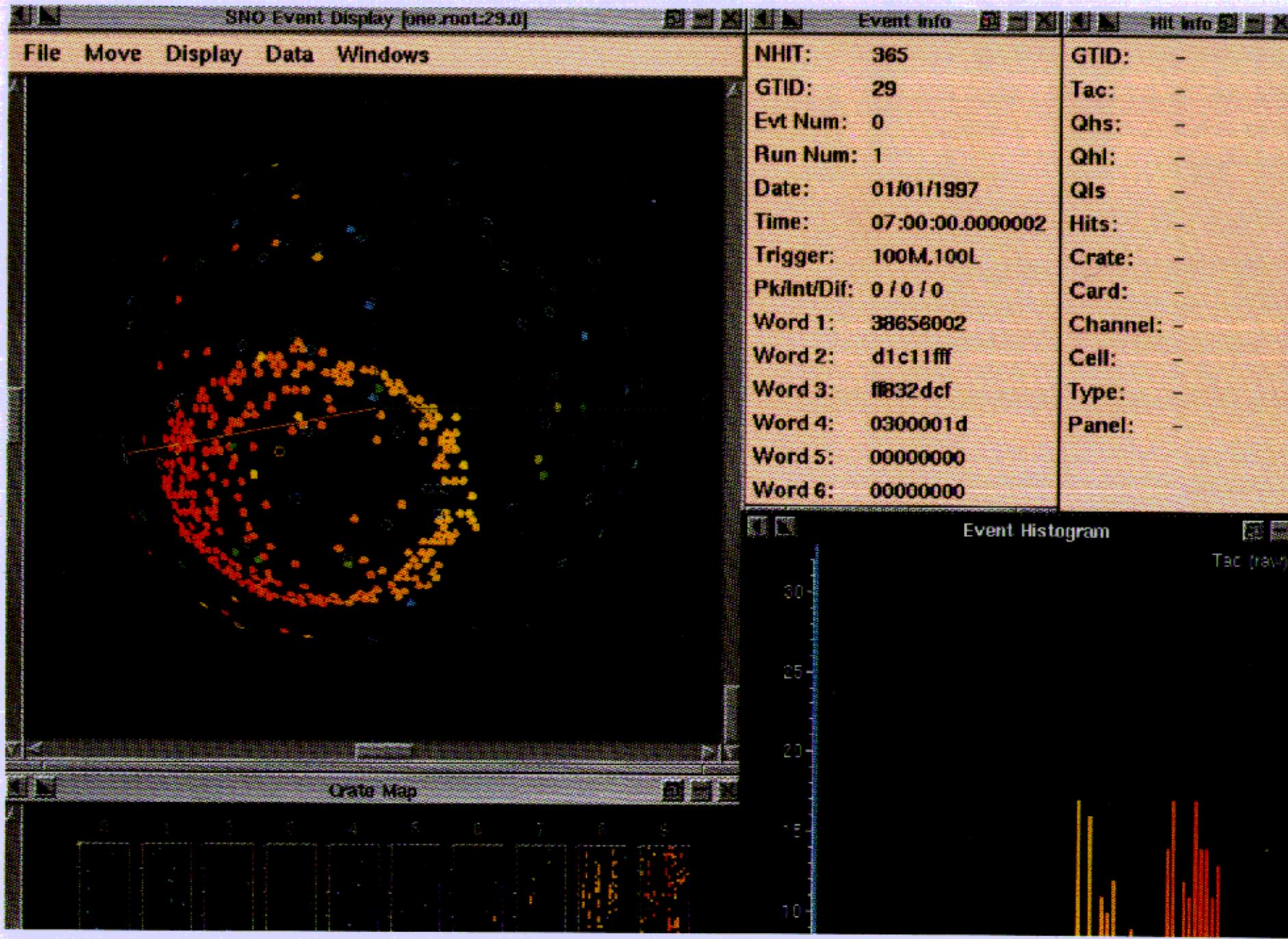
## **Atmospheric neutrinos**

About 40 each of  $\nu_\mu$ ,  $\nu_e$  per year below 1.3 GeV.

Distinction between neutrinos and antineutrinos (associated neutron)

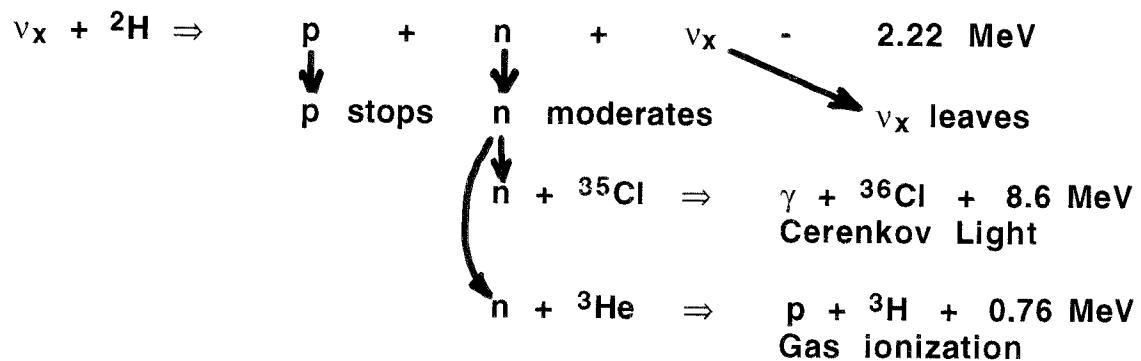




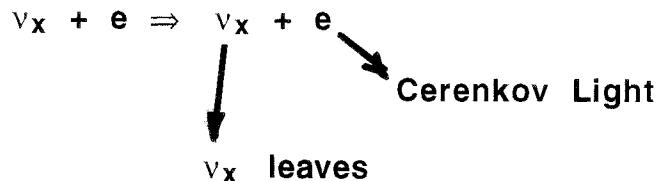


## Neutral-Current Detection in SNO

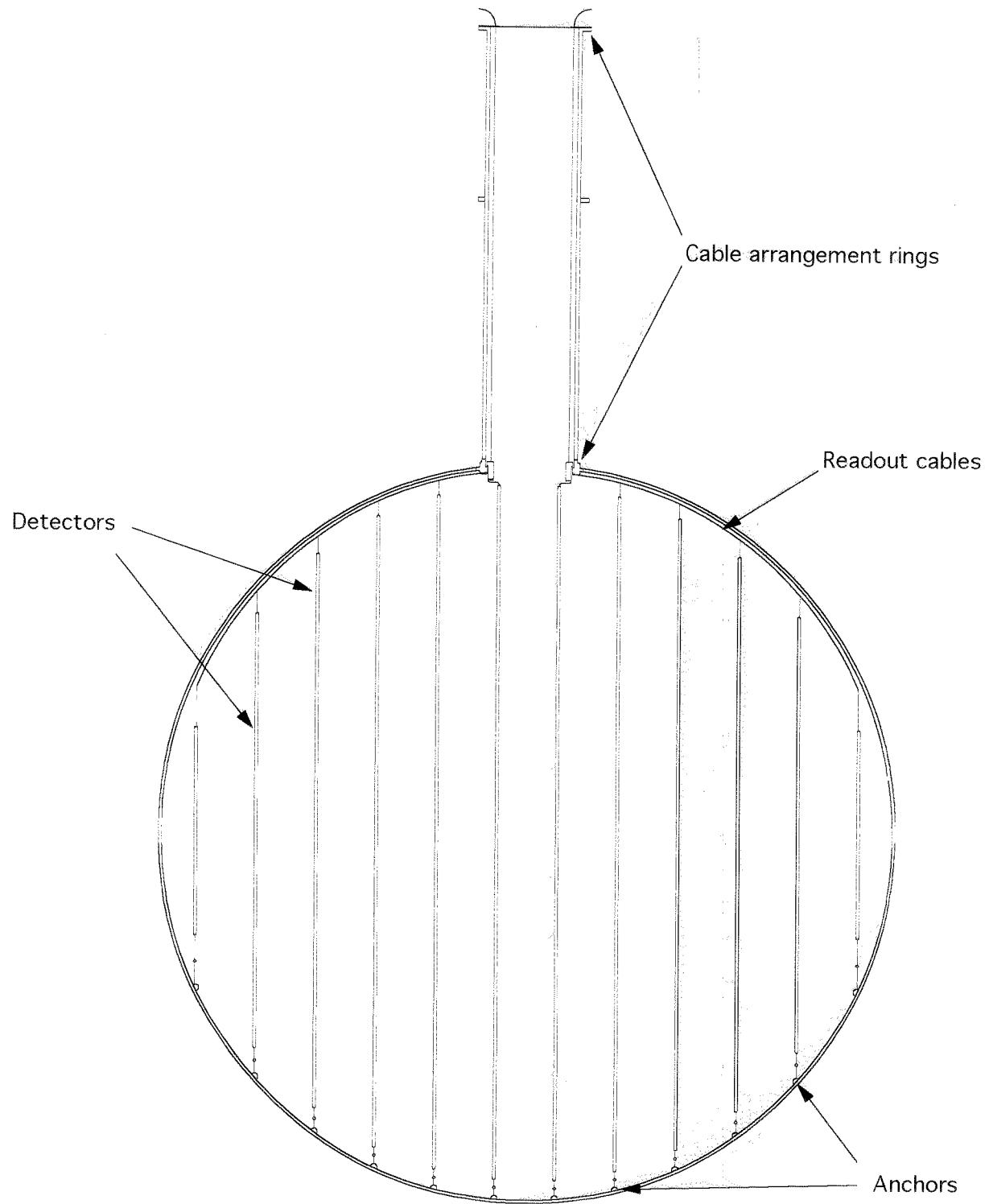
### Deuteron Breakup:



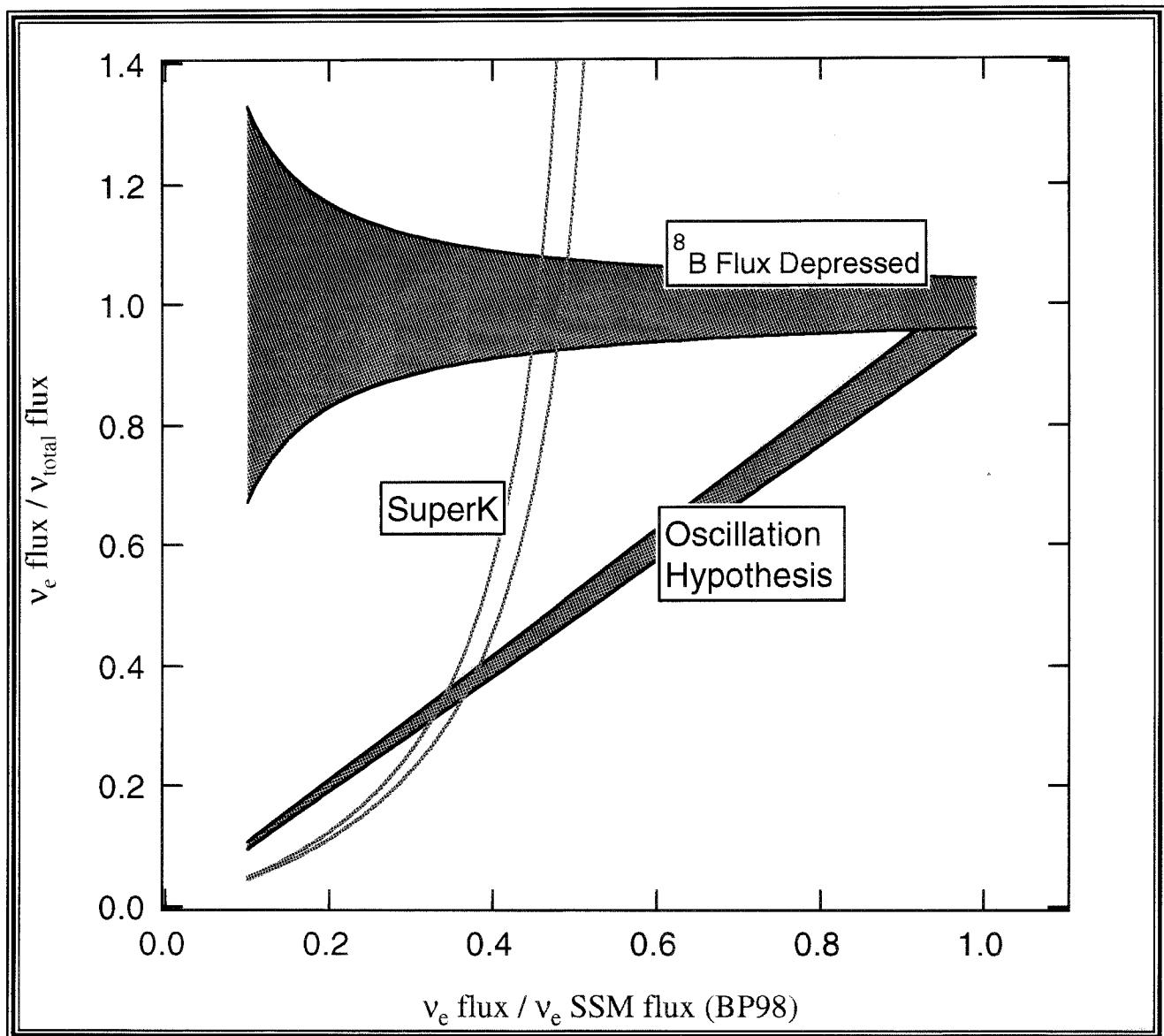
### Electron Elastic Scattering:



SIDE VIEW OF ACRYLIC VESSEL  
SHOWING LOCATION OF DETECTOR STRINGS



# CC/NC Ratio 1 Year



photodisintegration neutrons: 900/year

CC efficiency: 0.61, CC run time: 1 years

NC efficiency: 0.45, NC run time: 1 years

## Global Interpretation

If only three different mass eigenstates  $m_i$ ,  $i = 1, 2, 3$ , exist, the mass splittings must satisfy

$$\sum_{\text{Splittings}} \Delta m_\nu^2 = (m_3^2 - m_2^2) + (m_2^2 - m_1^2) + (m_1^2 - m_3^2) = 0, \quad (1)$$

a trivial condition which is not met by the independent  $\Delta m_\nu^2$  from the table of experimentally favored neutrino mass differences.

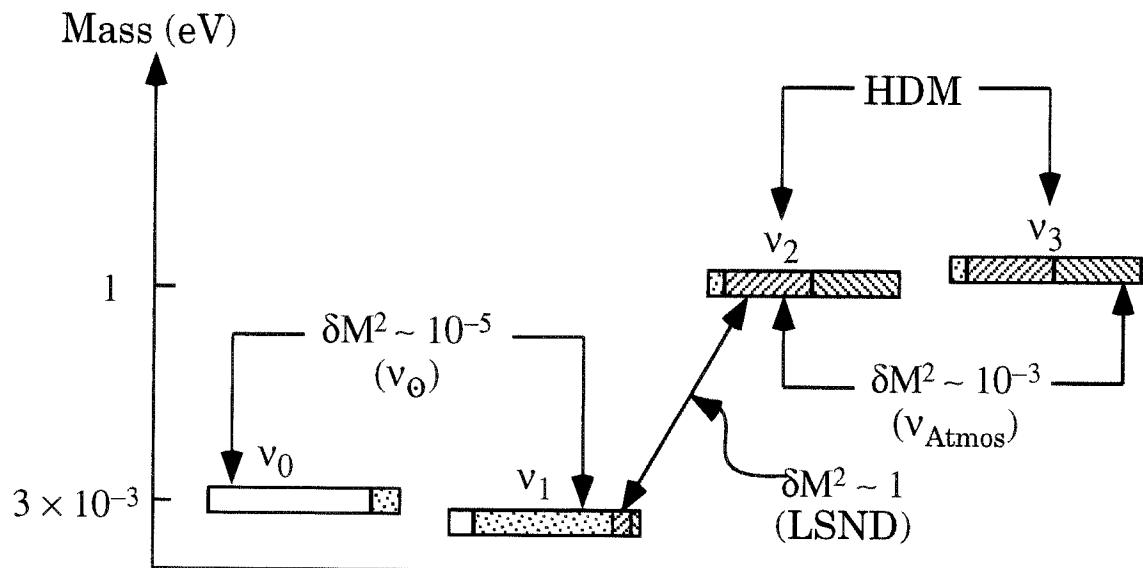
Experiment	Favored Channel	$\Delta m^2$ [eV $^2$ ]	$\sin^2 2\Theta$
LSND	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	0.2–10	$(0.2\text{--}3) \times 10^{-2}$
Atmospheric	$\nu_\mu \rightarrow \nu_\tau$	$(1\text{--}8) \times 10^{-3}$	0.85–1
	$\nu_\mu \rightarrow \nu_s$	$(2\text{--}7) \times 10^{-3}$	0.85–1
Solar			
Vacuum	$\nu_e \rightarrow \text{anything}$	$(0.5\text{--}8) \times 10^{-10}$	0.5–1
MSW (small angle)	$\nu_e \rightarrow \text{anything}$	$(0.4\text{--}1) \times 10^{-5}$	$10^{-3}\text{--}10^{-2}$
MSW (large angle)	$\nu_e \rightarrow \nu_\mu \text{ or } \nu_\tau$	$(3\text{--}30) \times 10^{-5}$	0.6–1

Raffelt *hep-ph/9902271*

## What Can Be Done?

- Usual choice – discard LSND (lack of confirmation, very constraining, etc...).
- Discard Chlorine-Argon to get large  $\Delta m^2$ . That no longer works because of Chooz.
- Can the atmospheric interpretation be moved toward LSND or solar (LMA) splittings?
- Sterile  $\nu$ .

*LSND has won!*

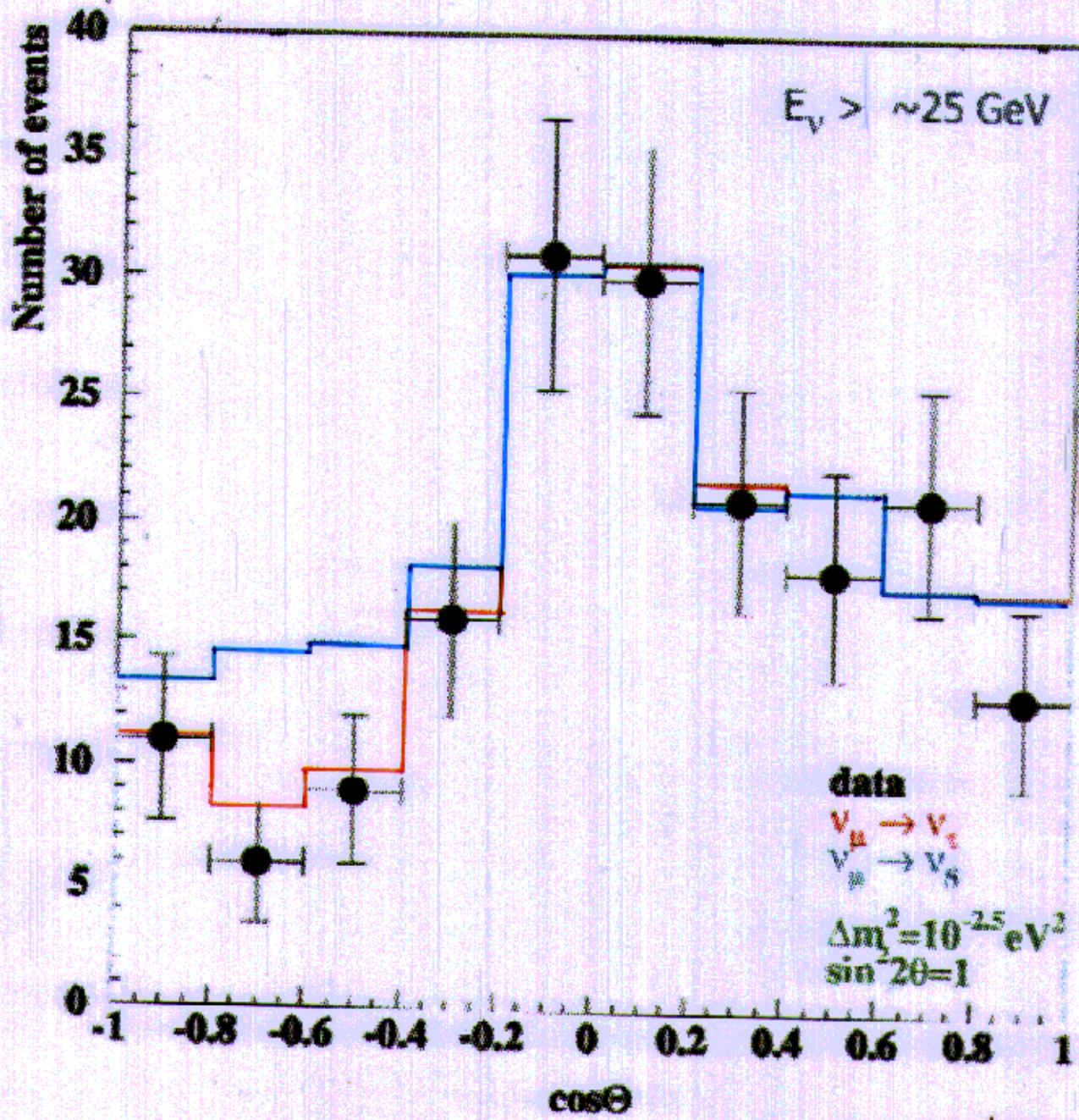


Four-neutrino mass and mixing scheme to accommodate all data. An inverted order for the large splitting is also possible.

*Smirnov, from hep-ph/9906244.*

# Why not $\nu_\mu \leftrightarrow \nu_s$ ?

- High energy sample (partially contained and upward-muon) analysis disfavors  $\nu_s$



WILKES '99

## Sterile neutrinos are not unnatural...

$$L_m^{PD} = -\frac{1}{2}[\overline{(\psi_L)^c}, \overline{\psi_R}, \overline{\psi_L}, \overline{(\psi_R)^c}] \begin{pmatrix} 0 & 0 & m_s & m_D \\ 0 & 0 & m_D & m_s \\ m_s & m_D & 0 & 0 \\ m_D & m_s & 0 & 0 \end{pmatrix} \begin{pmatrix} (\psi_L)^c \\ \psi_R \\ \psi_L \\ (\psi_R)^c \end{pmatrix}$$

The charge-conjugate pairs are again coupled by the new terms to make Majorana eigenstates,

$$\frac{1}{\sqrt{1+\epsilon^2}} \begin{bmatrix} (\tilde{\psi}_L)^c + \epsilon \tilde{\psi}_R \\ \tilde{\psi}_R - \epsilon (\tilde{\psi}_L)^c \\ \tilde{\psi}_L + \epsilon (\tilde{\psi}_R)^c \\ (\tilde{\psi}_R)^c - \epsilon \tilde{\psi}_L \end{bmatrix}$$

... P. ROSEN

but the masses are close together,  $m_\nu = |m_s \pm m_D|$ . This is the “pseudo-Dirac” case.

- All 3 flavors should have a sterile ghost,
- No understanding of why  $m_D$  (and  $m_s$ ) are so small,
- $\beta\beta0\nu$  greatly suppressed.

## What can cosmology tell us?

- Neutrino density  $\frac{3}{11}$  of photon density after recombination:  
 $115 \nu + \bar{\nu} \text{ cm}^3$  per flavor.
- Expansion rate of universe determines  $Y[\text{He}]$ , hence number of active flavors. Controversial now: limits range from 3 to as high as 6.  
*Olive and Thomas hep-ph/9811444.*
- Sterile neutrinos are not excluded, although lepton asymmetries may be large if they play a role in the atmospheric neutrino signal.  
*Foot and Volkas PRL 75, 4350 (1995)*
- Age of universe, new Hubble determinations ( $h_0 = 0.7$ ) give

$$\Omega h^2 \leq 0.4$$

- Big-bang nucleosynthesis (of  ${}^4\text{He}$ ,  ${}^3\text{He}$ ,  ${}^2\text{H}$ ,  ${}^7\text{Li}$ ) gives

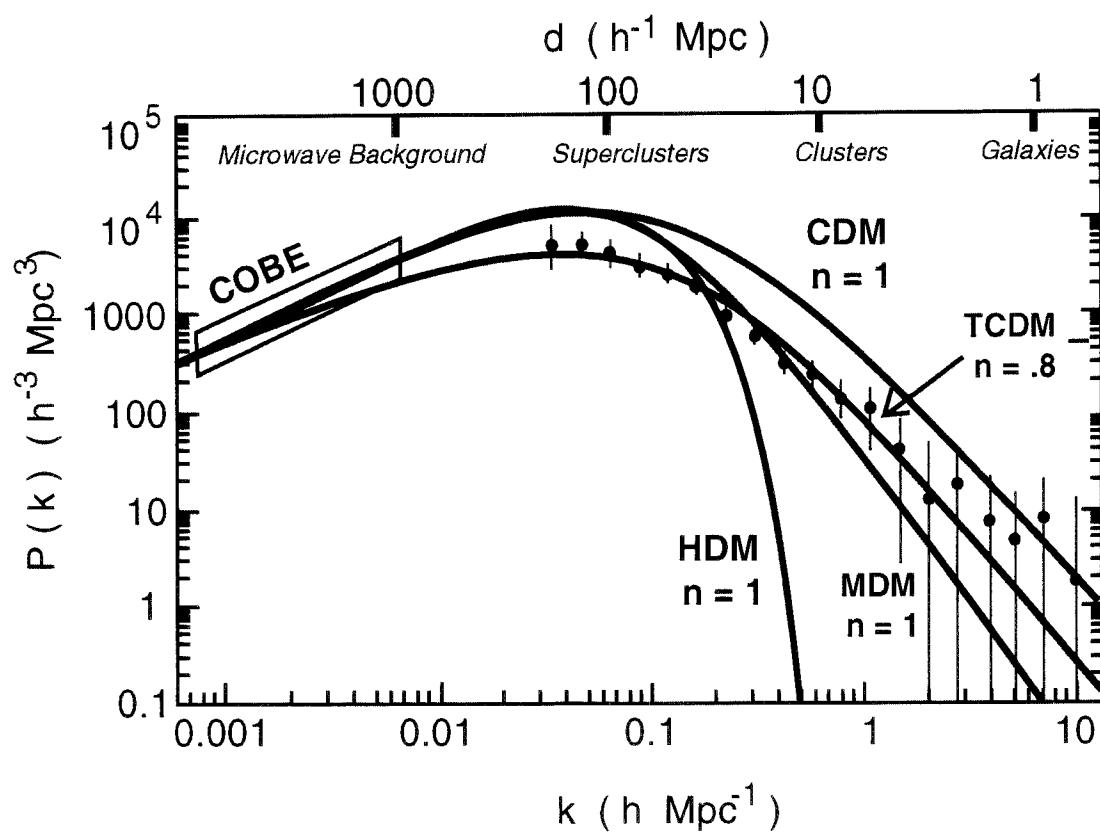
$$\Omega h^2 \simeq 0.05$$

- Hence

$$\sum m_\nu \leq 16 \text{ eV}$$

- But disagreement with structure calls for

$$\sum m_\nu \leq 5 \text{ eV}$$



Matter density power spectra: CDM (cold dark matter), TCDM (tilted cold dark matter), HDM (hot dark matter), MDM (mixed HC dark matter). *P. Steinhardt, from hep-ph/9902271*

physicists of Germany and to develop some ideas important for successful fulfillment of this work.

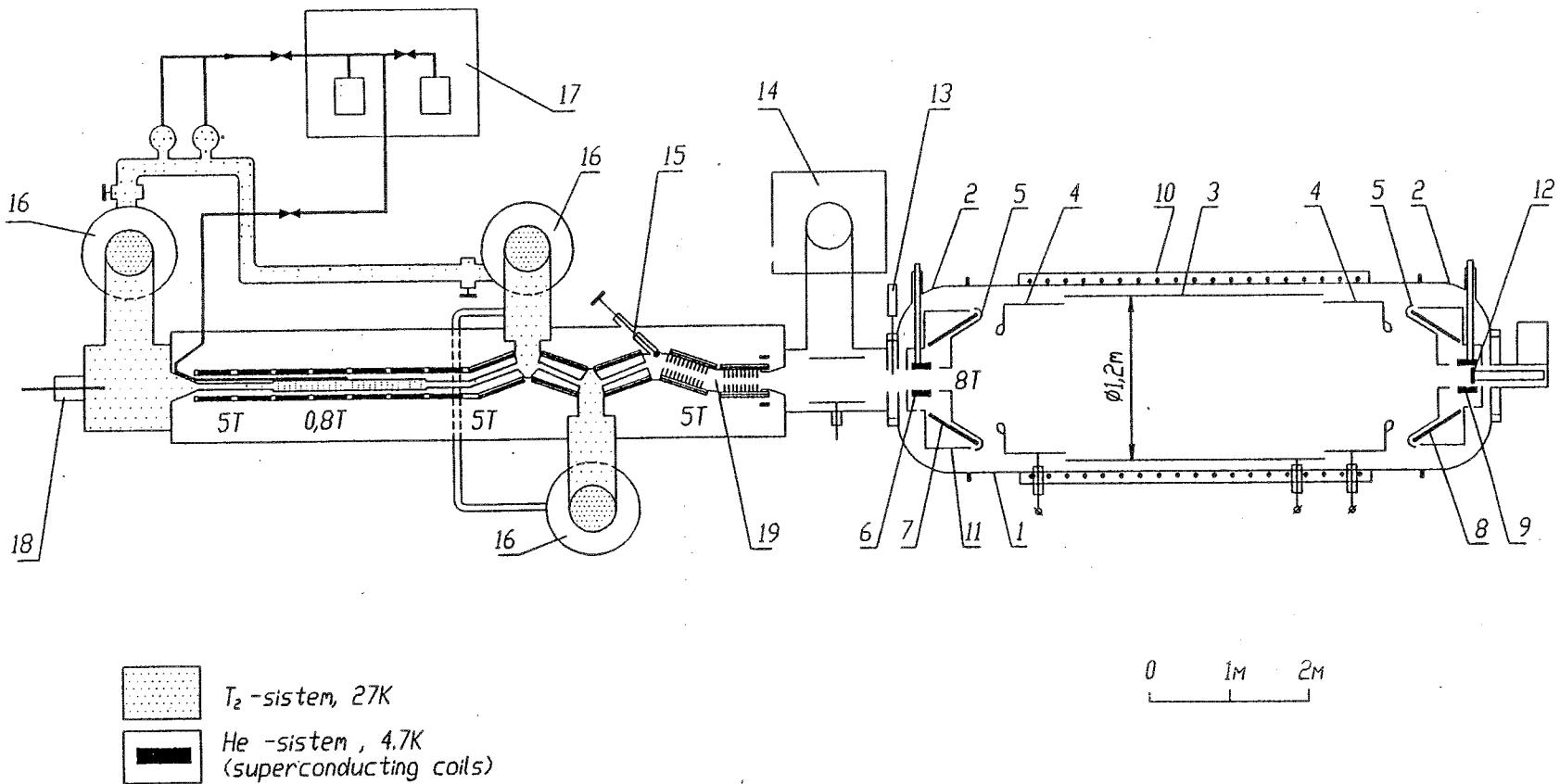


Fig. 1. Experimental set-up. 1,2 - vacuum tank; 3,4 - electrostatic analyzer; 5 - grounded electrode; 6,7,8,9 - superconducting solenoids; 10 - warm coil; 11 - liquid- $N_2$  jacket; 12 - detector; 13 - fast shutter; 14 - Ti-pump; 15 - cold valve; 16 -  $Hg$  diffusion pump; 17 -  $T_2$  purification system; 18 - electron gun; 19 - argon pump.

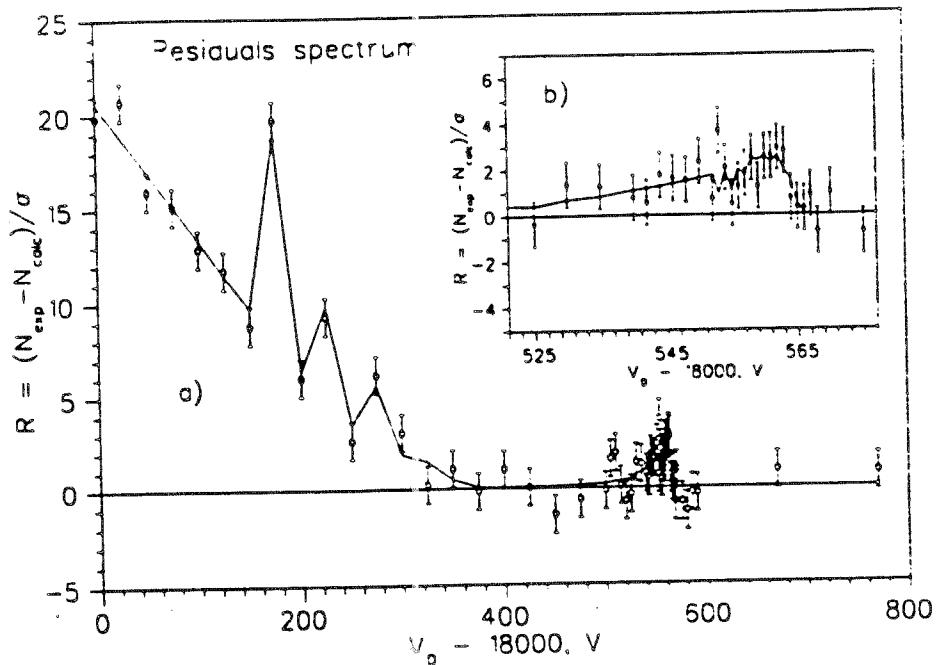
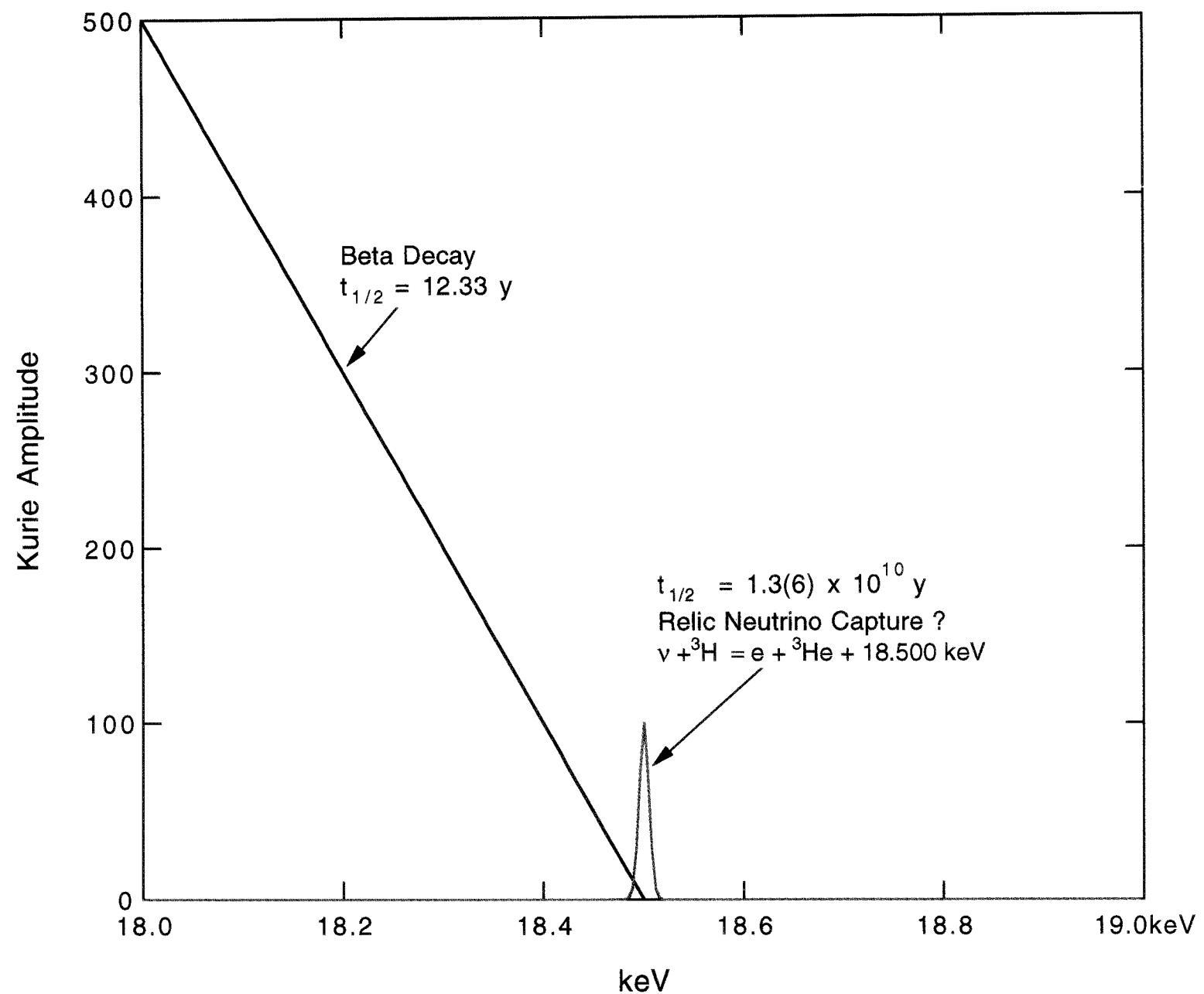
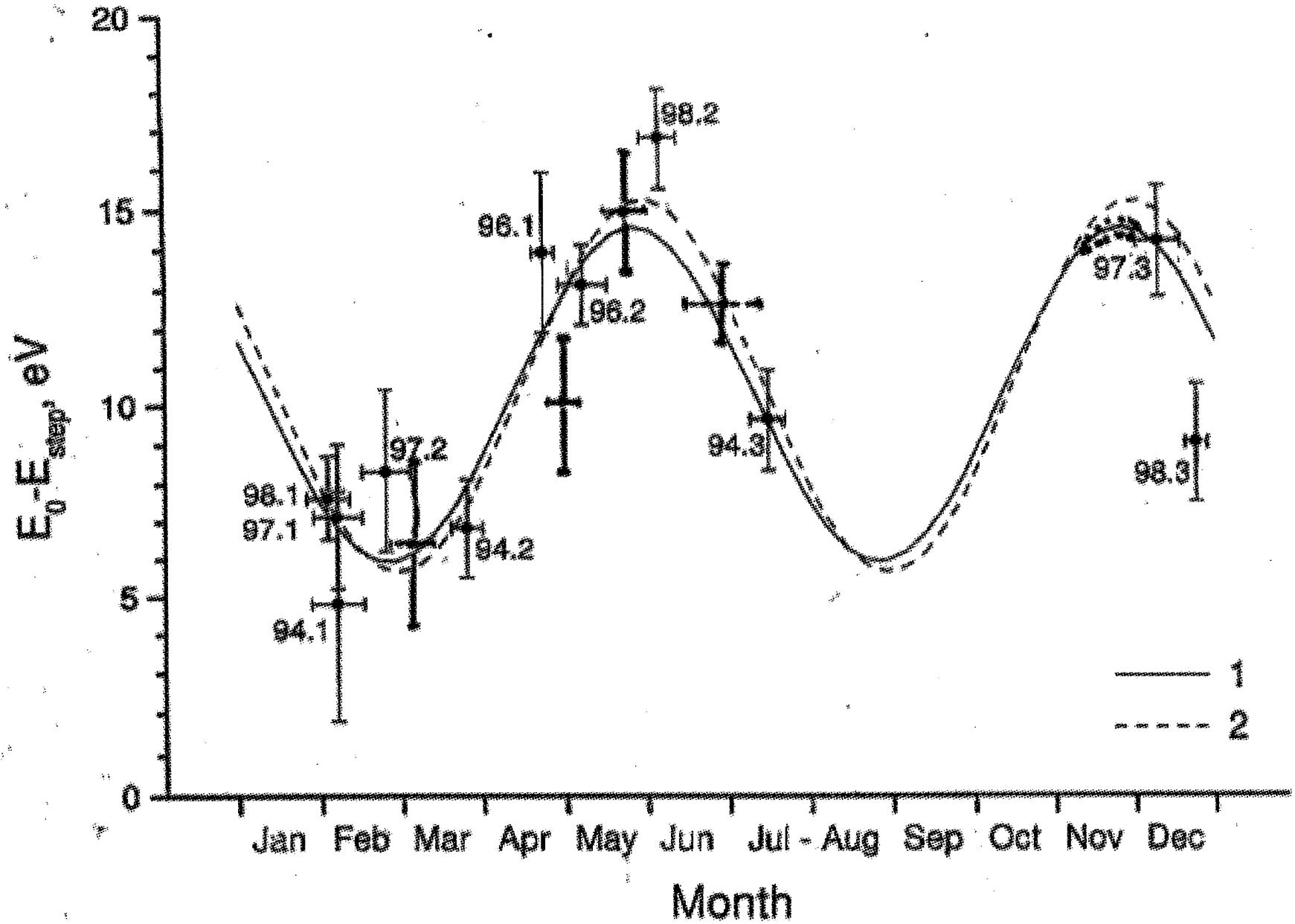
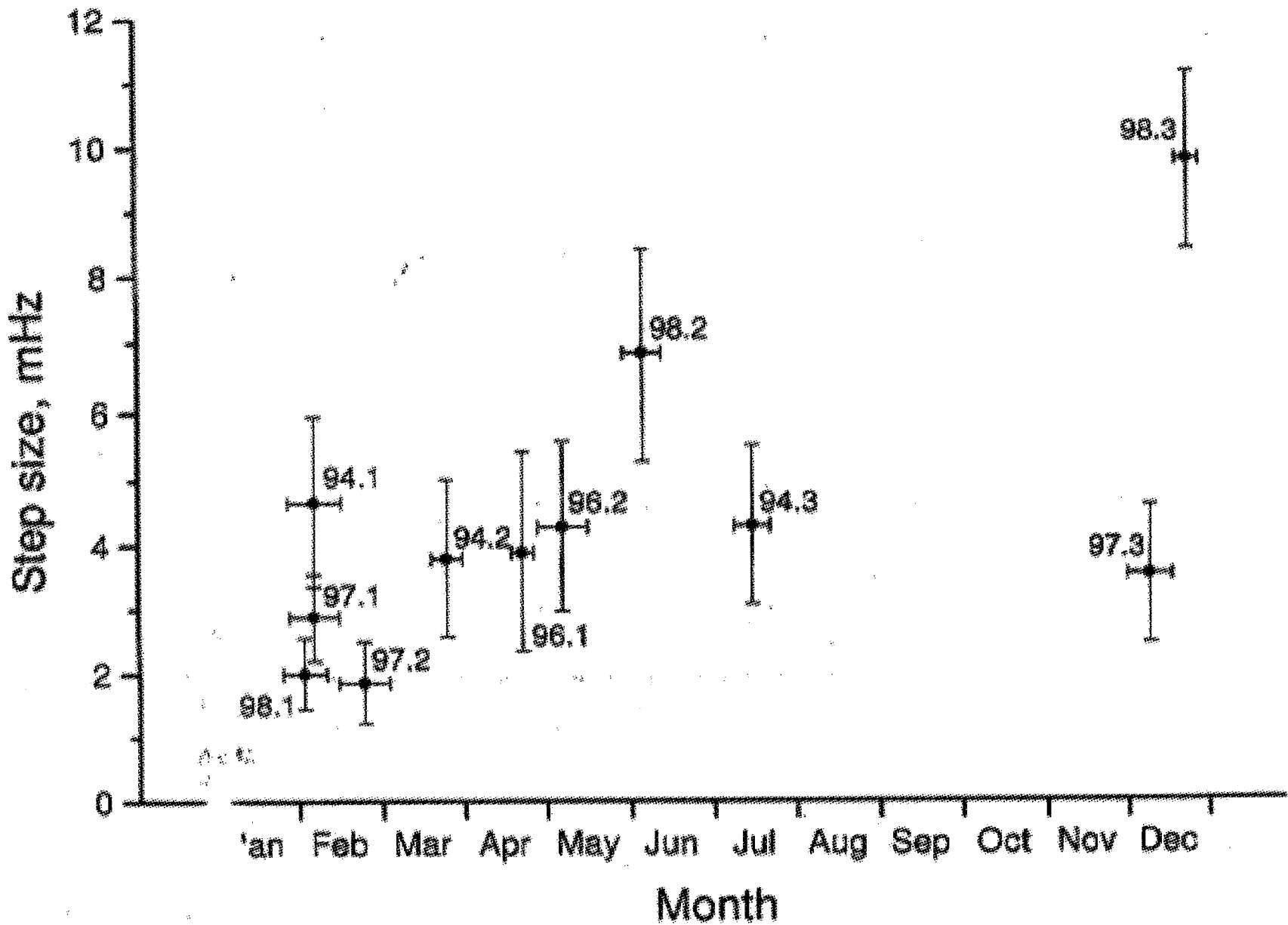


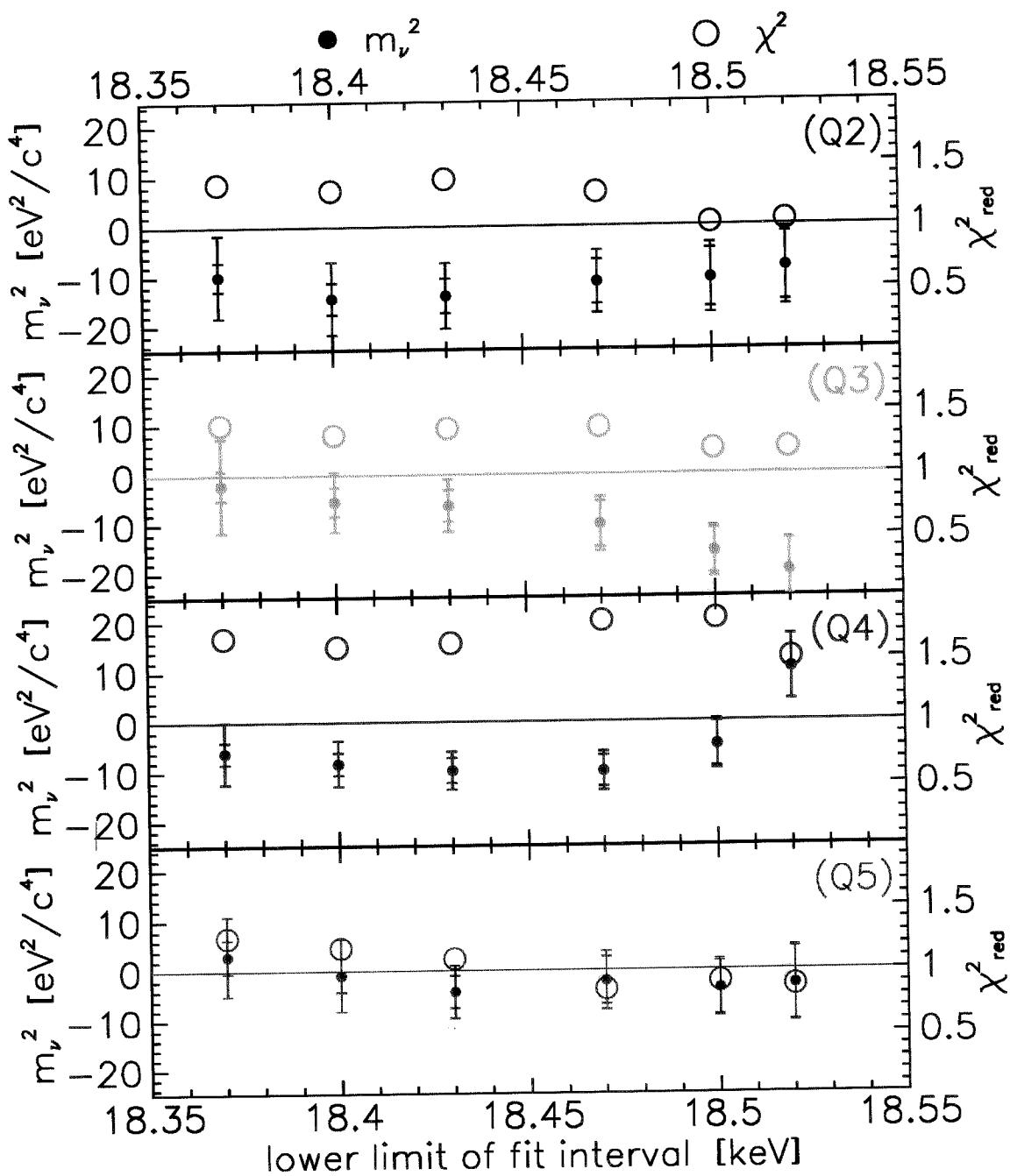
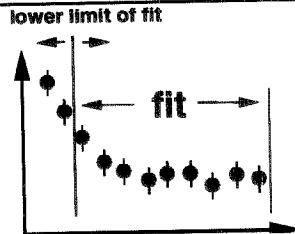
Fig. 3. Residuals from the fit of the tritium spectrum. The residual for each point is the difference between the measured value and the calculated one divided by the corresponding error. The zero line is the standard spectrum ( $m_\nu^2 = 0$ ) fitted with fixed background and  $E_{\text{low}} = 18350$  eV and extrapolated to 18000 eV. The solid line is fitted spectrum with variation of  $m_\nu^2$ ,  $\Delta N_{\text{step}}$ ,  $EM_0^C$ ,  $P^{\text{MC}}$  and of standard parameters. Jumps in the curve are due to the difference in measurement times of different points.





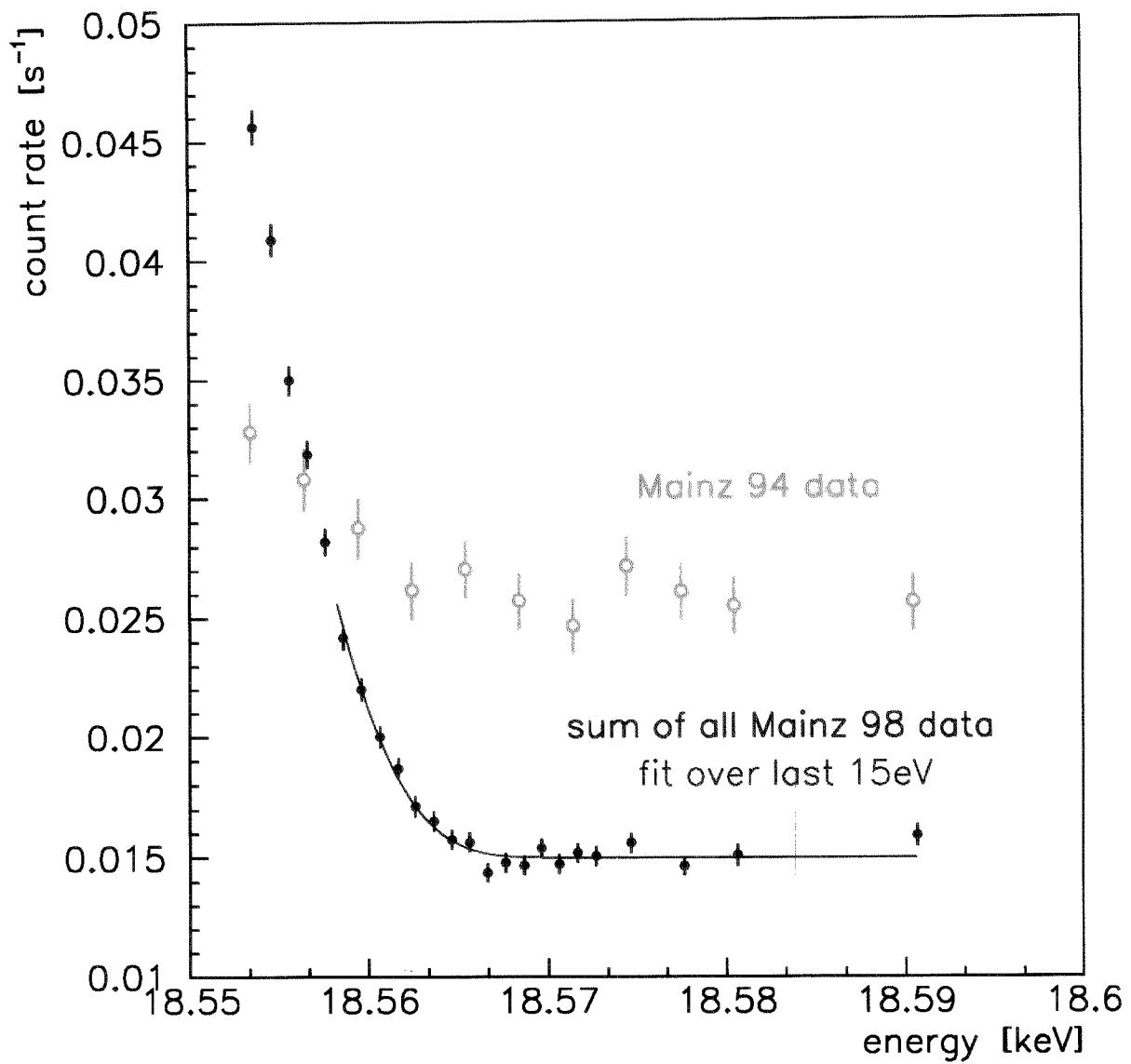


# $m_\nu^2$ (fit) versus fit interval



# Summing up all 1998 data

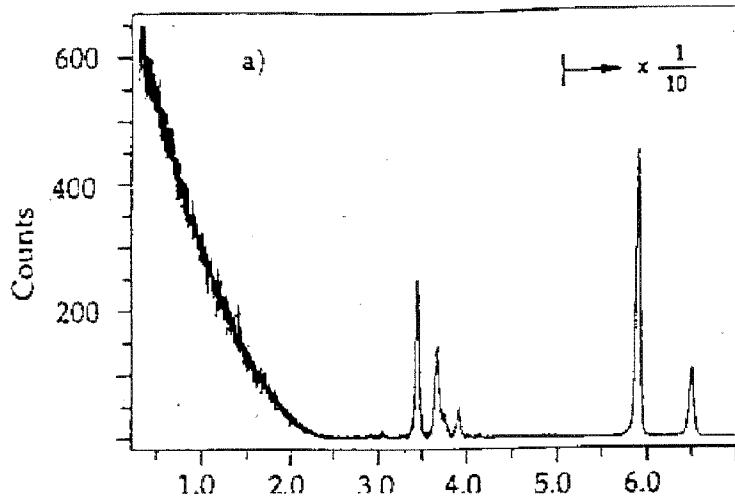
Q3+Q4+Q5



# An initial Experiment on $^{187}\text{Re}$ with Bolometric Techniques

Alessandrello et al., PLB 457, 253, 1999.

- Endpoint energy  $2460 \pm 5 \pm 10$  eV
- Resolution  $\simeq 25 - 60$  eV
- Neutrino mass not determined
- Better than  $m_{\nu_e} = 10$  eV determinable with 10 bolometers, 1 y.



Bolometric  $\beta$  spectrum of  $^{187}\text{Re}$  and Calibration Lines

# MASS SPECTRUM (eV)

	<u>Hierarchical</u>	<u>Degenerate</u>
$\nu_1$	$\sim 0$	1.5
$\nu_0$	$10^{-5} (\text{vac}) \text{ or } 2 \times 10^{-3} (\text{SMA})$	1.5
$\nu_2$	$0.7 (\text{LSND I}) \text{ or } 2.2 (\text{LSND II})$	1.7 (LSND I)
$\nu_3$	$0.7$ or $2.2$	1.7

for  $\sum m_\nu = 5 \text{ eV}$

## The road ahead...

<i>Future Observation</i>	<i>Solar <math>\nu</math> Oscillation</i>	<i>Atmospheric <math>\nu</math> Oscillation</i>	<i>LSND <math>\nu</math> Oscillation</i>
$\sim 1 \text{ eV mass in tritium decay}$ -- HDM	A near-degenerate partner	-	$\Delta m^2$ gives us masses of two eigenstates
$0\nu\beta\beta$ -- HDM	Majorana neutrinos, likely see-saw		
<i>SNO NC/CC = 3</i>	Active flavor mixing	Must be sterile = conflict?	If solar and atmos active, LSND conflict
<i>SNO NC/CC = 1</i>	Sterile	Active ok	Active ok
<i>Deep Borexino <math>{}^7\text{Be}</math> deficit &lt;NC</i>	Sterile, small-angle, matter-enhanced		
<i>Borexino yearly signal</i>	Vacuum oscillations	Must be sterile = conflict?	If solar and atmos active, LSND conflict
<i>Kamland anti-<math>\nu_e</math> disappearance</i>	Large angle, active	Must be sterile = conflict?	If solar and atmos active, LSND conflict
<i>Results from K2K, MINOS, CERN</i>		Measure $\nu_\mu \rightarrow \nu_\tau$	
<i>Results from Boone, MINOS, I-216</i>			Confirm LSND, measure $\nu_e \leftrightarrow \nu_\mu$

(after Fisher, Kayser, McFarland [hep-ph/9906244](#))

*That neutrinos oscillate, have mass, is now almost beyond doubt.*

*At last, the end of the beginning...*