特定・宇宙ニュートリノセンター共催・第2回研究会
@都立大
7/5/2000

太陽ニュートリノ実験の現状

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1. Solar neutrino
2. Results of the current experiments
3. SNO
4. Summary and Future

☀ Solar neutrinos

nuclear fusion reaction inside the Sun

$$4p \longrightarrow \alpha + 2e^{+} + 2\nu_e$$

⇓ go through the Sun immediately (~2 sec)

- P-P chain
- CNO cycle

Flux, spectrum, … are calcurated by
Standard Solar Model (SSM)

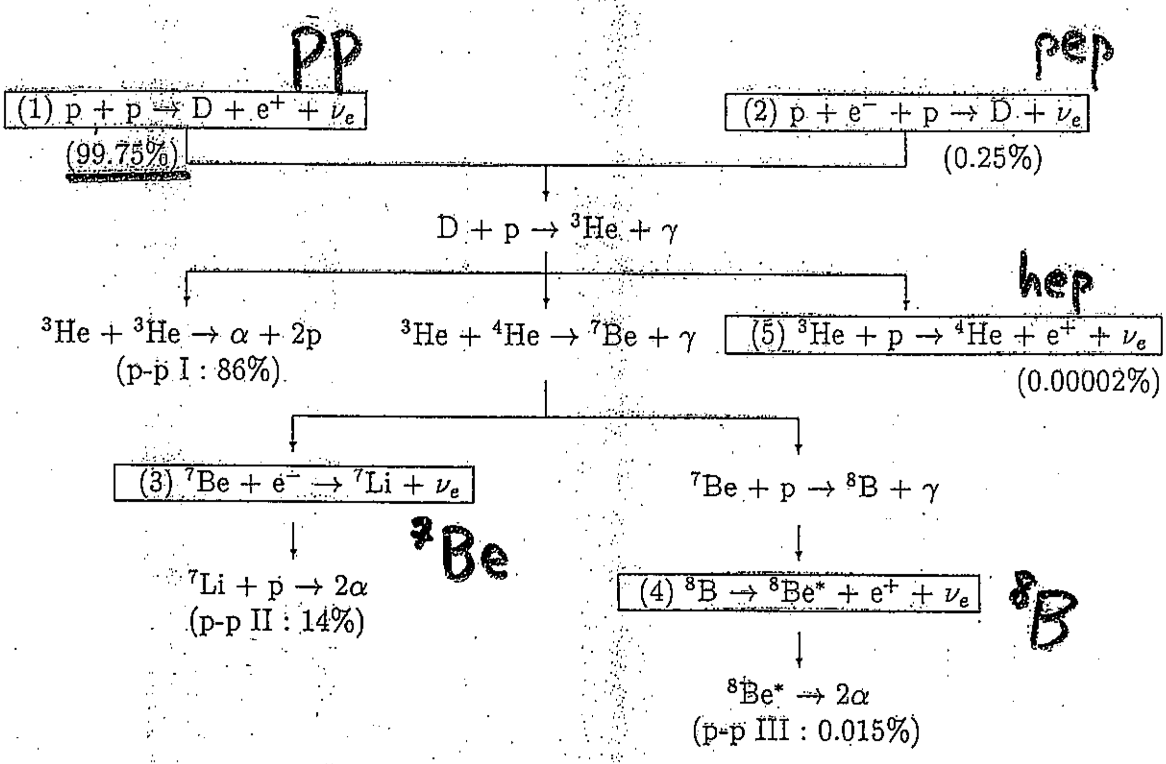


Figure 1.1: Proton-proton chain. P-P chain

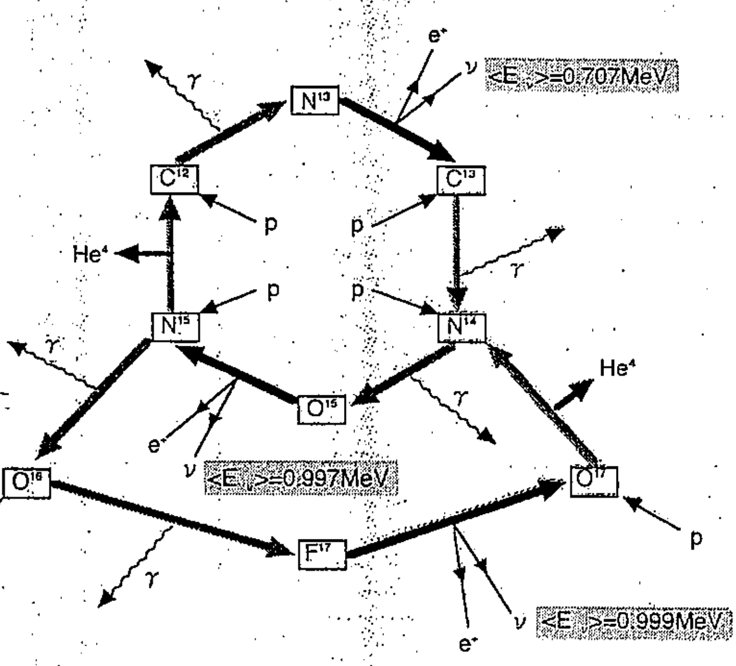
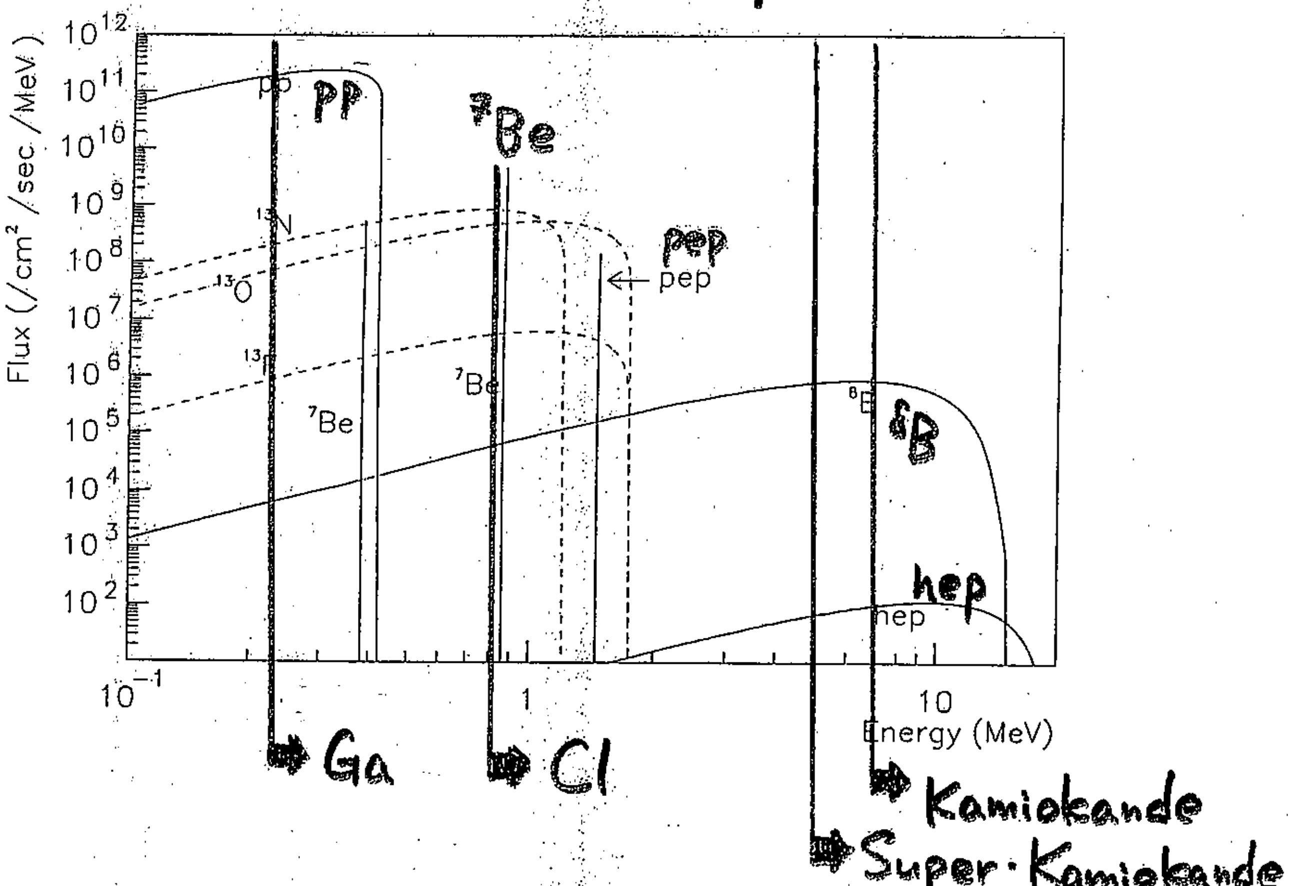


Figure 1.2: CNO cycle. CNO cycle

Solar Neutrino spectrum



Solar Neutrino Flux ($cm^{-1}s^{-1}$)

pp	5.94×10^{10}	(1.00 ± 0.01)
pep	1.39×10^{8}	(1.00 ± 0.01)
^{7}Be	4.80×10^{9}	(1.00 ± 0.09)
^{8}B	5.15×10^{6}	$(1.00 \pm ^{0.19}_{0.14})$
hep	2.10×10^{3}	
^{13}N	6.05×10^{8}	$(1.00 ^{+0.19}_{-0.13})$
^{15}O	5.32×10^{8}	$(1.00 ^{+0.22}_{-0.15})$
^{17}F	6.33×10^{6}	$(1.00 ^{+0.12}_{-0.11})$

BP98

ref.
Bahcall, Basu and Pinsonneault
Phys. Lett. B 433 (1998) 1

☀ Results of the current solar neutrino experiments

① Homestake (1970~)

$$\nu_e + {}^{37}Cl \longrightarrow e^- + {}^{37}Ar \quad (E_{th} = 0.814\,MeV)$$

(mainly ${}^{8}B$, ${}^{7}Be$)

~~realtime~~ ~~spectrum~~

$2.56 \pm 0.16 \pm 0.16$ SNU

ref. B.T.Cleveland et.al.
Astrophysic.J. 496(1998)505

$$\frac{DATA}{SSM(BP98)} = 0.332 \pm 0.021 \pm 0.021$$

②-1 SAGE (1990~)

$$\nu_e + {}^{71}Ga \longrightarrow e^- + {}^{71}Ge \quad (E_{th} = 0.233\,MeV)$$

(pp ν can be measured)

realtime ✗ spectrum ✗

$$75.4^{+7.0}_{-6.8}\,(\text{sta.})\,^{+3.5}_{-3.0}\,(\text{sys.})\ \text{SNU}$$

neutrino 2000

$$\frac{\text{DATA}}{\text{SSM(BP98)}} = 0.584^{+0.054}_{-0.053}\,^{+0.027}_{-0.023}$$

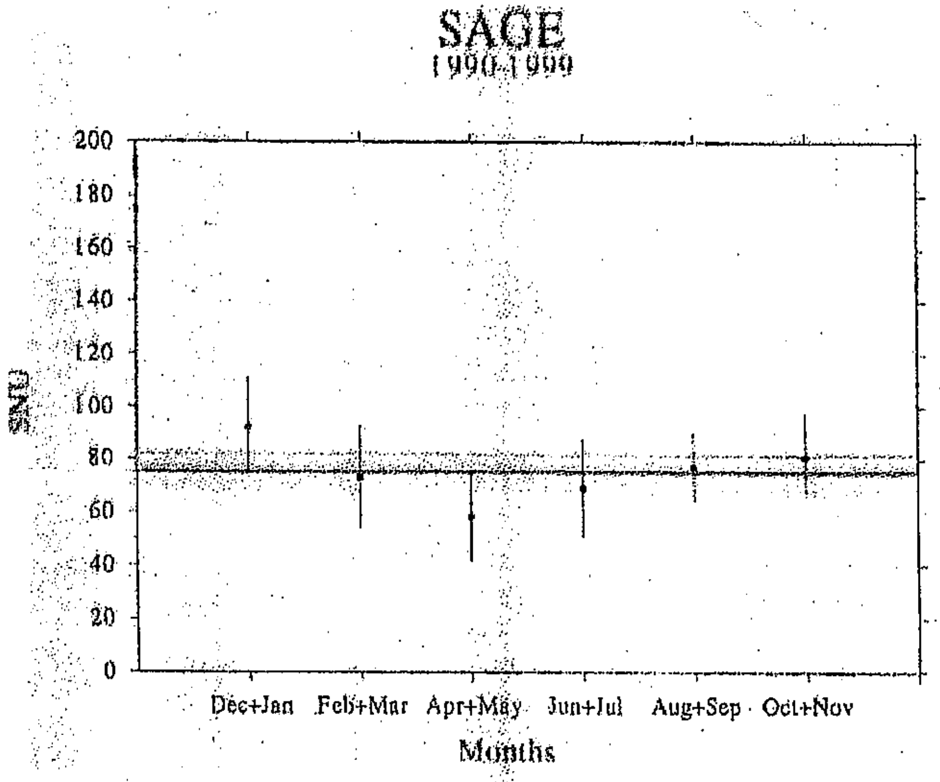
Future: ~2005

50ton → 58ton

^{37}Ar (ν source) calibration

neutrino 2000
Gavrin

Gavrin 15



②-2 GNO (GALLEX)

$$\nu_e + {}^{71}Ga \longrightarrow e^- + {}^{71}Ge \quad (E_{th} = 0.233\,MeV)$$

(pp ν can be measured)

realtime spectrum

(1991 ~ 1997)

GALLEX $77.5 \pm 6.2 \,{}^{+4.3}_{-4.7}$ (SNU)

(1998 ~) 20 May '98 ~ 14 Dec '99

GNO $65.8 \,{}^{+10.2}_{-9.6} \pm 3.5$

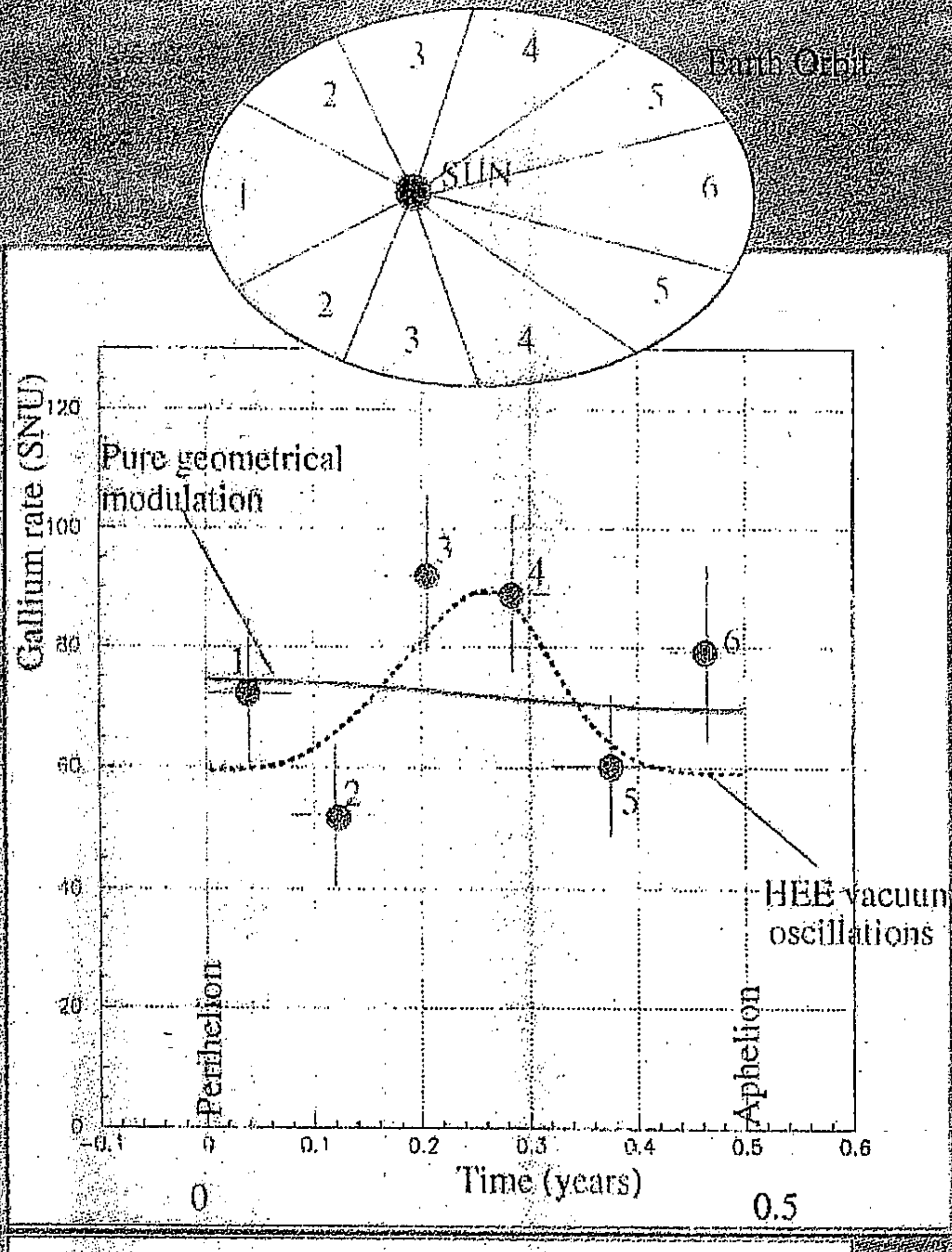
GALLEX + GNO $74.1 \,{}^{+6.7}_{-6.8}$

$$\frac{\text{DATA}}{\text{SSM(BP98)}} = 0.574 \,{}^{+0.052}_{-0.053}$$

Future:

30 ton ⟶ 60 ton ⟶ 100 ton
(2005) (2008)

GALLEX/GNO data binned with distance from the Sun



Geometrical : chi2 = 8.3 / 5 DOF C.L. = 14%

HEE VO : chi2 = 4.4 / 5 DOF C.L. = 49%

③ Kamiokande, Super-Kamiokande

$\nu_x + e \longrightarrow \nu_x + e$ $\quad E_{th} = 7.0$ MeV (for Kam)
$\quad\quad 5.5$ MeV (for SK)

(^{8}B, hep)

realtime spectrum

(1987 ~ 1995)

Kamiokande $2.80 \pm 0.19 \pm 0.33$ $(\times 10^6/\mathrm{cm}^2/\mathrm{s})$

$$\frac{\mathrm{DATA}}{\mathrm{SSM(BP98)}} = 0.544 \pm 0.037 \pm 0.064$$

(1996 ~)

Super-Kamiokande ···> presented by Y. Fukuda

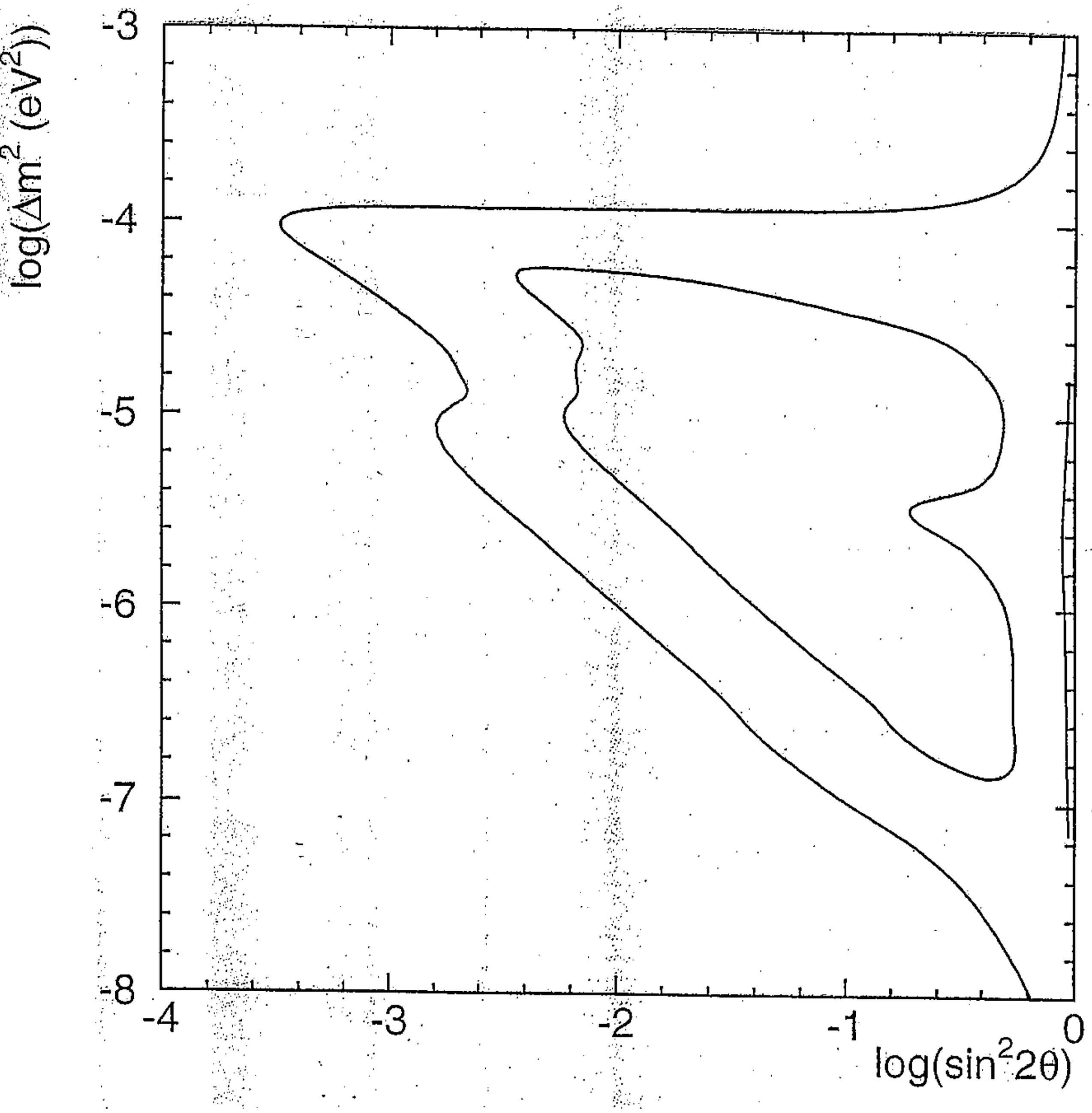
Less neutrinos detected by all the experiments than calcurated flux

⇓

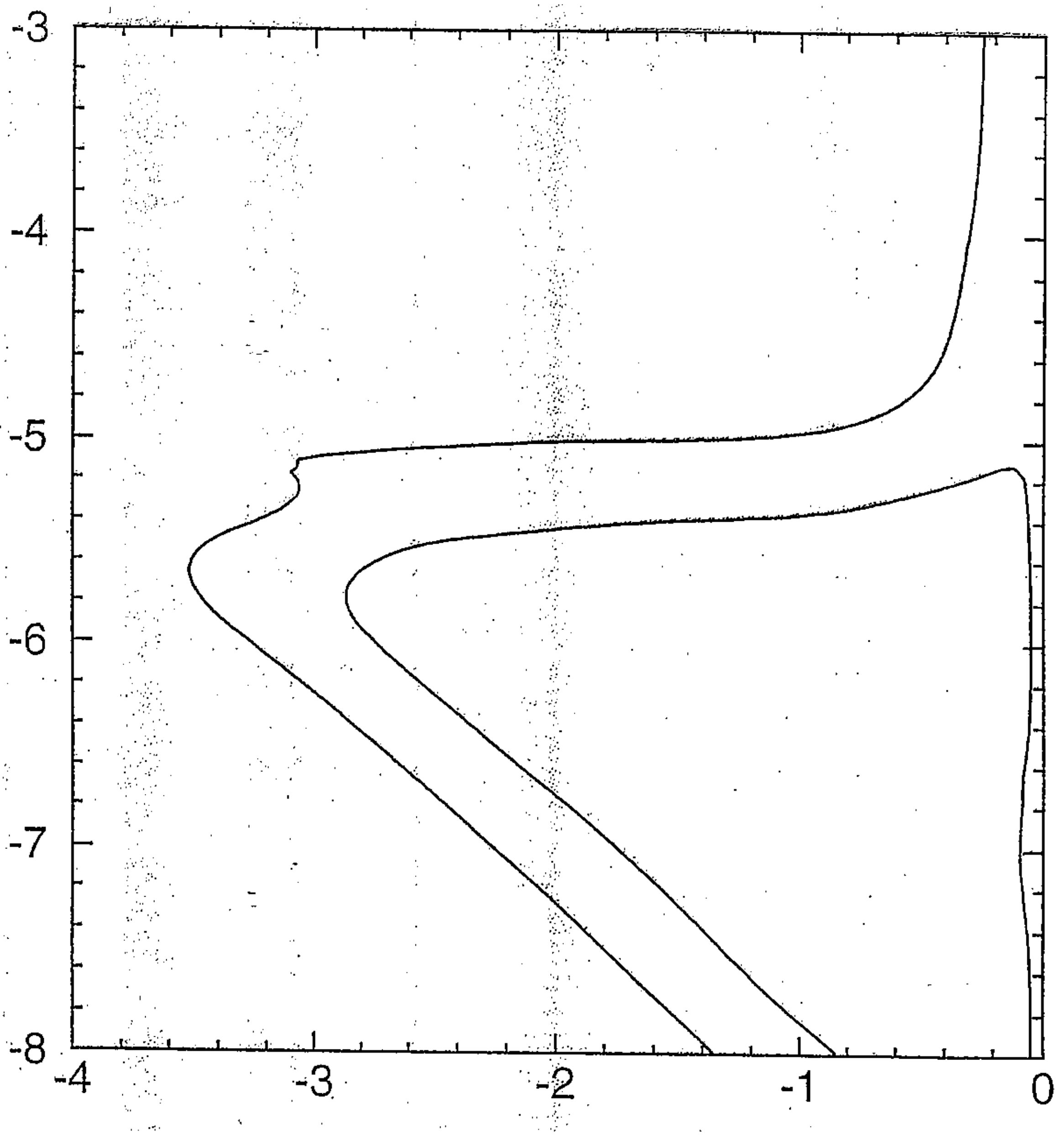
Solar neutrino problem

· neutrino oscillation ?

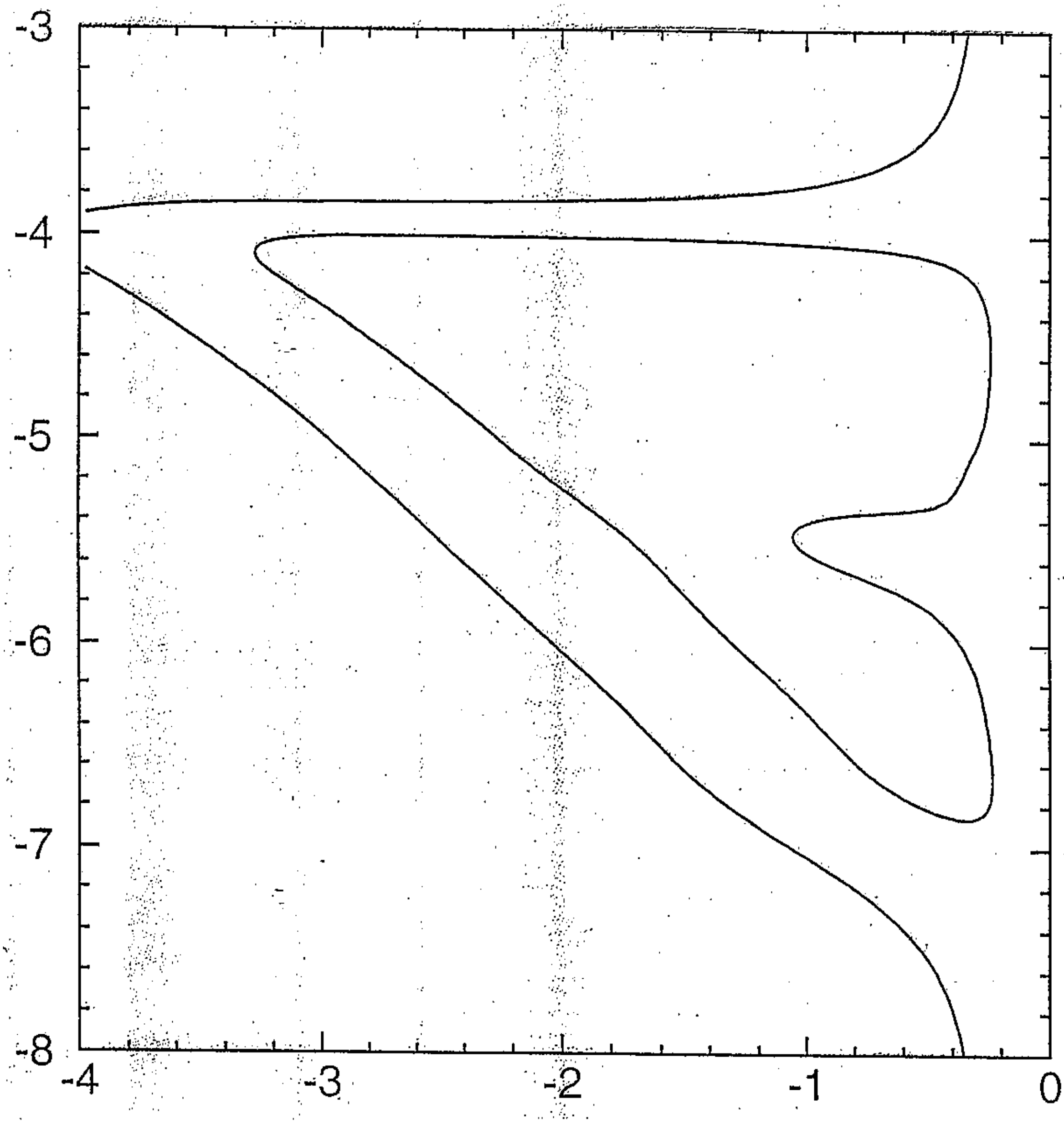
MSW
C1



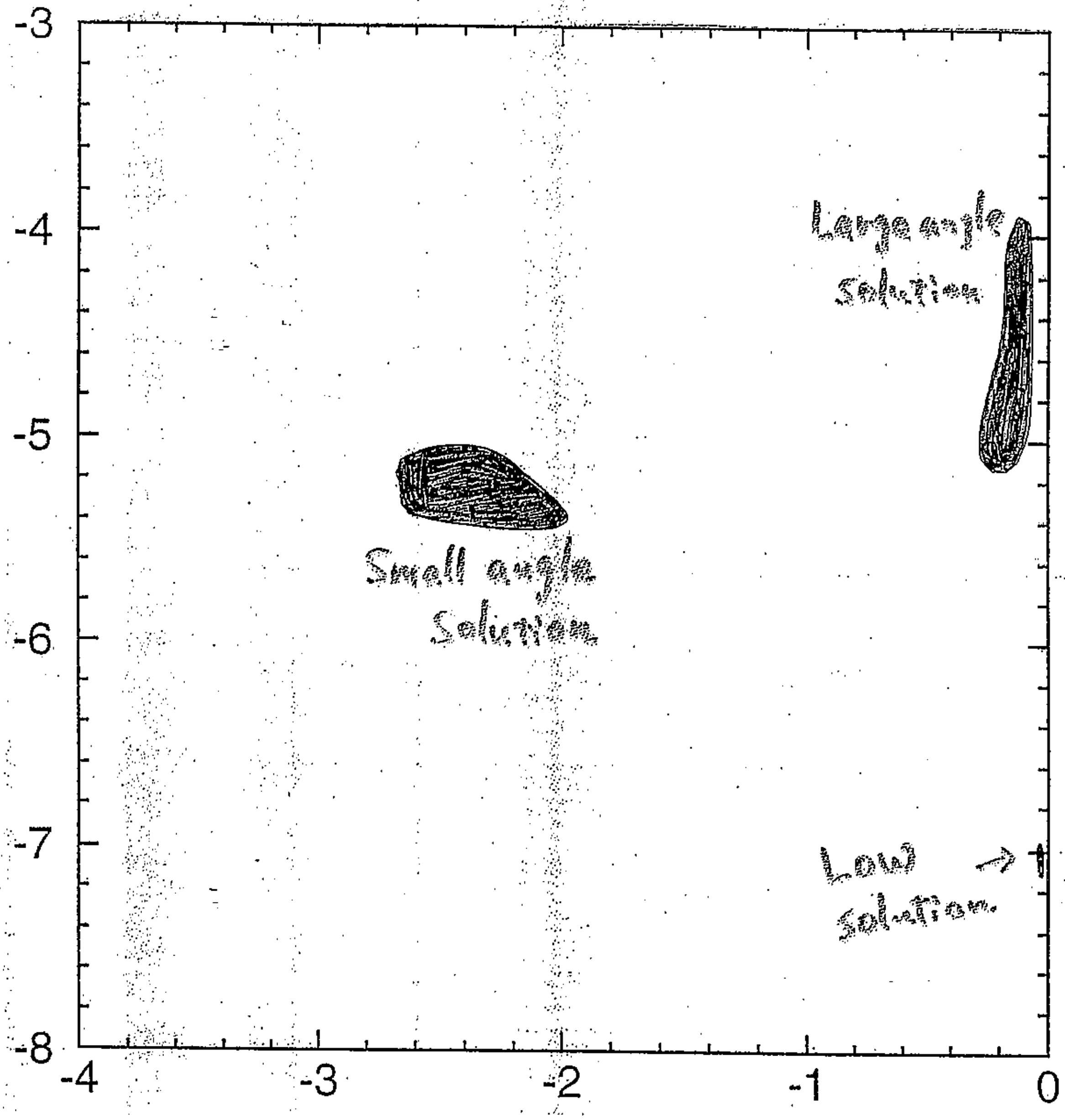
MSW
Ga



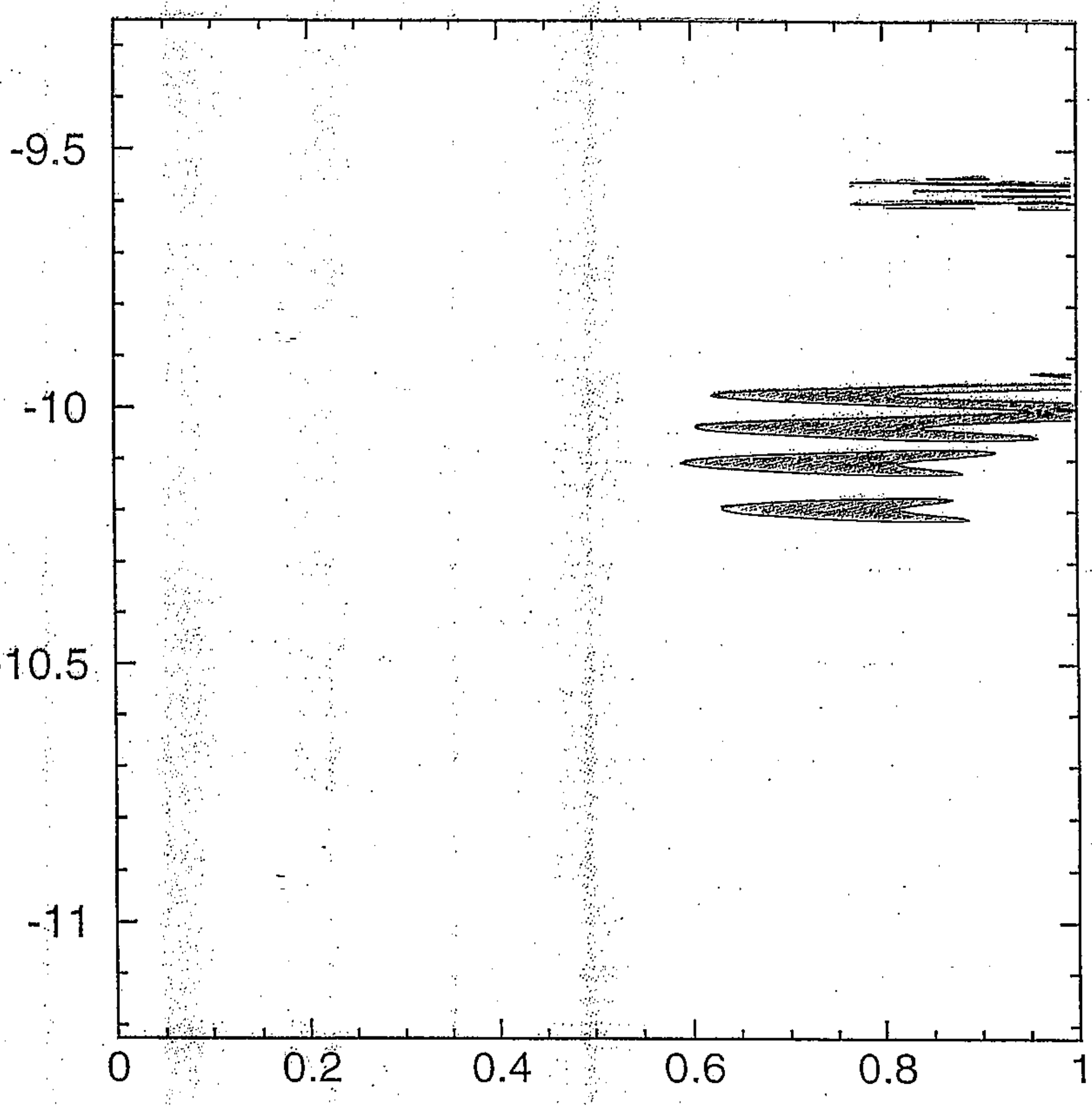
MSW
SK



combine (95% C.L.)

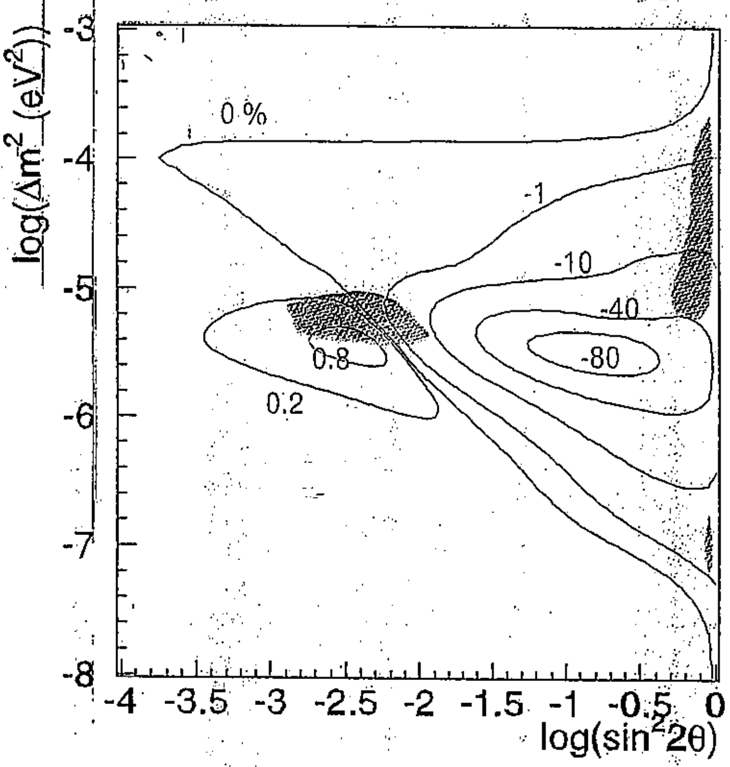


Vacuum oscillation



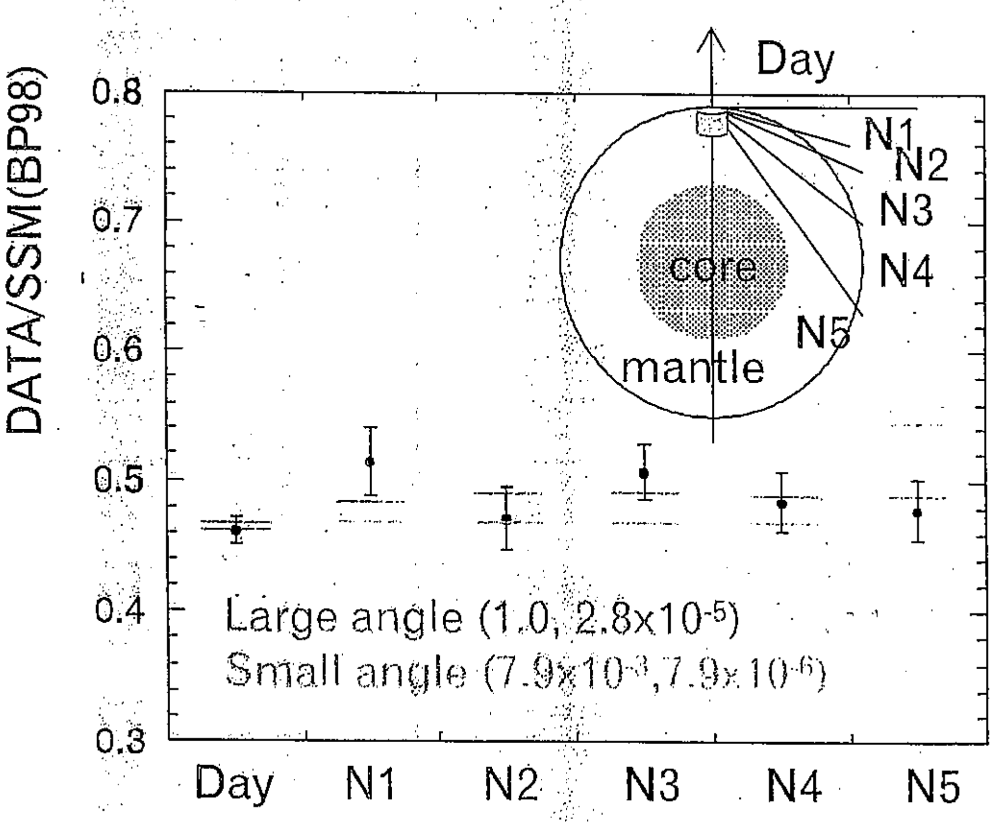
Analysis(1) --- Day/Night difference

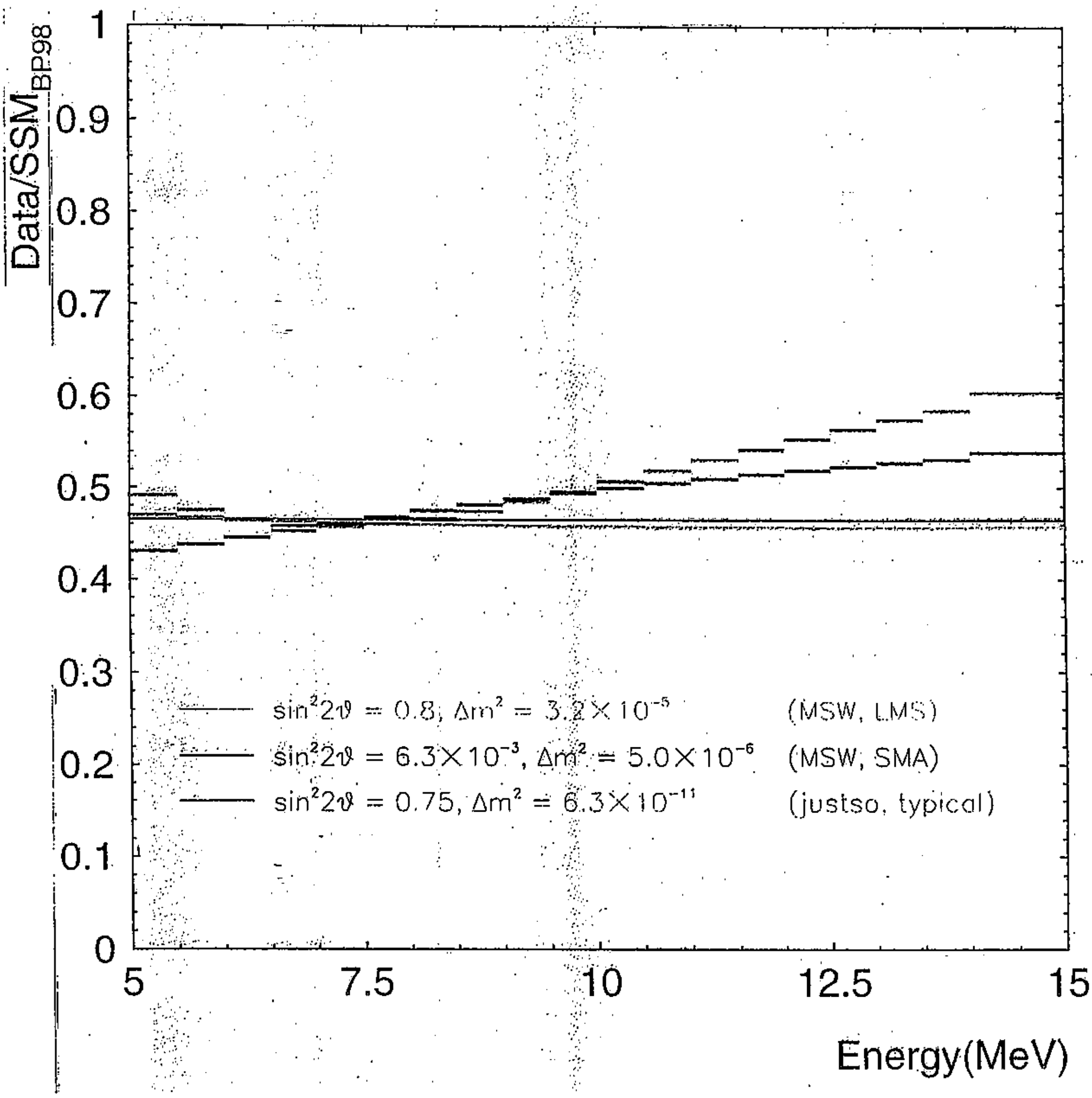
Day/Night effect sensitive region

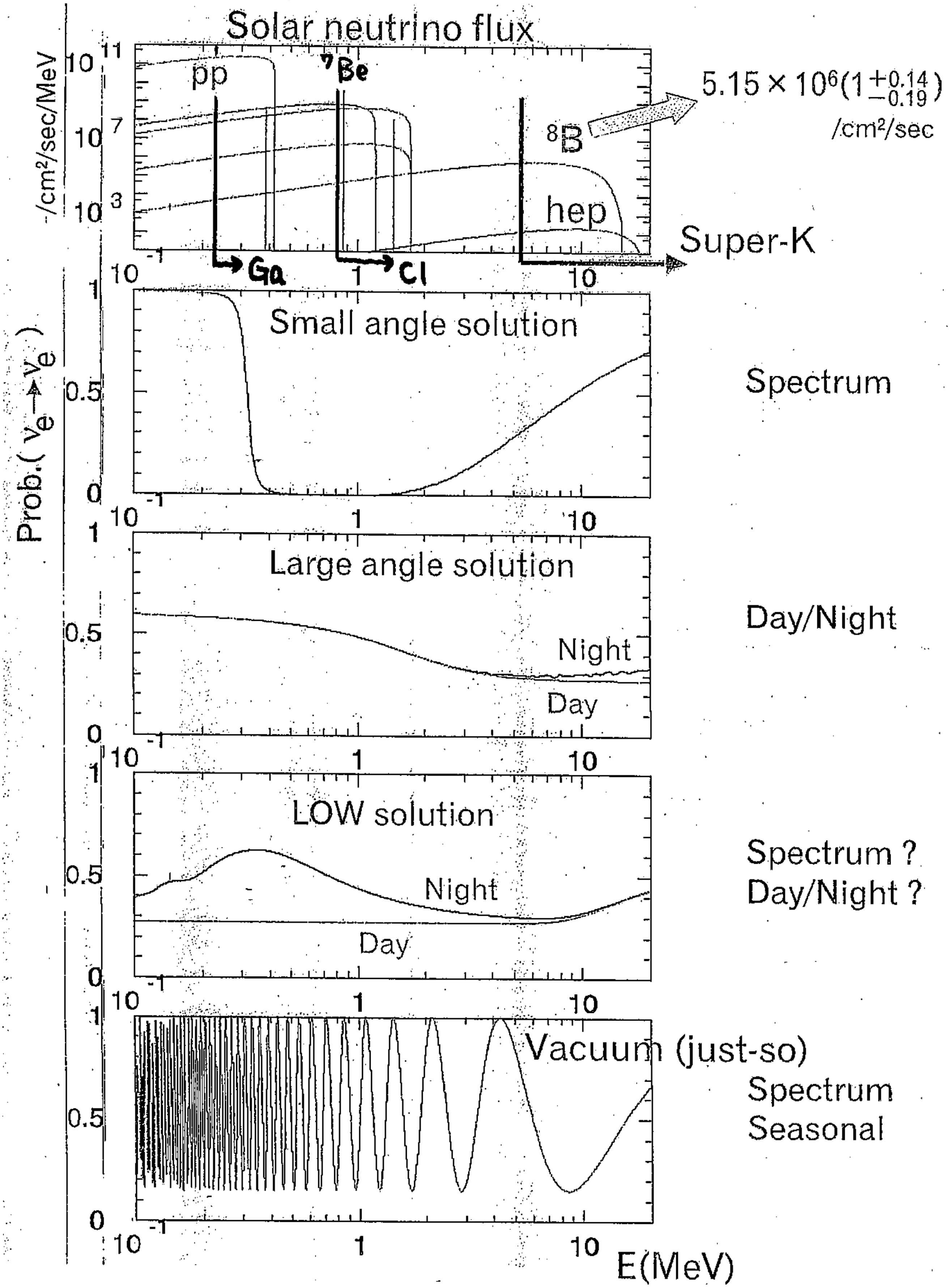


$$\frac{\text{Day}-\text{Night}}{\frac{1}{2}(\text{Day}+\text{Night})}$$

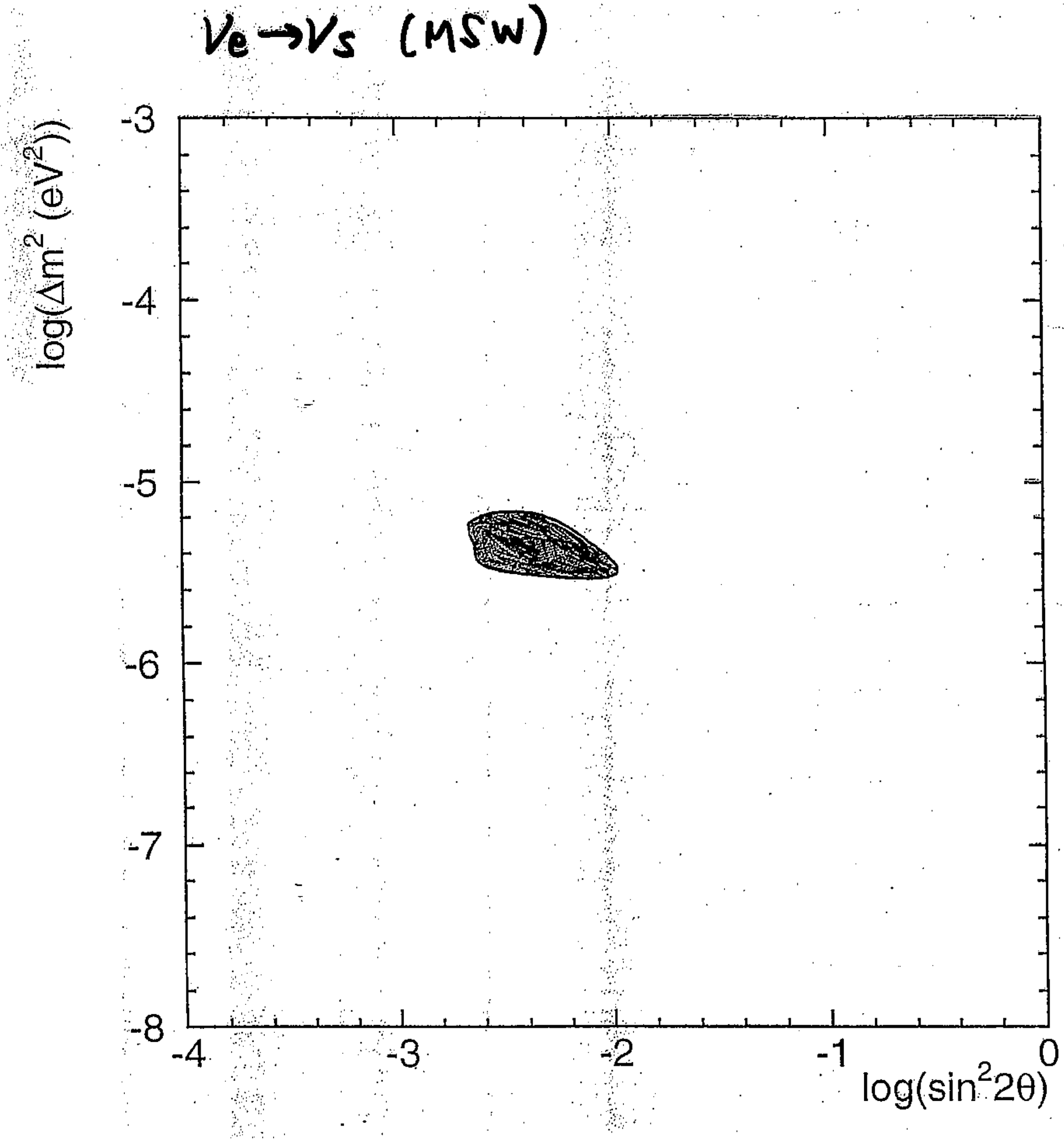
$\left(\begin{array}{c}-0.067\pm0.033\pm0.013 \\ \text{measured by Super-K}\end{array}\right)$



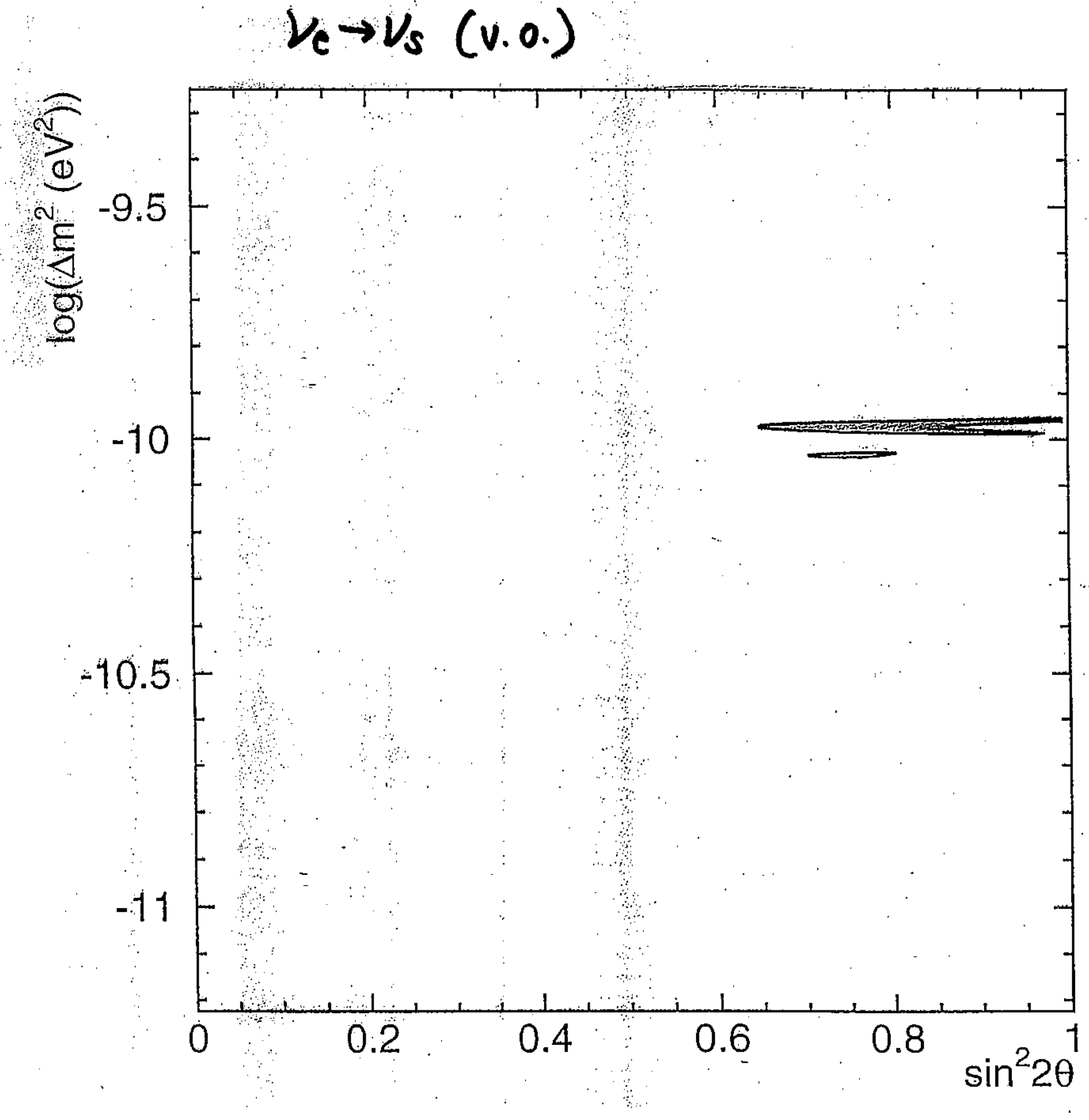

Data/SSM$_{BP98}$
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5
7.5
10
12.5
15
Energy(MeV)
$\sin^2 2\vartheta = 0.8,\ \Delta m^2 = 3.2\times10^{-5}$ (MSW, LMS)
$\sin^2 2\vartheta = 6.3\times10^{-3},\ \Delta m^2 = 5.0\times10^{-6}$ (MSW, SMA)
$\sin^2 2\vartheta = 0.75,\ \Delta m^2 = 6.3\times10^{-11}$ (justso, typical)



Solar neutrino flux
/cm²/sec/MeV
pp
⁷Be
⁸B
hep
Ga
Cl
Super-K
5.15 × 10⁶(1 +0.14 −0.19)
/cm²/sec
Prob.(νe → νe)
Small angle solution
Spectrum
Large angle solution
Night
Day
Day/Night
LOW solution
Night
Day
Spectrum ?
Day/Night ?
Vacuum (just-so)
Spectrum
Seasonal
E(MeV)



νe→νs (MSW)
log(Δm² (eV²))
-3
-4
-5
-6
-7
-8
-4
-3
-2
-1
0
log(sin²2θ)



νe→νs (v.o.)
log(Δm² (eV²))
-9.5
-10
-10.5
-11
0
0.2
0.4
0.6
0.8
1
sin²2θ

SNO

D_2O

C.C. $\nu_e + d \longrightarrow p + p + e^-$ $E_{th} = 1.4\,MeV$

(only ν_e) $E_\nu = E_e + 1.4\,MeV$

N.C. $\nu_x + d \longrightarrow \nu_x + p + n$ $E_{th} = 2.2\,MeV$

(all ν types)

E.S. $\nu_x + e^- \longrightarrow \nu_x + e^-$

(mostly ν_e) $0.86\nu_e + 0.14(\nu_\mu + \nu_\tau)$

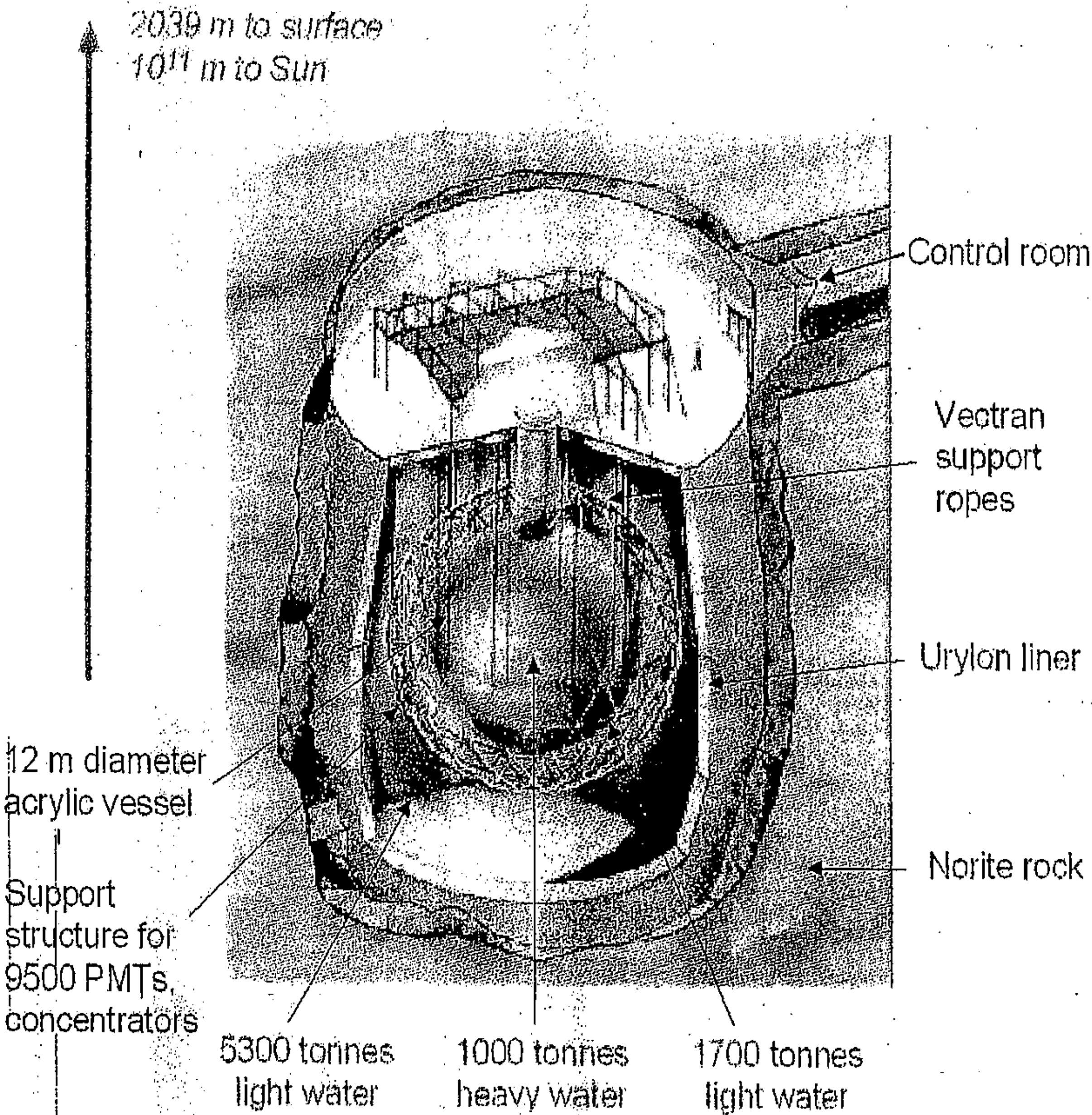
Physics motivation for solar ν

- Search for flavor change (ν-oscillation)
- ^8B ν energy spectrum
- Total ^8B ν flux
- Time dependence

Comparing C.C. and SK

neutrino 2000
A. McDonald

The SNO Detector



- **Location:** 6800 ft. level of INCO's Creighton mine near Sudbury, ON, Canada (~70 muons / day)

- **SNO Detector:** 9438_{inward} + $91_{outward}$ Hamamatsu 8" PMTs + concentrators = 64% coverage

hep-ph/9911248
Bahcall, Krastev and Smirnov

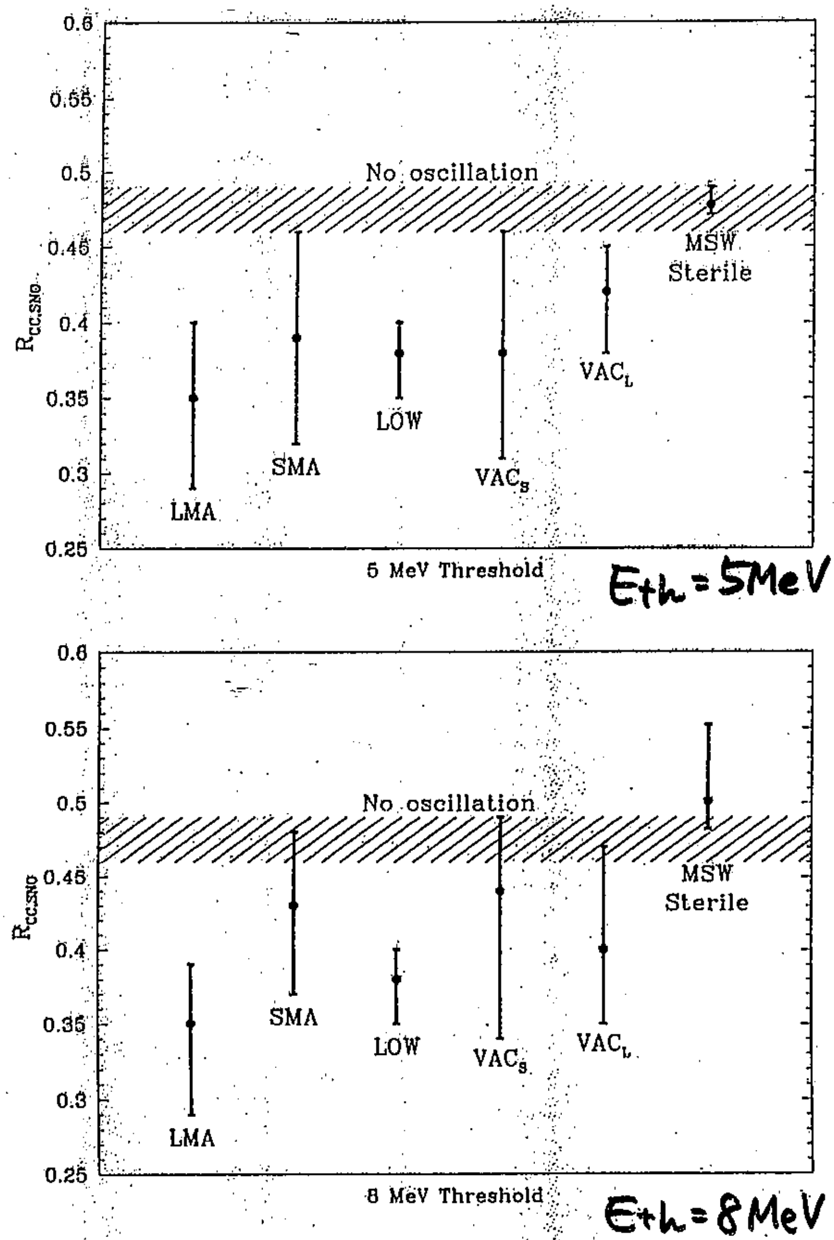


Fig. 2. Comparison of the CC SNO rate and the no oscillation prediction. The shaded area is the no oscillation prediction based upon the measured SuperKamiokande rate for $\nu - e$ scattering, see Eq. (3) and Eq. (7). The SNO CC ratios, Eq. (6), are shown on the vertical axes for different neutrino scenarios and two different total electron energy thresholds, 5 MeV and 8 MeV. The error bars on the neutrino oscillation results represent the range of values predicted by the 99% CL allowed neutrino oscillation solutions displayed in Fig. 1.

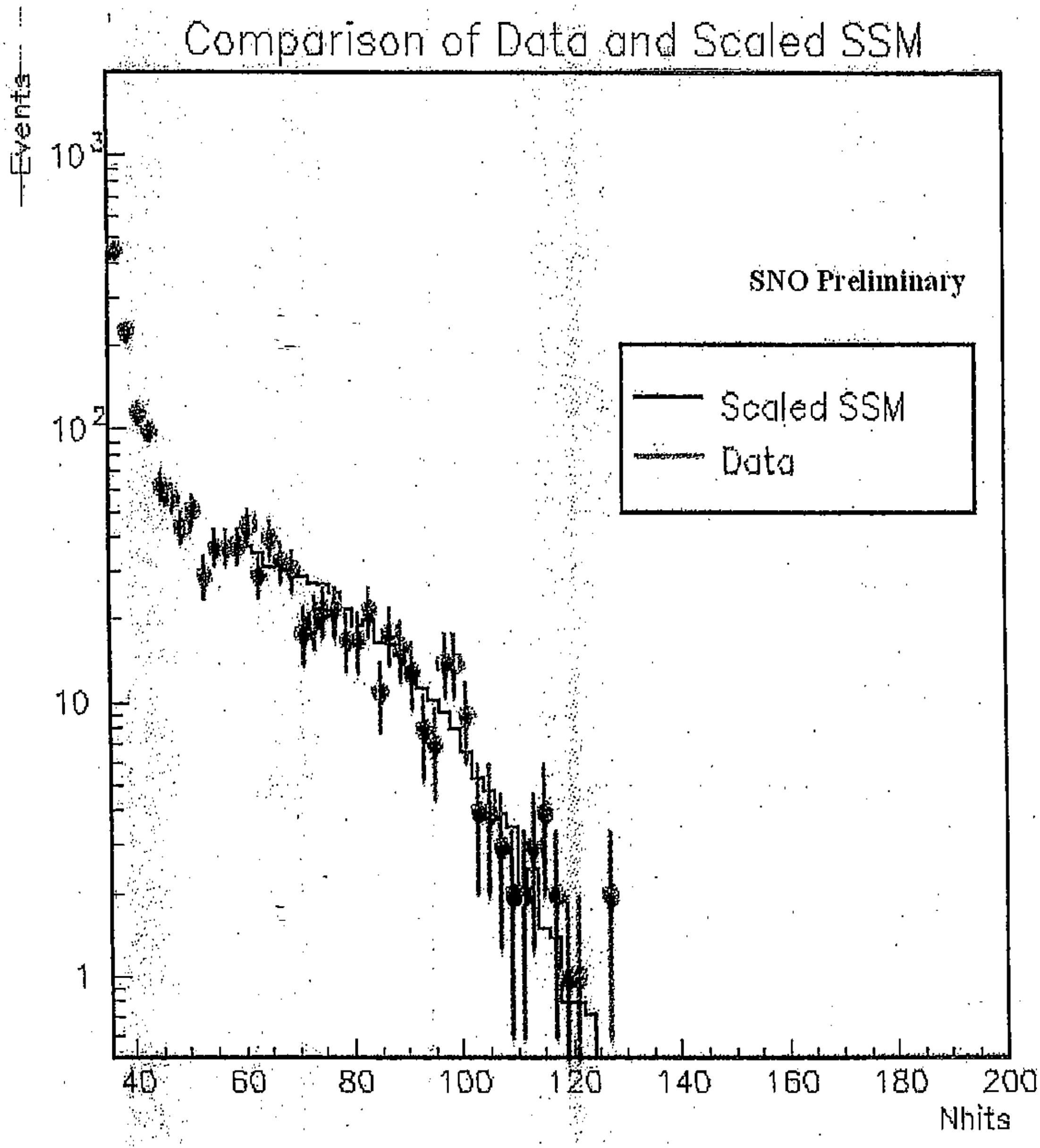
or slightly larger than 0.48, then a measurement of the shape of the recoil electron energy spectrum to as low an energy as possible will be an important test of the predicted small energy dependence of the survival probability of the MSW Sterile solution.

SNO C.C. rate

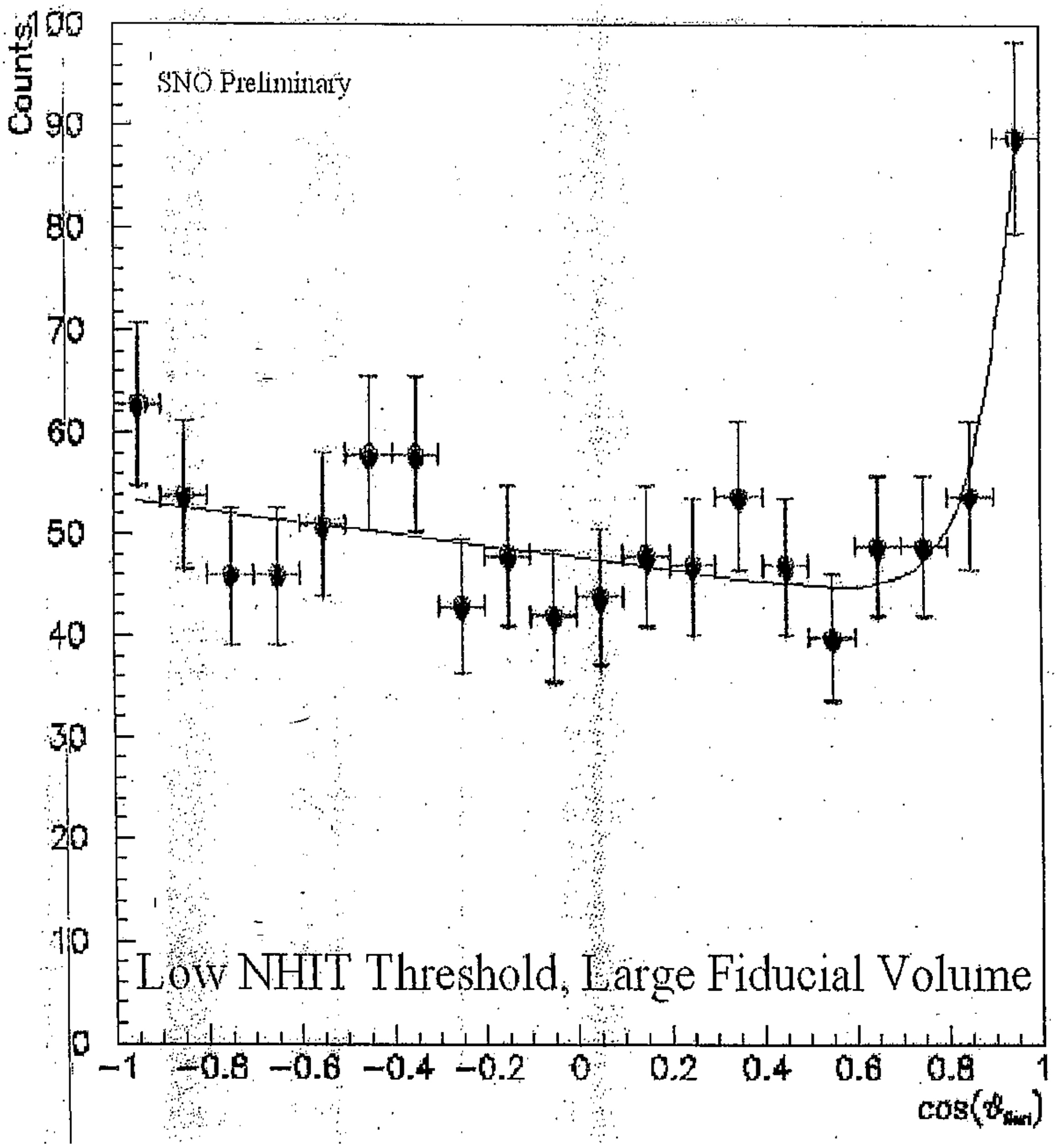
⇓

not yet

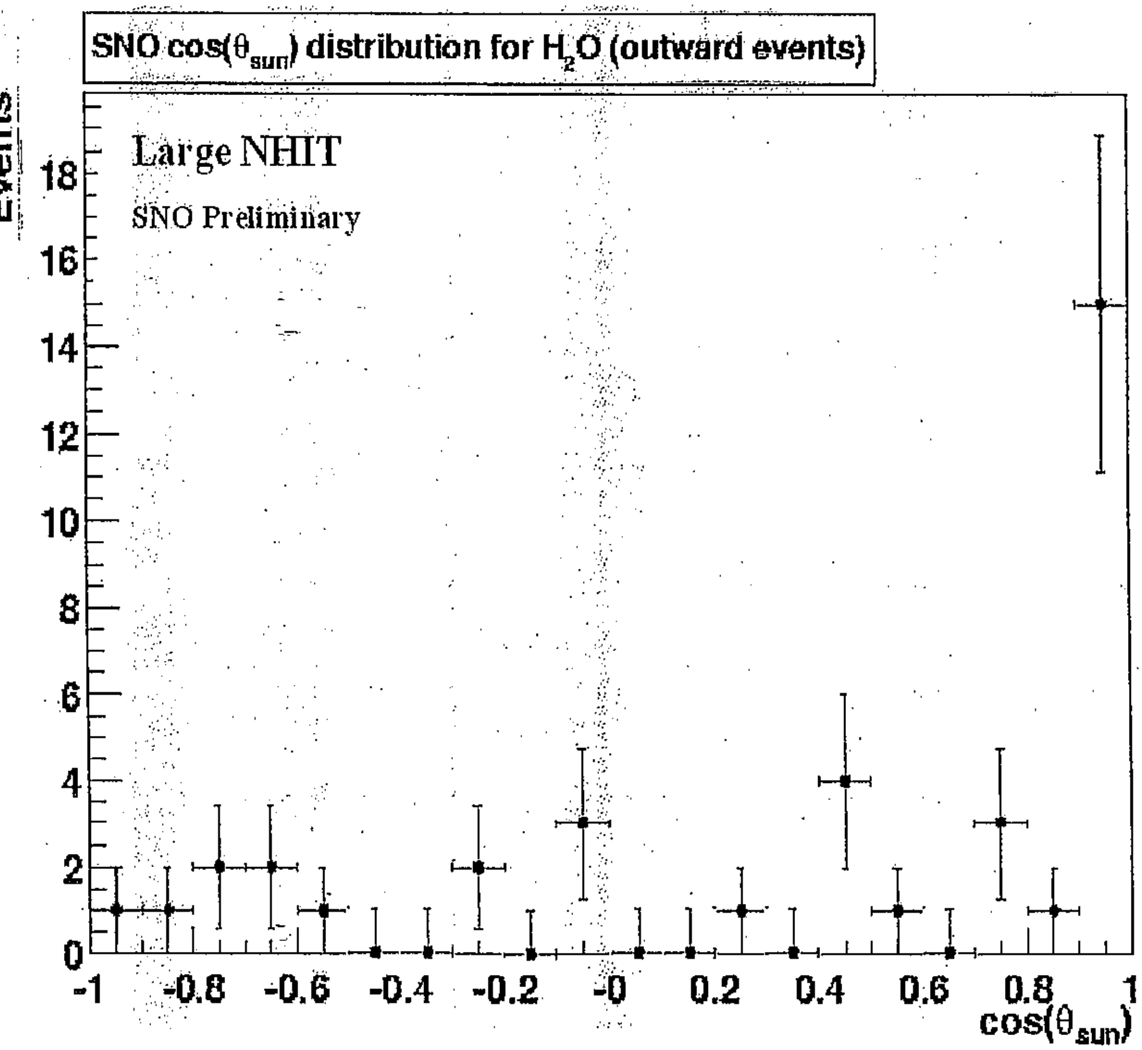
neutrino 2000
A. McDonald



neutrino 2000
A. McDonald



Neutrino 2000
A. McDonald



SNO Experimental Plan

Three Phases (About 1 year Each):

Phase 1: Pure D_2O

- Good sensitivity for CC, lower for ES, NC

Phase 2: Added Salt

- Enhanced sensitivity for NC

Phase 3: ^3He detectors in Pure D_2O

- Independent sensitivity for NC

Neutron Detection Methods In 3 Phases:

1. Neutron capture on deuterium in pure D_2O:

$$n + d \rightarrow t + \gamma \ldots \rightarrow e^- \quad (E_\gamma = 6.3\ \text{MeV})$$

-capture efficiency, $\varepsilon_{D_2O} = 24\%$

2. Neutron capture on Cl using Salt in D_2O:

$$n + {}^{35}Cl \rightarrow {}^{36}Cl + \Sigma\gamma \ldots \rightarrow e^- \quad (E_{\Sigma\gamma} = 8.6\ \text{MeV})$$

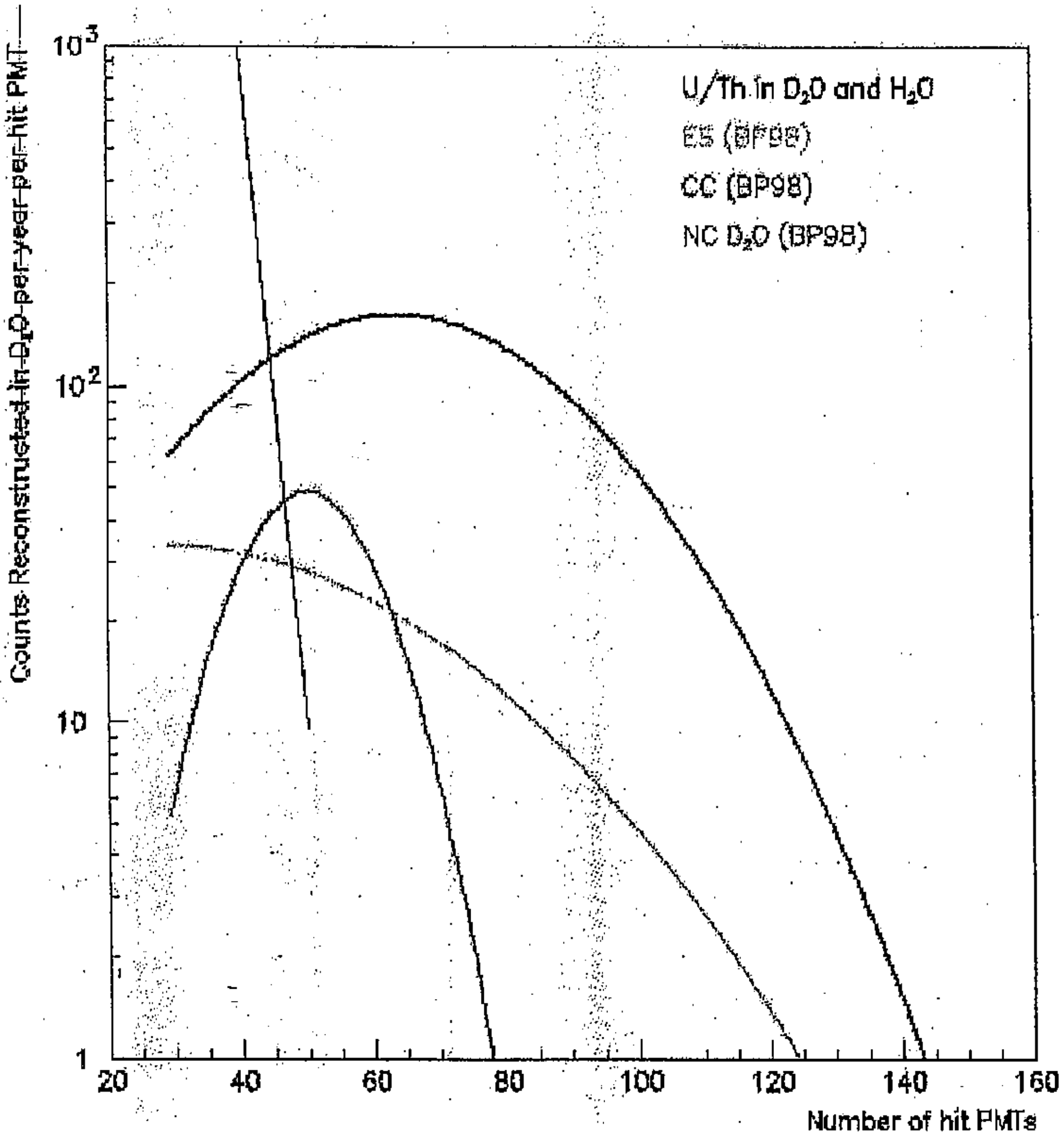
- capture efficiency, $\varepsilon_{salt} = 83\%$

3. Neutron capture on He using proportional counters:

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

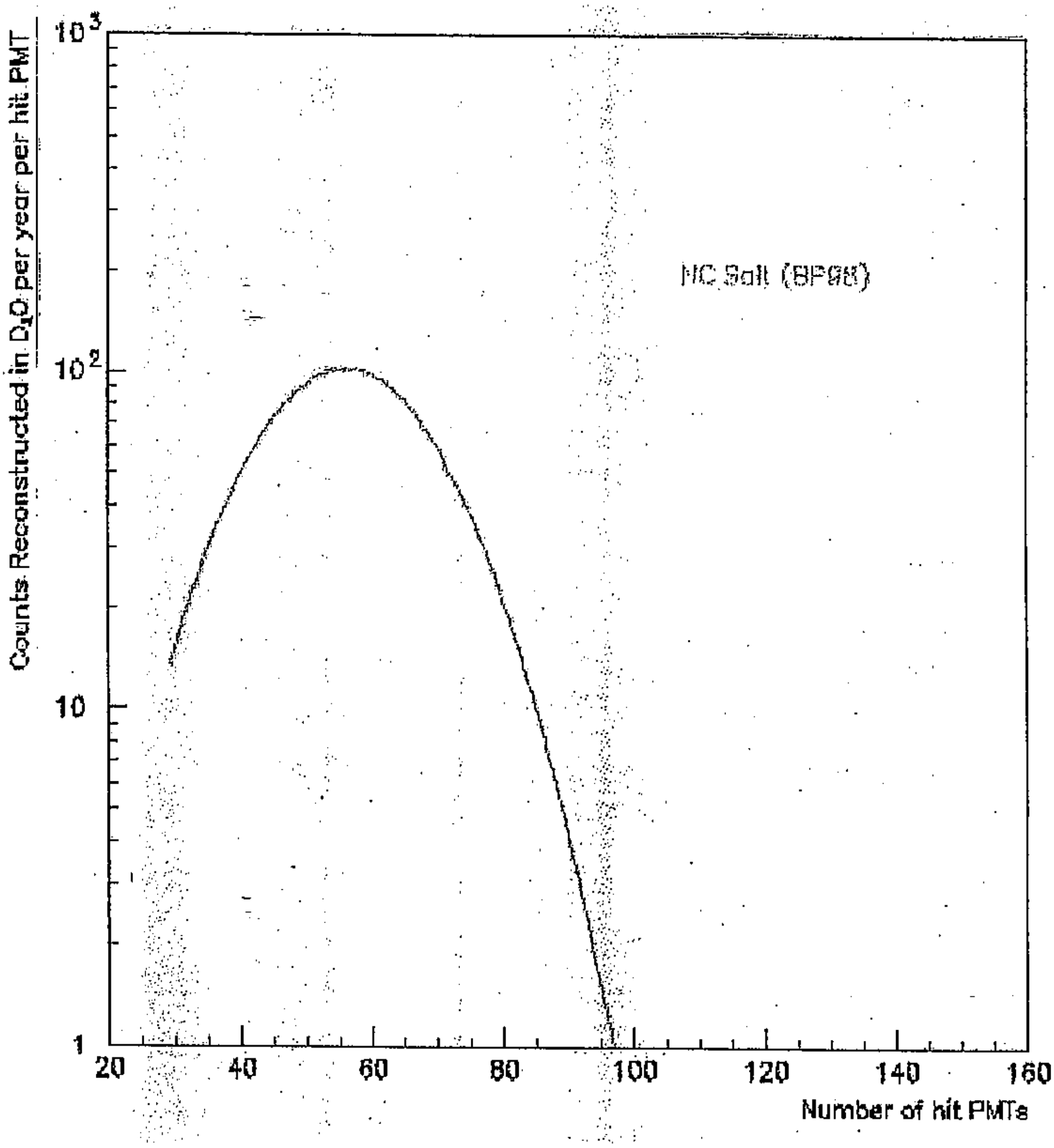
-capture efficiency, $\varepsilon_{NCD} = 45\%$

neutrino2000
A. McDonald



~ 9 NHIT/MeV

Neutrino 2000
A. McDonald



☀ Summary and Future

~ Now

Homestake, Gallium, Kamioka

→ solar neutrino problem

ν-oscillation ?

Now ~

- SNO

観測順調 → 今後1~2年で結果?

flavor changing

energy spectrum.

C.C. vs SK

- KamLand, Borexino

建設中(来年スタート) → 今後3~5年で結果?

- other pp-ν detectors

R&D → presented by S. Moriyama

Neutrino 2000
G. Ranucci

The Borexino program

- First direct measurement of ^7Be flux

Expected rates (ev/d) in a F.V. of 100 T

Recoil Energy window MeV	SSM	LMA	SMA	LOW	VO
		$\Delta m^2 = 1.8 \times 10^{-5}$ eV^2 $\sin 2\theta = 0.76$	$\Delta m^2 = 5.4 \times 10^{-6}$ eV^2 $\sin^2\theta = 5.5 \times 10^{-3}$	$\Delta m^2 = 7.9 \times 10^{-8}$ eV^2 $\sin^2\theta = 0.96$	
0.25 - 0.8	55.2	30.7	11.7	29.0	
				day/night effect	**seasonal variation**

- Probing vacuum oscillations via seasonal variation of the flux

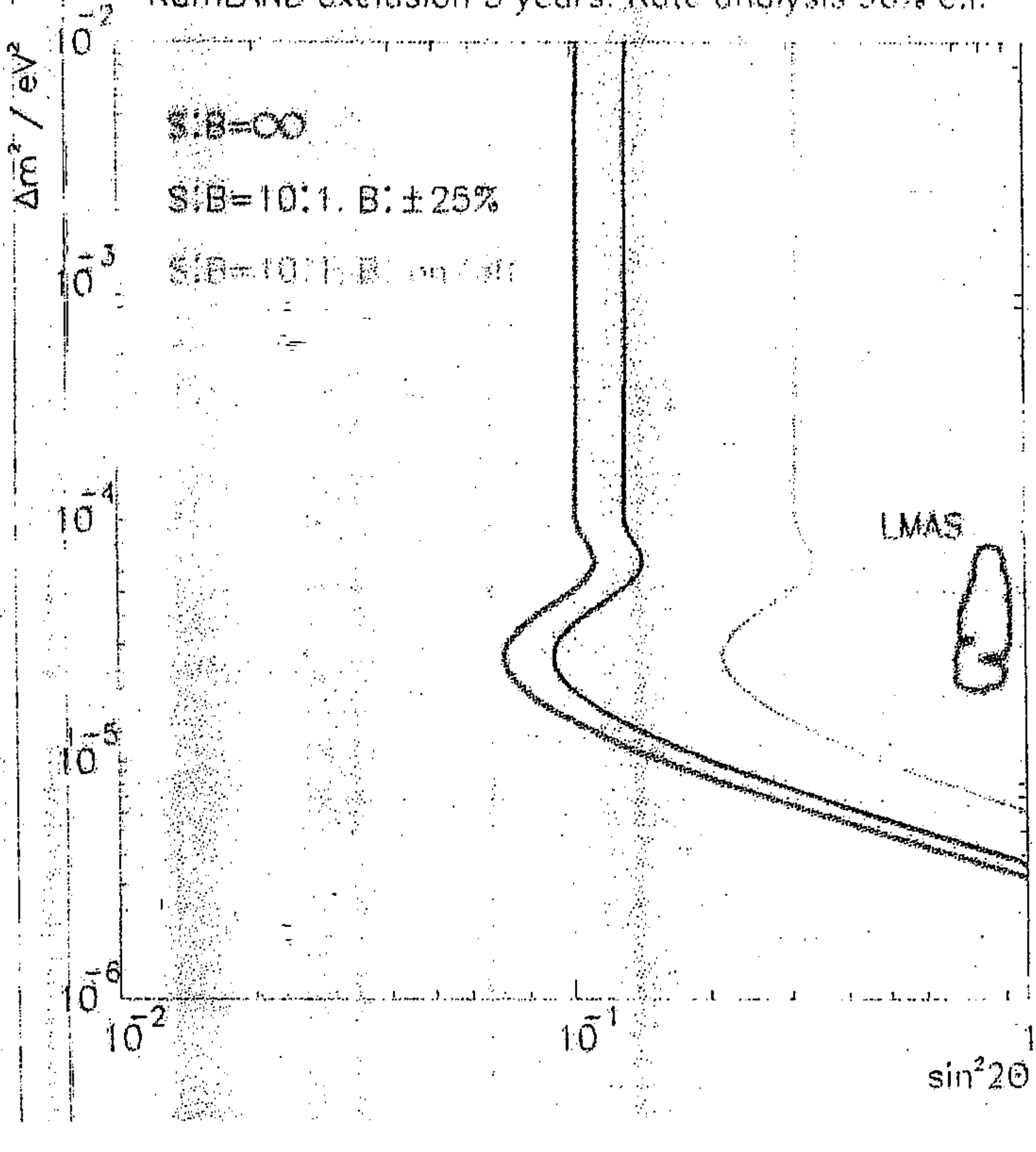
- In absence of other time variations, demonstration of the solar origin of the signal through the 7% variation due to the Earth-Sun distance variation during the year

- Background ~ 15 ev/d

neutrino 2000
A. Piepke

KamLAND

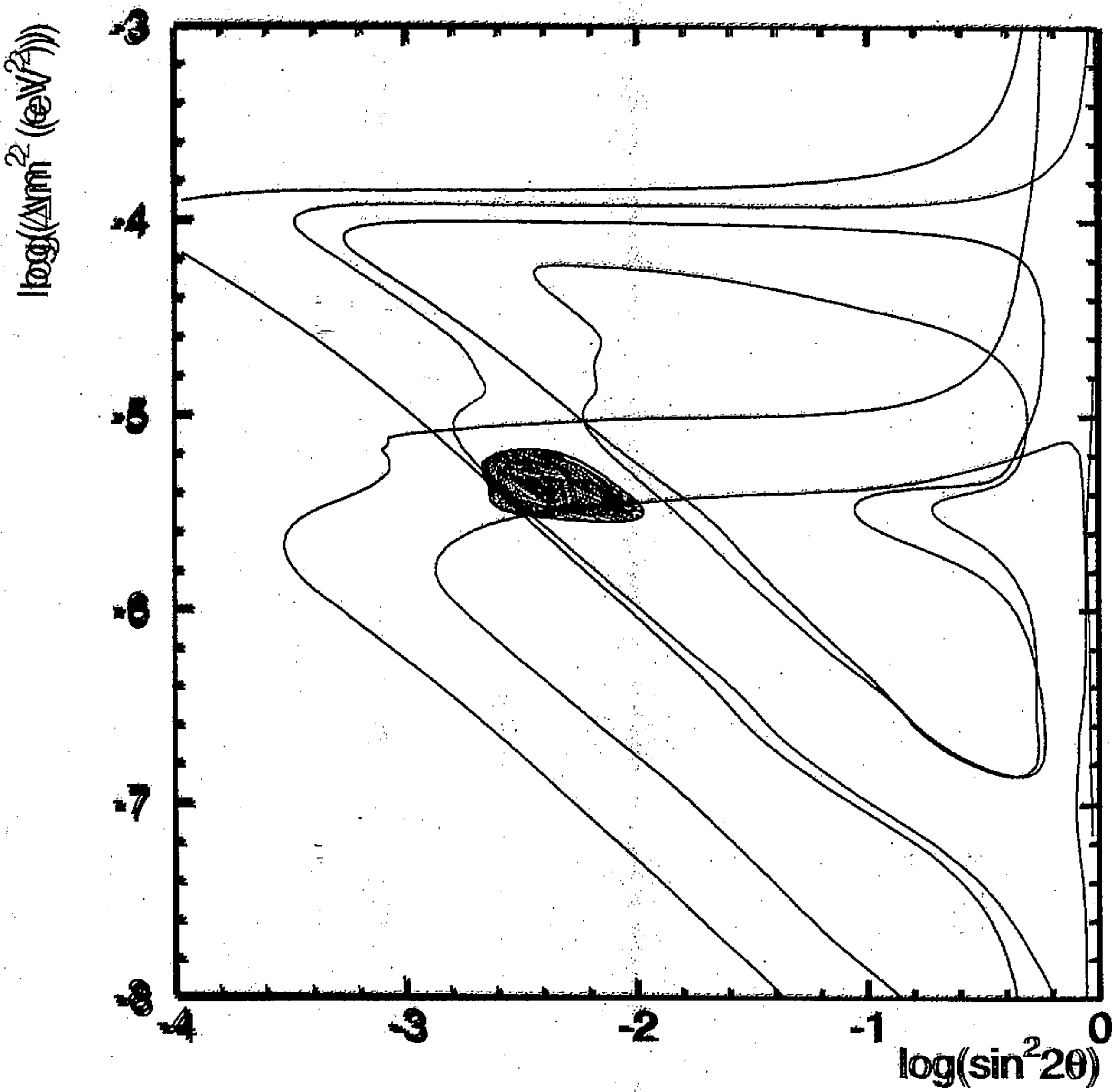
KamLAND exclusion 3 years. Rate analysis 90% c.l.



12 +13 + 14 + 20

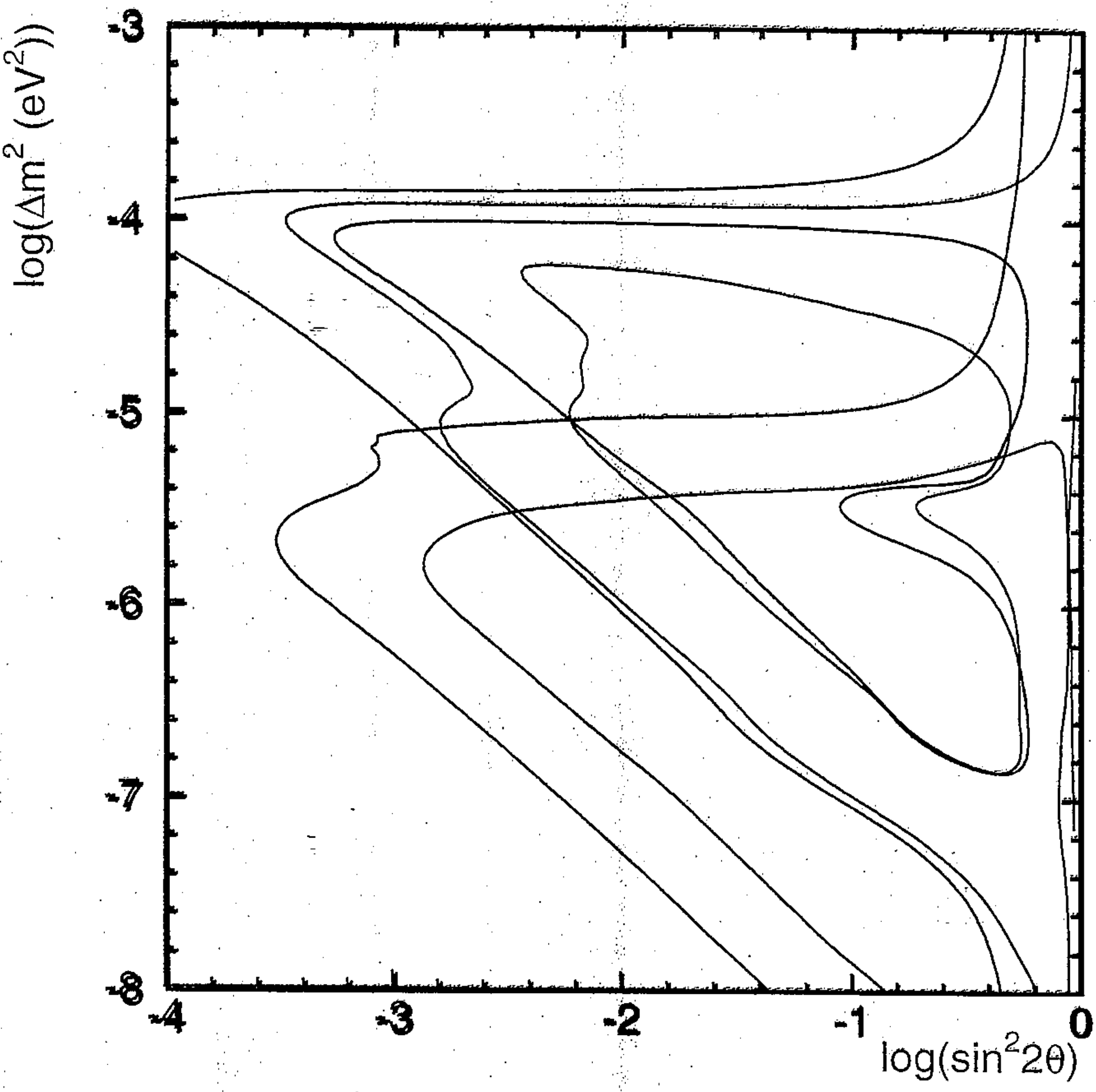
MSW
Cl

$\nu_e \to \nu_s$ (MSW)



|2+|3+|4

MSW
CI



12+13+14+15

MSW
CI

combine (95% C.L.)