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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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SMR.996 - 15

Lecture III

SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

2 June - 4 July 1997

NEUTRINO PHYSICS

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Solar Neutrinos

Neutrinos from the Sun

Energy of the Sun:

$$4p \to {}^4He + 2e^+ + 2\nu_e$$

- 25 MeV released → γ's → 10^4 y
- 2 ν's emitted ~ 2 MeV → few sec.

Total energy flux in sunlight → 1400 $J/m^2\text{-}s$

$$\text{Total \# } \nu\text{'s} = \frac{2}{25\,\text{MeV}} \times \{\ \}$$

$\simeq 10^{11}$ per cm^2 per sec.

Come directly from the interior of the Sun. (Not surface)

Solar Cycle

	Reaction		% of terminations	Maximum neutrino energ
	$p + p \rightarrow {}^2H + e^+ + \nu$	(1)	(99.75)	0.420
	or			
	$p + e^- + p \rightarrow {}^2H + \nu$		(0.25)	1.44(monoenergetic)
	${}^2H + p \rightarrow {}^3He + \gamma$	(2)	(100)	
*	${}^3He + {}^3He \rightarrow {}^4He + 2p$	3A	(86)	
	or			
*	${}^3He + {}^4He \rightarrow {}^7Be + \gamma$	3B		
	${}^7Be + e^- \rightarrow {}^7Li + \nu$	4A	(14)	0.861 (90%), 0.383 (10%) (both monoenergetic)
	${}^7Li + p \rightarrow 2\,{}^4He$			
	or			
*	${}^7Be + p \rightarrow {}^8B + \gamma$	4B		
	${}^8B \rightarrow {}^8Be^* + e^+ + \nu$		(0.015)	14.06
	${}^8Be^* \rightarrow 2\,{}^4He$			

* Crucial reactions whose x-sections needed at E~1 keV. Current expts. measuring at ~100 keV to check old results.

SOLAR MODELS [Bahcall, Book]

Basic Ingredients:

- Hydrostatic Eqlbm: $\frac{dP}{dr} = -GM\rho/r^2$
- Energy Transport: $L_r = -\frac{4\pi r^2 ac}{3}\frac{1}{\kappa\rho}\frac{dT^4}{dr}$
  - ↳ opacity

$$P = \frac{a}{3}T^4 + \frac{1}{\mu}\frac{k\rho T}{m_H}(1+D)$$

$$\hookrightarrow \frac{1}{\mu} = \underbrace{2X + \frac{3}{4}Y + \frac{1}{2}Z}_{\text{abundances}}$$

- Energy Generation: $\frac{dL}{dr} = \rho(4\pi r^2)\left(\epsilon_{Nuc} - T\frac{dS}{dt}\right)$
  - ↳ Nuclear reactions
- Luminosity: $L_\odot = \int_0^{R_\odot}\frac{dL_r}{dr}\,dr$

B.C. at surface.

Input: abundances
opacities
eq. of state
Nuclear Reaction Rates.

Iterate until $M_\odot, R_\odot, L_\odot$, for a $t \sim 4.6\cdot 10^9$ yr
(X etc.)

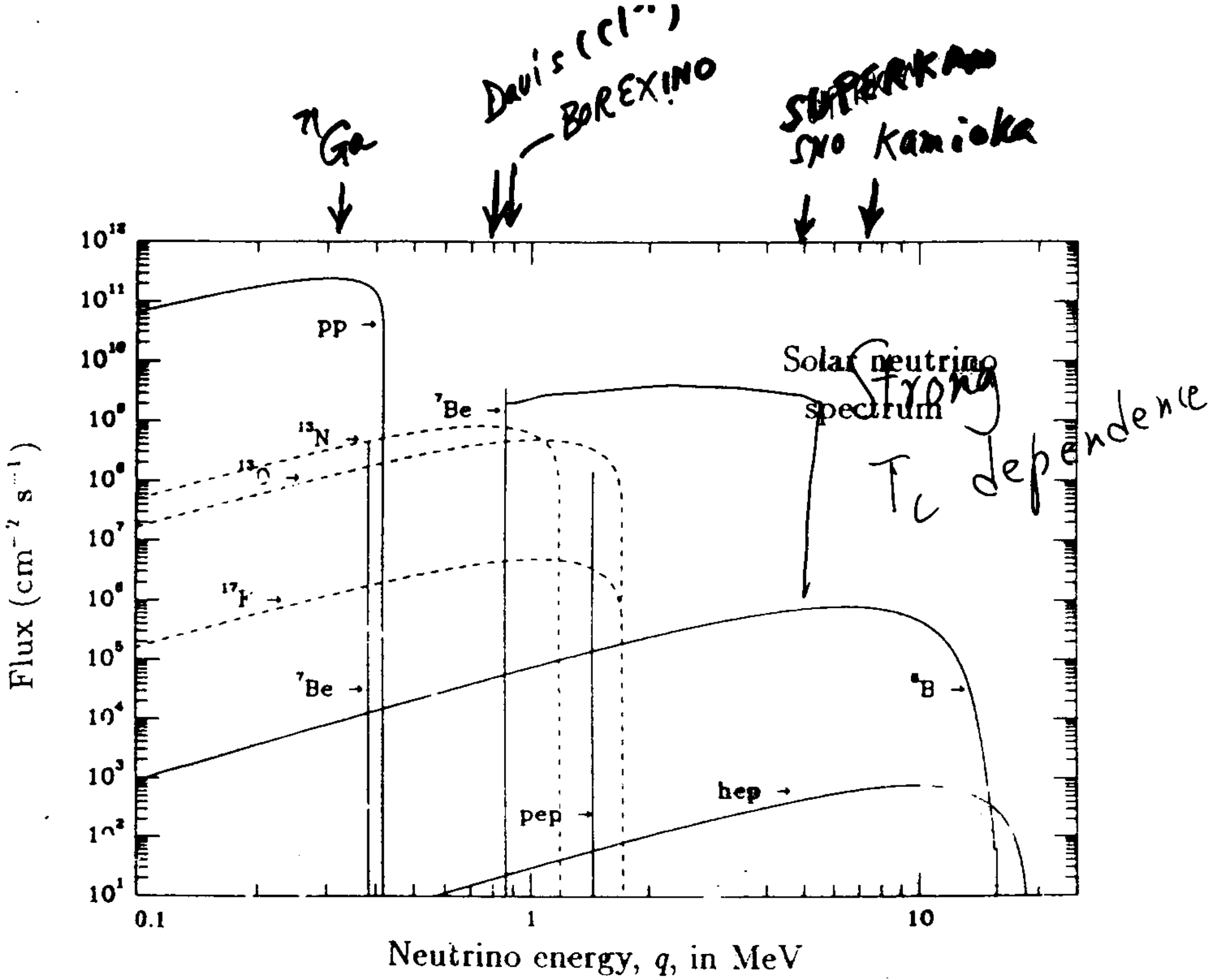


Figure 1.1 Solar neutrino spectrum This figure shows the energy spectrum of neutrinos predicted by the standard solar model. The neutrino fluxes from continuum sources (like pp and ^{8}B) are given in the units of number per cm^2 per second per MeV at one astronomical unit. The line fluxes (pep and ^{7}Be) are given in number per cm^2 per second. The spectra from the pp chain are drawn with solid lines; the CNO spectra are drawn with dotted lines. Chapter 6 discusses the neutrinos that are believed to be produced in the Sun.

$4p \rightarrow {}^4He + e^+ + e^+ + \nu_e + \nu_e$ E released 25 MeV

ν_e's carry about 1 MeV each

Solar Constant of 1.4 KW/m^2 $\Rightarrow \phi_{\nu_e} \sim 10^{11}$ cm^{-2}s^{-1}

The ^{37}Cl Experiment

Reaction: $\nu + {}^{37}Cl \rightarrow {}^{37}Ar + e$

Size: 610 tons C_2Cl_4

Location: Homestake Gold Mine
depth 4400 m. water equivalent

Procedure:

1. Exposed for period 35-100 days with 0.1 cm^3 STP ^{36}Ar or ^{38}Ar carrier
2. ^{37}Ar removed by helium purge
   Tank → Condenser → Absorber → Charcoal → Tank
3. Argon purified by gas chromatography and getter
4. ^{37}Ar measured by gas proportional counter
5. Mass-spec :rometer analysis of ^{36}Ar o1 ^{38}Ar to measure yield

Running since 1967-8.

Current Result: $2.55 \pm 0.17 \pm 0.18$ SNU

$= (0.318 \pm 0.051)\ CR_{BP}$

K. Lande

Davis's Detector

$C\text{-}Cl_4$; 20 ft dia, 48 ft Long. } ~10^5 Gallons

5000 ft underground in Homestake Mine

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

$$Ar^{37} + e^- \longrightarrow Cl^{37} \quad (\tau_{1/2} \sim 35 \text{ days})$$

(K-capture)

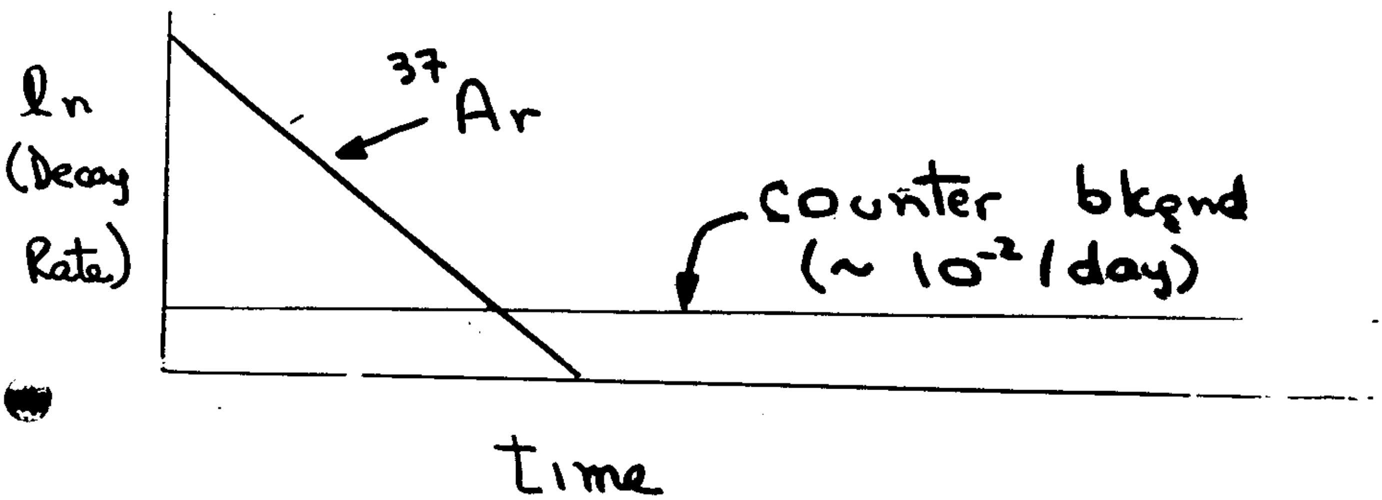
σ for ν's from Sun. (10^{-46} cm^2)

	$pp \to e$	pep	B^8	Be^7	CNO
σ	0	17	1.3×10^4	3	
$\phi_\nu \sigma$	0	0.23	6	1	0.34

$\sum \phi_\nu \sigma = 8 \pm 1$ (1992). SNUS (10^{-36} per sec per atom)

^{37}Ar decays by orbital e^- capture & emission of 2.82 keV Auger electrons.

$\tau_{1/2} = 35$ days.



Measure pulse size & rise time in miniature proportional counter.

Current Result: 2.55 ± 0.17 ± 0.18 SNU

$= (0.318 \pm 0.051)\ CR^{BP}_{SSM}$

K. Lande

Gallium Experiments

- $^{71}Ga + \nu_e \rightarrow ^{71}Ge + e^-$
- $T_{1/2} = 11.43$ days
- Two experiments:
  - SAGE Experiment – Baksan Neutrino Observatory
  - 57 Tons of Ga Metal (39.6% ^{71}Ga)
  - Ge Chemical Extraction $\rightarrow GeH_4 \rightarrow Counter$
  - ^{51}Cr Calibration – Measured/Predicted = 0.95 ± 0.11

$^{51}Cr + e^- \rightarrow ^{51}V + \nu$ 90% ~750 keV 10% ~426 keV

  - GALLEX Experiment – Gran Sasso Laboratory
  - 30.3 Tons of Ga in form of Gallium Chloride
  - Air purge $\rightarrow GeCl_4 \rightarrow GeH_4 \rightarrow Counter$
  - ^{51}Cr Calibrations – Measured/Predicted = 0.92 ± 0.07

- Counting of $Xe - GeH_4$ in miniaturized GPC's

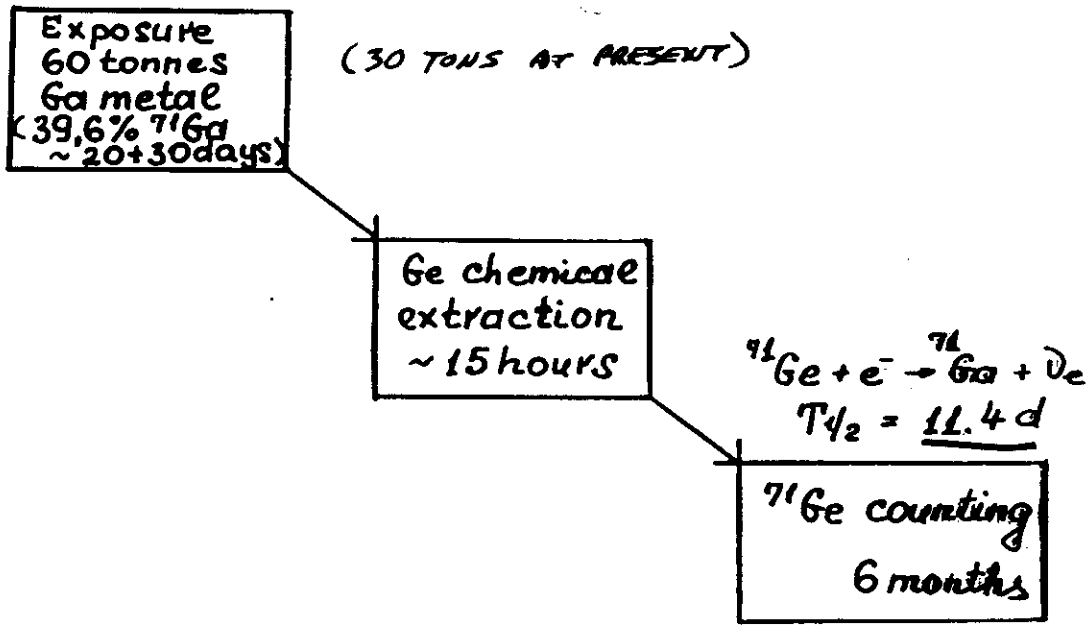
GALLEX [$GaCl_3$ 30T]

SAGE

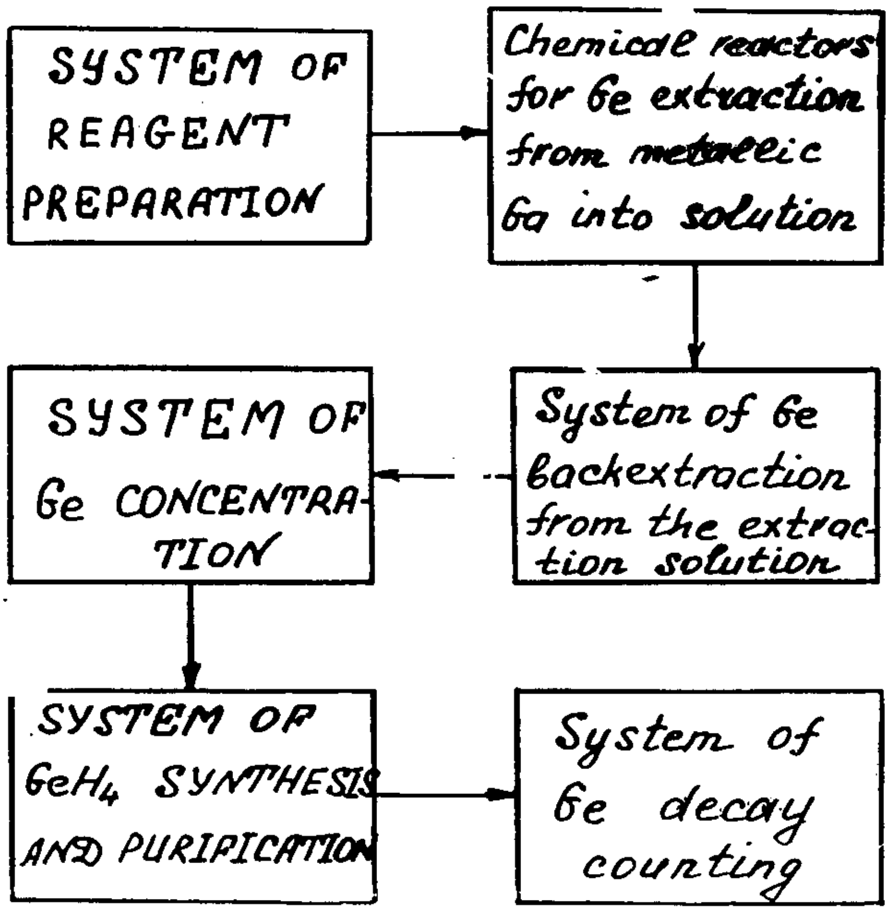
Ga (60T)

EXPERIMENT OVERVIEW

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



SCHEME OF GGNT



V.N. Gavrin

that is,

$$\Phi^{^7Be} \; < \; 2.0 \times 10^9 \; cm^{-2} sec^{-1}. \tag{11}$$

Similarly, he has used the Gallium plus Kamiokande plus Luminosity constraint to show that $\phi^{^7Be} \; < \; 0.53$ at 95% C.L. that is,

$$\Phi^{^7Be} \; < . \; 2.6 \times 10^9 \; cm^{-2} sec^{-1}. \tag{12}$$

These results suggest that $\phi^{^7Be} \; < \; \phi^{^8B}$. Remember however that both the ^7Be and ^8B neutrinos are produced from the same parent in the sun, that is, ^7Be via electron and proton interactions respectively. Also the ^8B neutrinos are more sensitive to changes in the solar core temperature, T_c, than the ^7Be neutrinos, T_c^{18} verses T_c^8 respectively. Therefore it is very difficult to arrange $\phi^{^7Be} \; < \; \phi^{^8B} \; < \; 1$ in standard solar models.

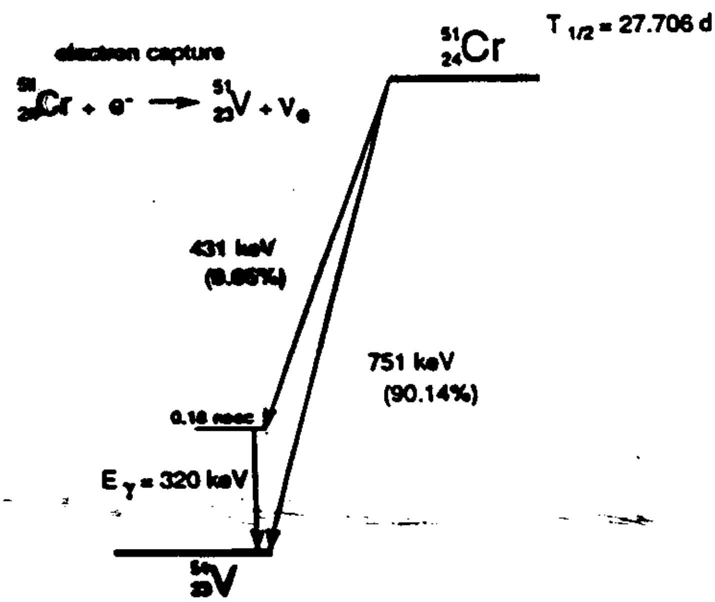


Figure 3: Characteristics of the decay of ^{51}Cr. The "751 keV" line combines the 746 and 751 keV lines and "431 keV" line combines the 426 and 431 keV lines.

Calibration of the Gallium Experiment

From June to October 1994 the Gallex detector [12] was exposed to a $61.9 \; \pm \; 1.2 \; PBq$ neutrino source which emits neutrinos in electron capture in ^{51}Cr, see Fig. 3. This source

Gallex Calibration

was made by bombarding enriched chromium in a nuclear reactor. The initial source activity produced a flux of neutrinos at the detector which was approximately 15 times the solar neutrino flux. This collaboration used three different methods to measure the initial source strength; neutron flux capture calculation, calorimetry and by measuring the 320 keV gamma ray emitted from small samples. The average of these measurements was used to compare with the strength obtained from observing the neutrino capture in the Gallex detector of **64.1 ± 6.6 ± 3.3 *PBq*, see Fig. 4.**

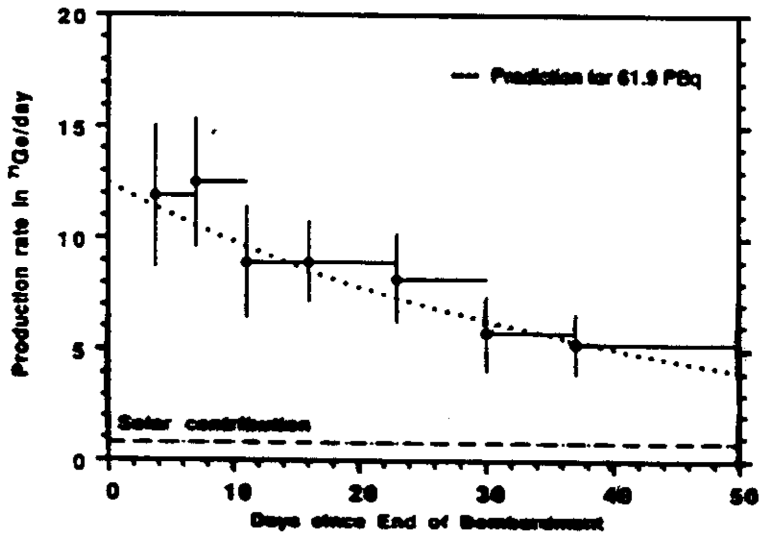
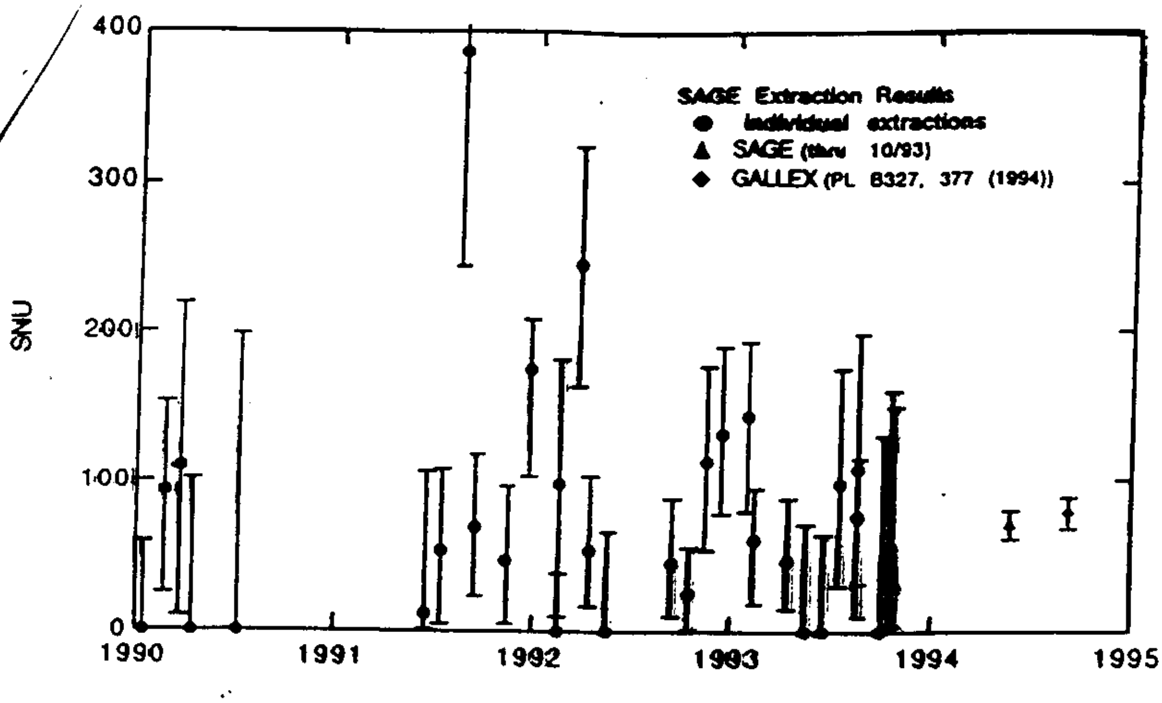


Figure 4: Number of ^{71}Ge atoms produced per day during the course of the source experiment (first 7 runs only). The points for each run are plotted at the beginning of each exposure, with the horizontal lines showing the duration of the exposures. The predicted curve (dotted line), which decreases with the known half-life of ^{51}Cr, is based on the relationship between the directly measured source strength and the 0.189 ^{71}Ge production rate per day. The curve also includes the constant 0.78/day production rate due to solar neutrinos and side reactions (dashed line).

The ratio of the source activity as measured by Gallex to that obtained from the other methods was

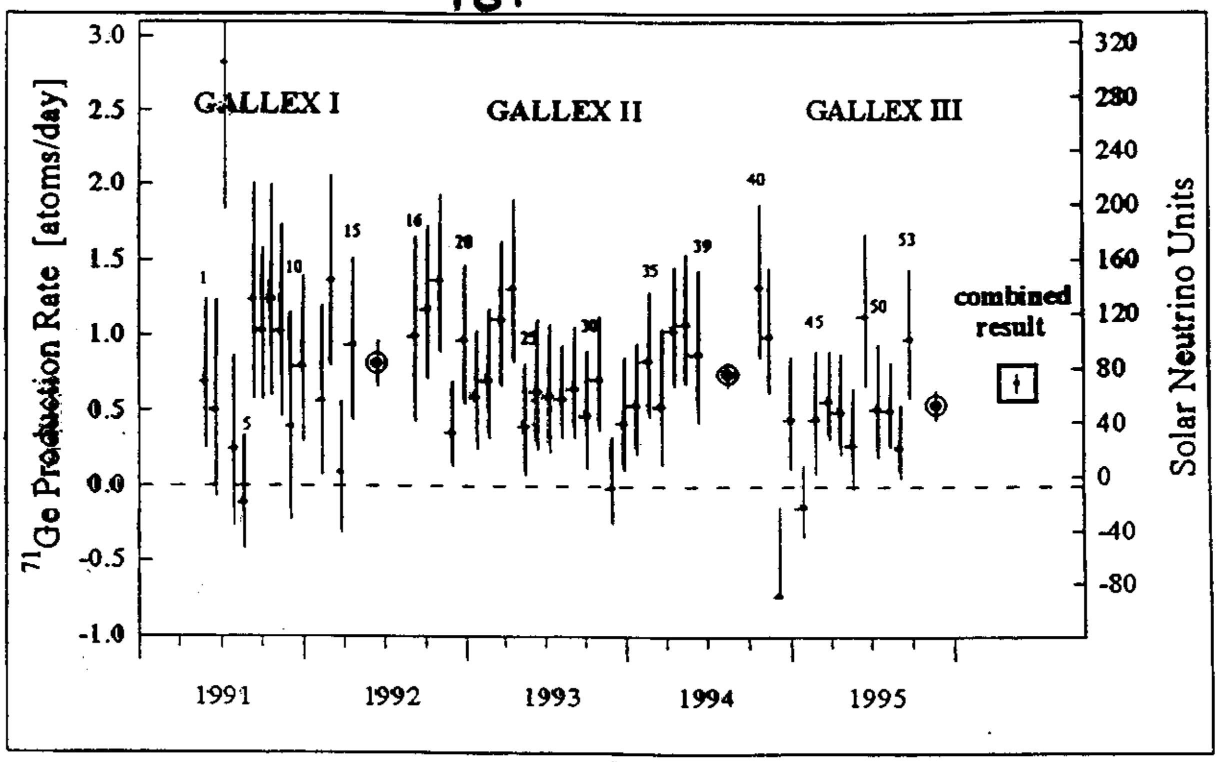
$$1.04 \pm 0.12. \qquad (13)$$

This result validates the radiochemical methods of the Gallex experiment and since 90% of



⇒ $72 \begin{smallmatrix} +12 & +5 \\ -10 & -7 \end{smallmatrix}$

$\left.\frac{\text{observed}}{\text{Predicted}}\right|_{BP} = .53 \pm .10$



⇒ $69.7 \pm 6.7 \begin{smallmatrix} +3.9 \\ -4.5 \end{smallmatrix}$

$\left.\frac{\text{observed}}{\text{Predicted}}\right|_{20} = 0.54 \pm .07$

Kamiokande-II

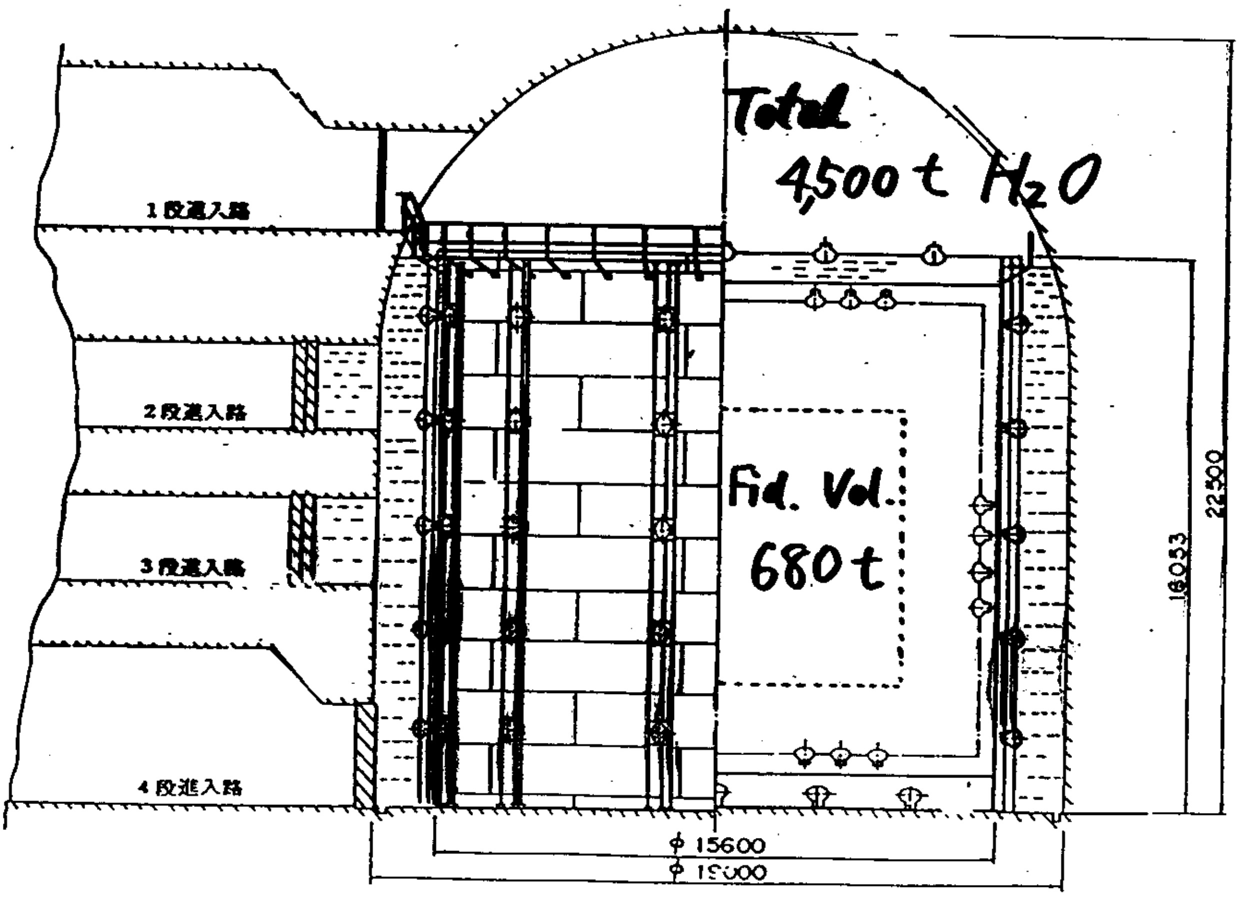
∘ Basic Reaction } "Calibrated" by SN1987A

$\nu e^- \to \nu e^-$

♠ Detect Cherenkov Photons (E_e >7.5MeV)

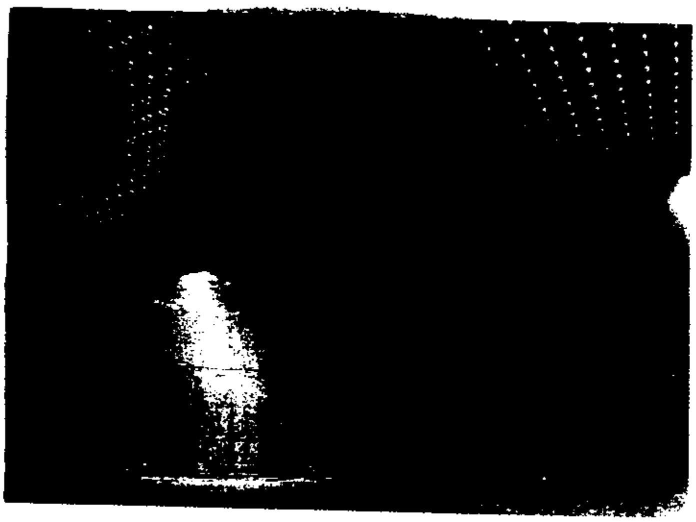
∘ Advantages

- Directional Correlation ~ 30°
- Energy Information 10 MeV = 30 hit PMTs.
- Real-Time



空洞完成 平成6年6月

水槽完成間近 平成7年4月



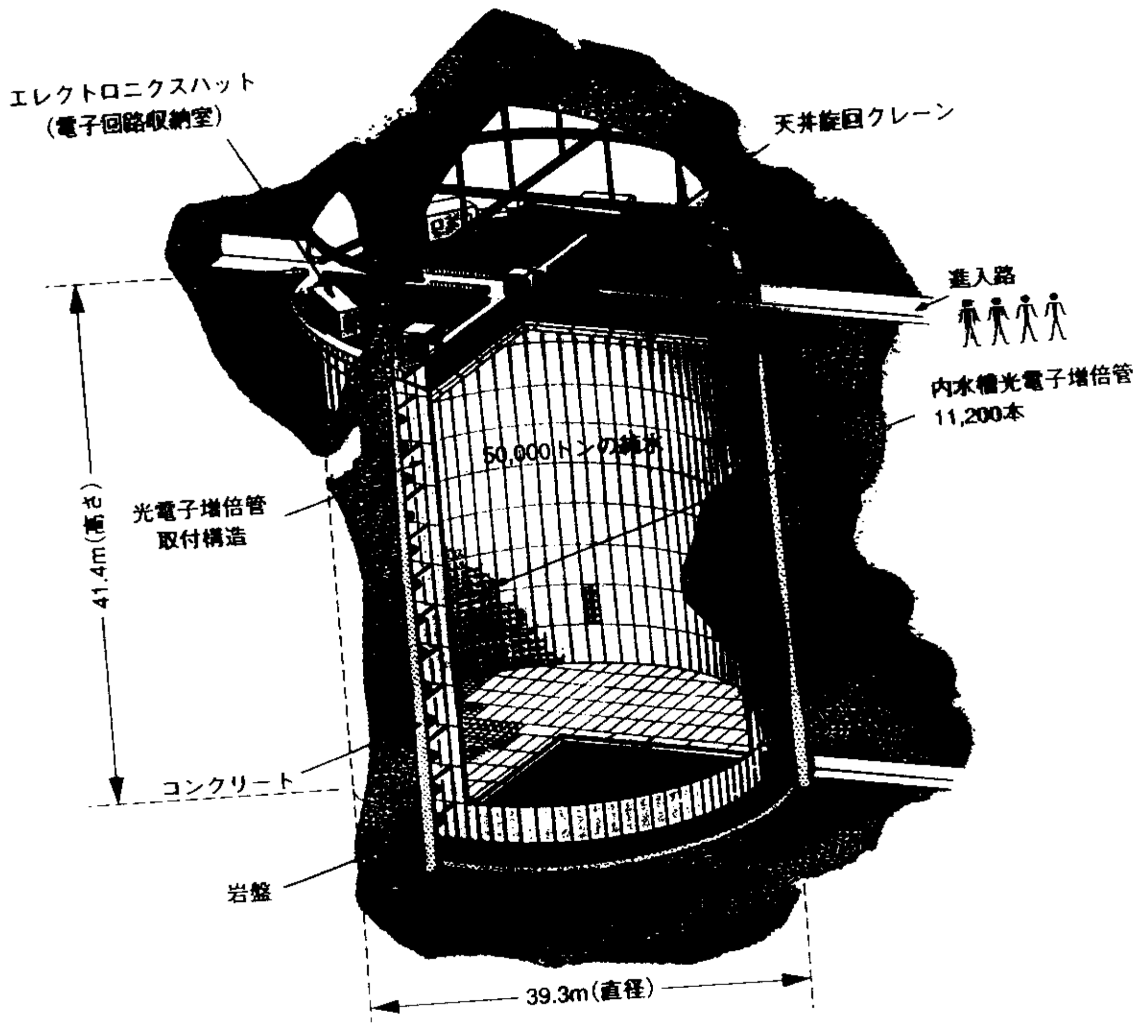
上部光電子増倍管取付後
上架中の上部架構
平成7年7月

大型水チェレンコフ宇宙素粒子観測装置 (スーパーカミオカンデ)

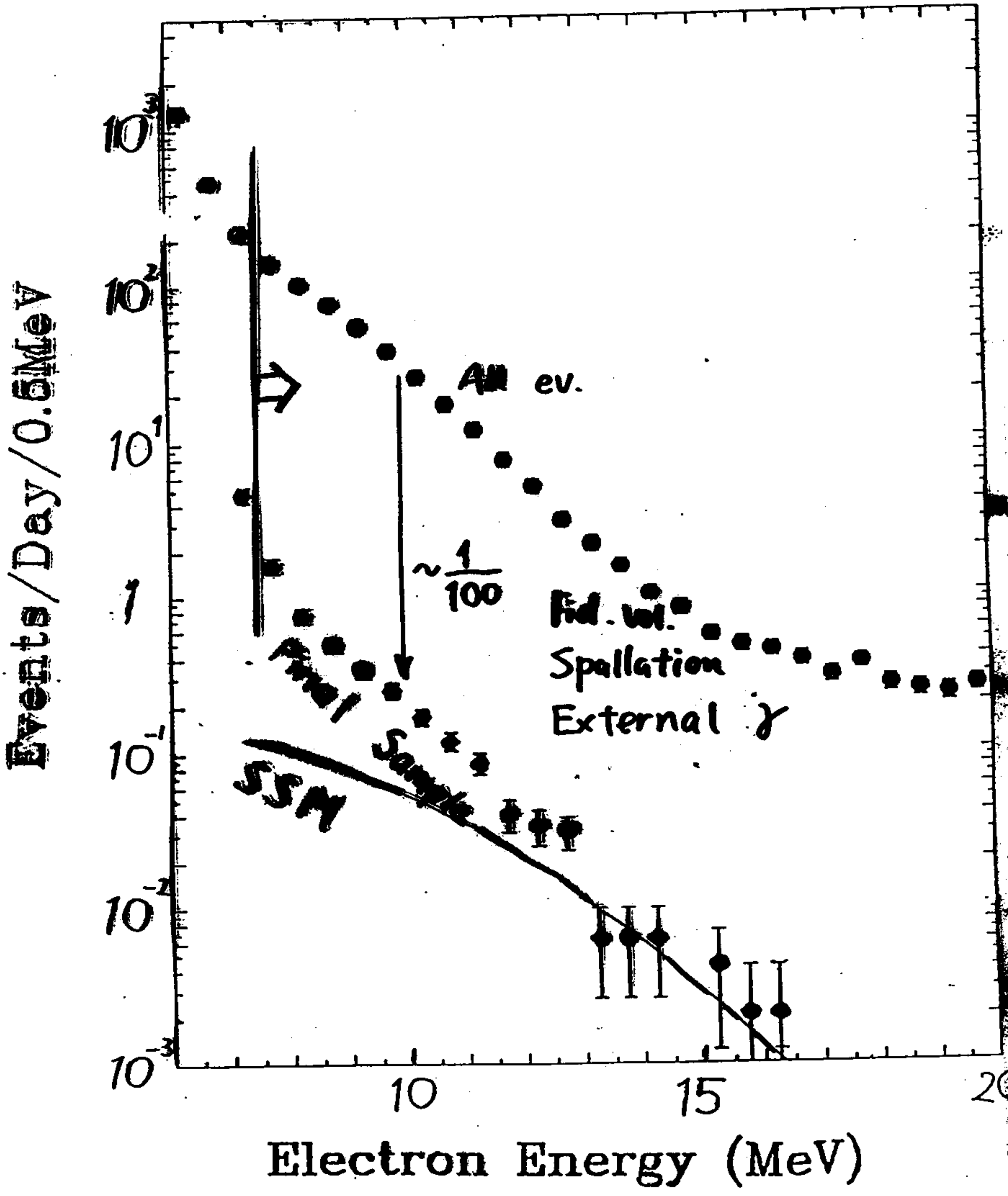
装置

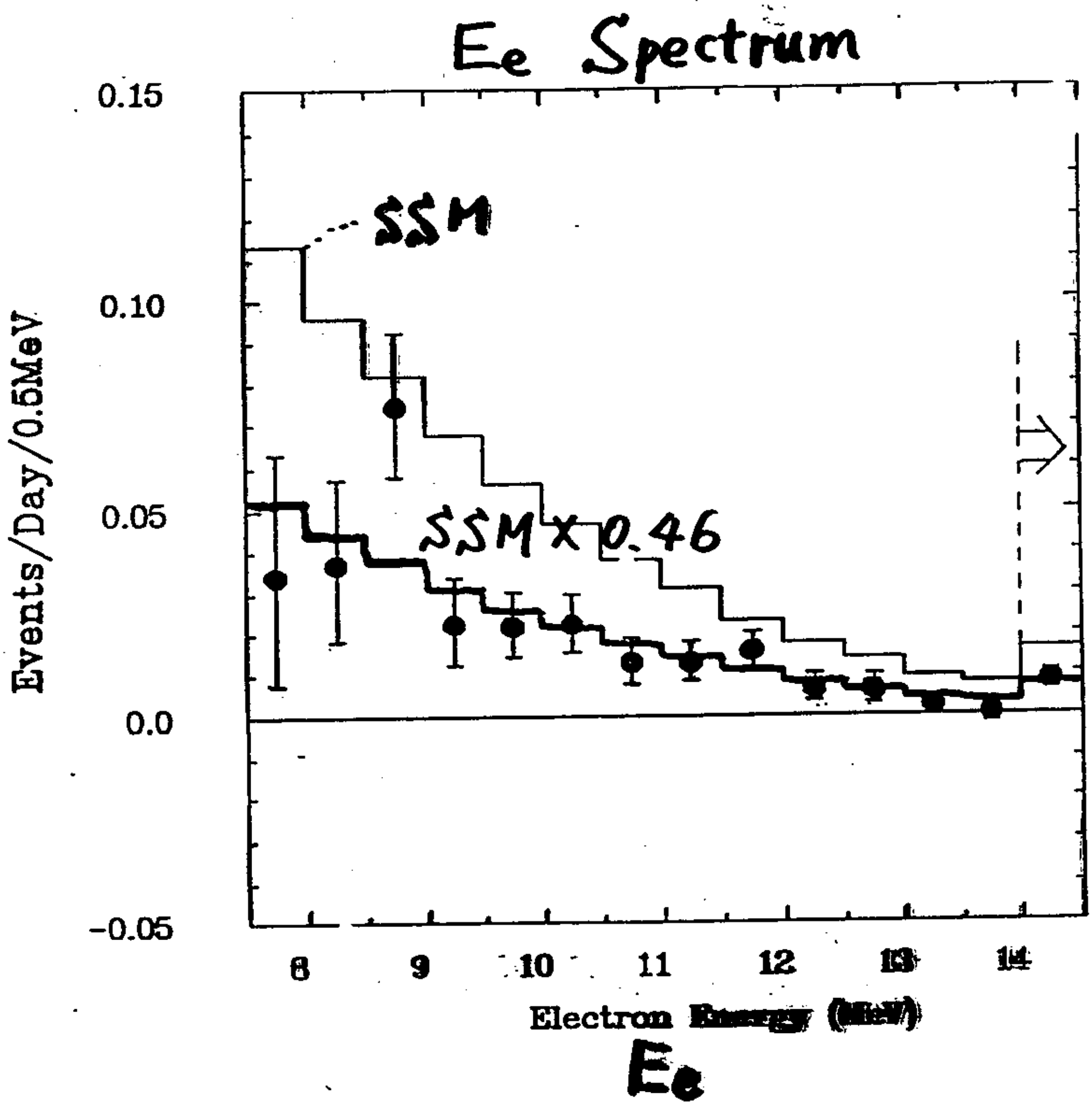
1）大きさ	41.4m（高さ）×39.3m（直径）の円筒形
2）重量	純水50,000トン
3）光センサー	光電子増倍管（世界最大の直径50cm）11,200本
4）エネルギー精度	2.5%（1GeVに対して）～16%（10MeVに対して）
5）エネルギー下限	5MeV
6）設定場所	岐阜県神岡町（神岡鉱業（株）茂住鉱山　地下1,000m）
7）建設費	6年計画（平成3年度～8年度）で約104億円 （東京大学宇宙線研究所試算）

大型水チェレンコフ宇宙素粒子観測装置



Data Reduction





1. Evidence for $\nu_\odot$

♠ Directional Correlation.

♠ Energy Information.

⇒ The Sun is shining by Nuclear Fusion.

2. **Data/"SSM" = 0.46 ±0.05(stat) ±0.06(syst).**

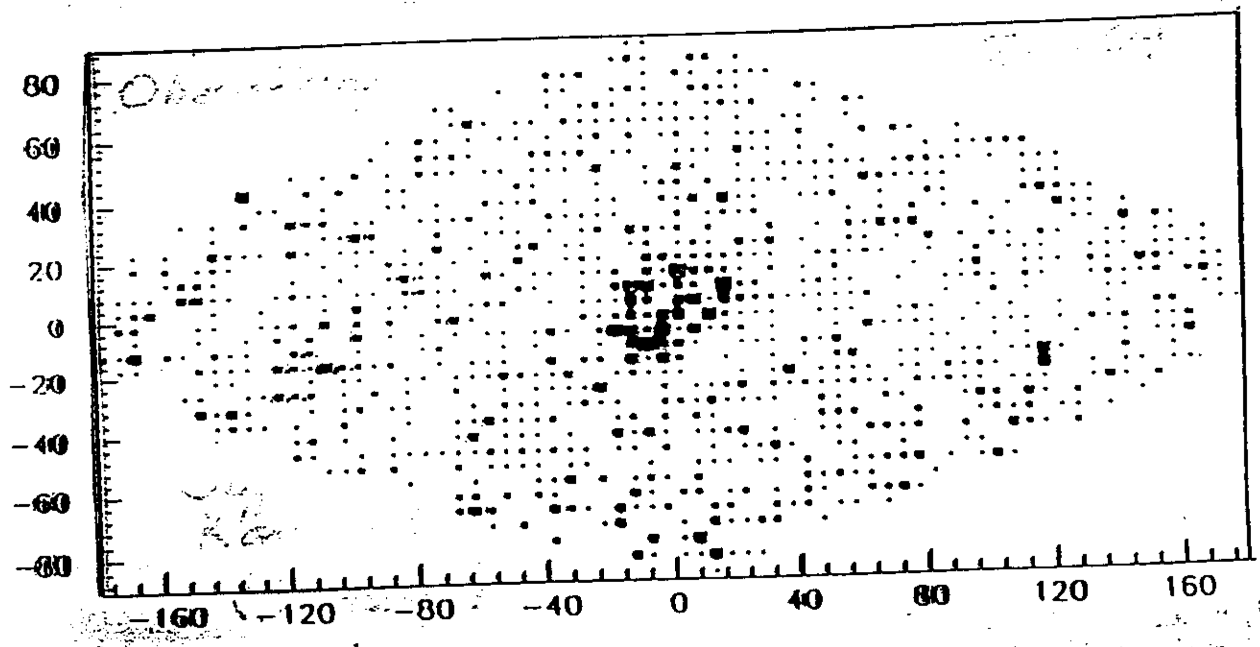
($E_e > 7.5$MeV)

⇒ Confirmation of the OLD $\nu_\odot$ Problem.

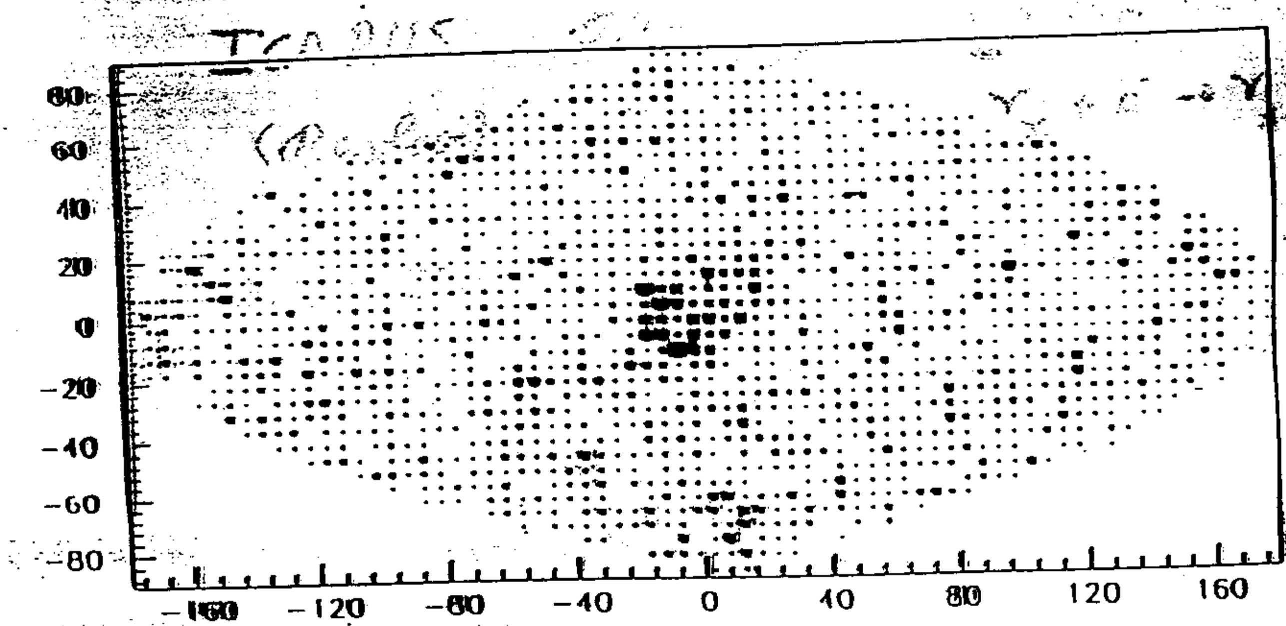
T. Kajita

Neutrino Heliograph

Typical



$E_e \geq 9.5$ MeV



$E_e \geq 8.5$ MeV

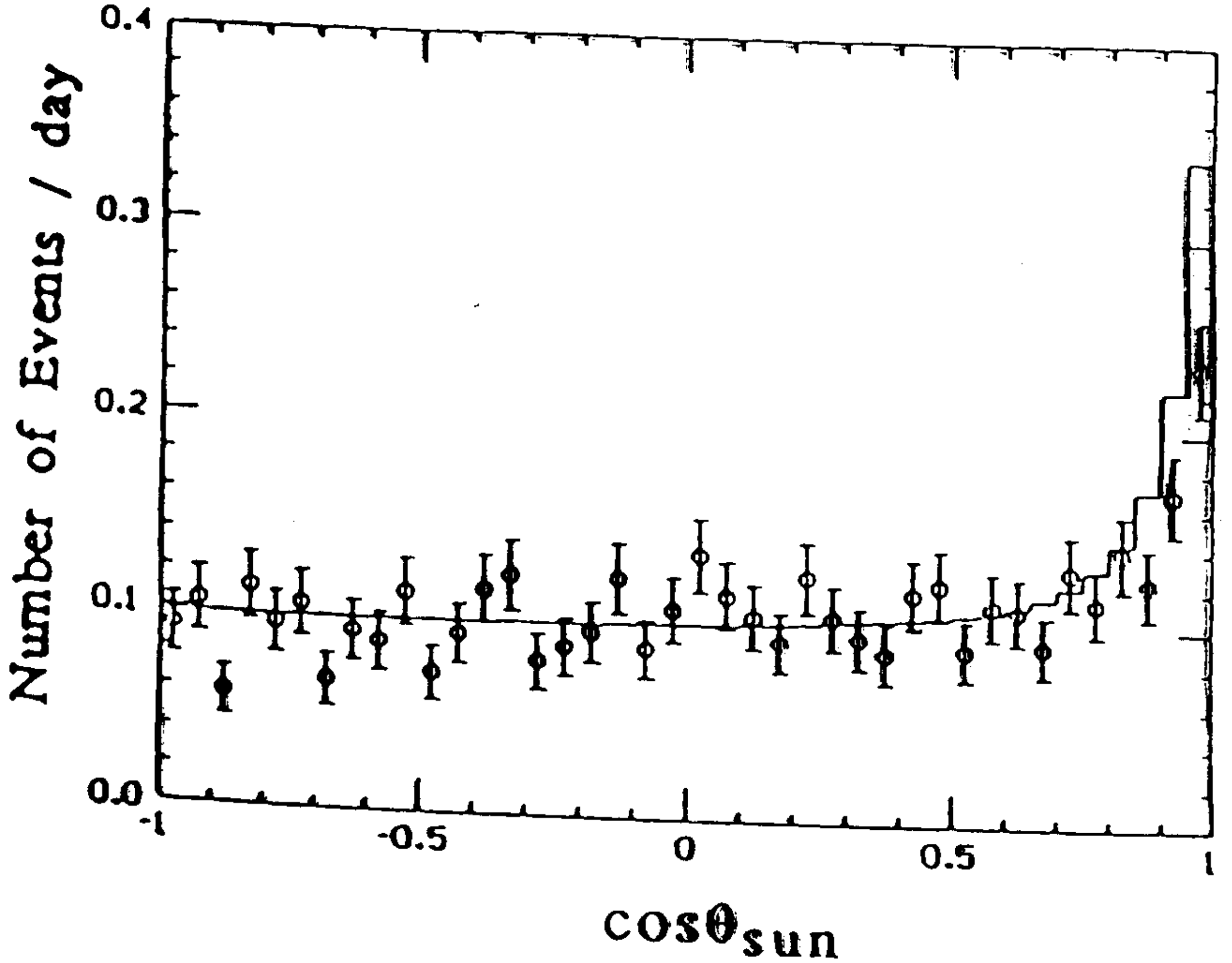
Kamiokande

Sun has been seen in neutrinos!

Direction of Final Events in Celestial Coordinates

Final result:

$$\phi^{8B} = (2.9 \pm 0.2 \pm 0.3)\, 10^{6}\ (\mathrm{cm}^{-2}\mathrm{s}^{-1})$$
$$= (0.51 \pm .04 \pm .06)\, \phi^{BP}_{SSM}$$



Kamiokande $\nu - e$

events after many cuts:

- Fiducial
- Spallation
- $E_e > 7.5$ MeV/c

2.1 *Calculated versus Observed Absolute Rate*

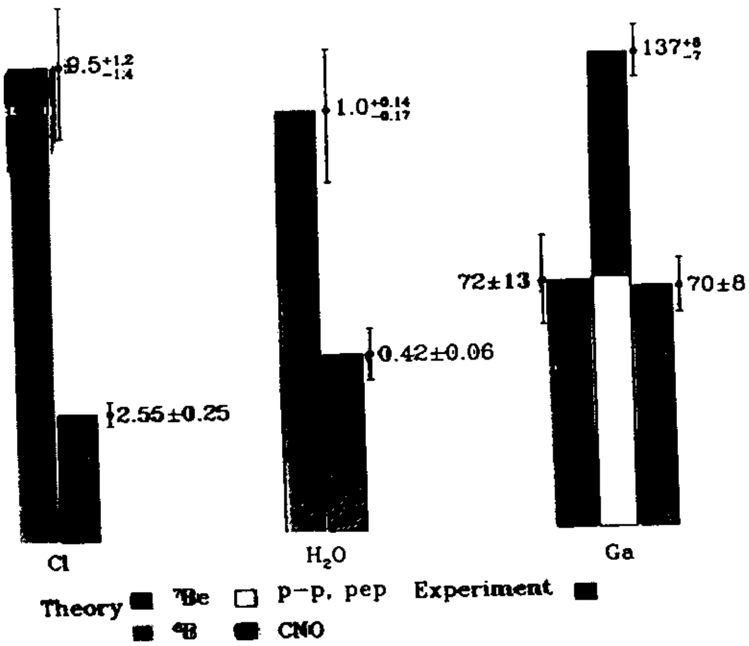


Figure 1: Comparison of measured rates and standard-model predictions for four solar neutrino experiments.

The first solar neutrino experiment to be performed was the chlorine radiochemical experiment, which detects electron-type neutrinos that are more energetic than 0.81 MeV. After more than 25 years of the operation of this experiment, the measured event rate is 2.55 ± 0.25 SNU, which is a factor ~ 3.6 less than is predicted by the most detailed theoretical calculations, $9.5^{+1.2}_{-1.4}$ SNU[17,18]. A SNU is a convenient unit to describe the measured rates of solar neutrino experiments: 10^{-36} interactions per target atom per second. Most of the predicted rate in the chlorine experiment is from the rare, high-energy ^{8}B neutrinos, although the ^{7}Be neutrinos are also expected to contribute significantly. According to standard model calculations, the *pep* neutrinos and the CNO neutrinos (for simplicity not discussed here) are expected to contribute less than 1 SNU to the total event rate.

Bahcall

TABLES

TABLE I. The standard solar model predictions of Bahcall and Pinsonneault (BP SSM) [7] and the results of the solar neutrino experiments.

	BP SSM	Experiments
Homestake	$9.3^{+1.2}_{-1.4}$ SNU	$2.55 \pm 0.14 \pm 0.14$ SNU (0.273 ± 0.021 BP SSM)
Kamiokande		$2.80 \pm 0.19 \pm 0.33$ [a] (0.423 ± 0.058 BP SSM)
Super-Kamiokande	$6.62^{+0.93}_{-1.12}$ [a]	$2.51^{+0.14}_{-0.13} \pm 0.18$ [a] (0.379 ± 0.034 BP SSM)
Combined		2.586 ± 0.195 [a] (0.391 ± 0.029 BP SSM)
SAGE		$69 \pm 10^{+5}_{-7}$ SNU (0.504 ± 0.089 BP SSM)
GALLEX	137^{+8}_{-7} SNU	$69.7 \pm 6.7^{+3.9}_{-4.5}$ SNU (0.509 ± 0.059 BP SSM)
Combined		69.5 ± 6.7 SNU (0.507 ± 0.049 BP SSM)

[a]In units of 10^6 cm^{-2}sec^{-1}.

TABLE II. The best fit parameters, the χ^2 minimum, and confidence levels of GOF for the combined MSW fits.

	Small Angle	Large Angle
$\sin^2 2\theta$	8.2×10^{-3}	0.63
Δm^2 (eV^2)	5.1×10^{-6}	1.6×10^{-5}
χ^2 (7 d.f.)	5.9	6.3
P (%)	45	49

TABLE III. The best fit parameters, χ^2 minimum, and GOF for the combined MSW fits for oscillations to sterile neutrinos.

	Small Angle	Large Angle
$\sin^2 2\theta$	1.0×10^{-2}	0.72
Δm^2 (eV^2)	4.0×10^{-6}	8.9×10^{-6}
χ^2 (7 d.f.)	6.7	13.7
P (%)	54	94

Can Solar Neutrino Results
be accounted for by
- Uncertainties in Solar Modeling
- " " Nuclear Physics Input?

- A change in T_c would yield
$$R_{Kam} < R_{Cl} < R_{Ga}$$
but observe: $R_{Cl} < R_{Kam} < R_{Ga}$.
Simple red. of T_c not enough.
(detailed quant. analysis : {Bludman, Hata, PGL, K. Shi, Schramm, Castellani, Fiorentini...})

- Suppose allow that true ^8B flux seen by Kam. (i.e. incl. possible σ_{Nucl} effects) then can show that ^{37}Cl CR should be <u>at least 4 SNUS</u>
but observed : 2.3 ± 0.2 SNUS.

<u>CONCLUSION</u>: If take all data at face value, have to blame ν properties for the solar ν "problem".

In any case ν_e Beam with high flux & largest L/E is available!

Once ^7Be is made:

$$\phi_\nu(^7Be) \sim \frac{R(^7Be + e \rightarrow \nu\, Li)}{R(^7Be + e \rightarrow \nu Li) + R(Be + p \rightarrow \gamma\, ^8B)}$$

and

$$\phi_\nu(^8B) \sim R(Be + p \rightarrow \gamma\, ^8B).$$

- Now $\phi_\nu(^8B)$ can be reduced by reducing $R(Bep)$ by a factor 2.

- But to reduce $\phi_\nu(^7Be)$ $R(Bep)$ has to be <u>increased</u> by <u>2 orders of magnitude</u>

[Since that is the relative rate].

and cannot change $^7Be + e \longrightarrow \nu\, Li$ Rate!

Can Solar Neutrino data be reconciled without ν-oscillations?
(Or how many solar nu experiments must be wrong?)
(Or what is the ^{7}Be problem?)

Make the following assumptions

(i) Sun powered by pp cycle (w. some CNO)

(ii) Steady state sun i.e.
L_γ (10^4 yrs from now) $\approx L_\gamma$ (now)
→ related to ϕ_ν (now)

(iii) $m_{\nu_i} = 0$

(iv) β-decay spectra standard shape

From $\mathcal{L}_\gamma$, R_{Cl}, R_{Ga}, R_K can show:

$f_{Be} = \phi_{Be} / \phi_{Be}^{SSM}$ is negative.

(Even with one expt. removed).

Consider ν producing reactions:

(1) $pp \to d\, e\, \nu_e$ ($E_\nu < 0.4$ MeV)

($pep \to d\, \nu_e$) $E_\nu \sim 1$ MeV

(2) $pd \to {}^3He + \gamma$

(2b) ${}^3He + {}^3He \to {}^4He + 2p$

(2a) ${}^3He + {}^4He \to {}^7Be +$ [illegible]

(3a) ${}^7Be + e^- \to \nu_e + {}^7Li$, $E_\nu =$ [illegible]

(3b) ${}^7Be + p \to \gamma + {}^8B$

(4) ${}^8B \to 2\alpha + e + \nu_e$, $E_\nu < 14$ MeV

3 ways to go from $4p \to {}^4He$

(2b) $4p \to {}^4He + 2e + 2\nu^{pp}$

(3a) $4p \to {}^4He + 2e + \nu^{pp} + \nu^{Be}$

(4) $4p \to {}^4He + 2e + \nu^{pp} + \nu^{B}$

$$Q = 27.75 \text{ MeV}.$$

$$\begin{cases} E_1 = Q - 2\langle E^{pp}\rangle \\ E_2 = Q - \langle E^{pp}\rangle - \langle E^{Be}\rangle \\ E_3 = Q - \langle E^{pp}\rangle - \langle E^{B}\rangle \end{cases}$$

→ into photons.

$$\frac{L_\odot}{4\pi d^2} = K = 8.54 \cdot 10^{+11} \text{ MeV cm}^{-2} \text{s}^{-1}$$

Solar Constant

$$= \sum_i \left\{ \frac{Q}{2} - \langle E_i \rangle \right\} \phi_i$$

ν fluxes

Define $f_i = \phi_i / \phi^{BP}_{SSM}$

e.g. $\phi^{pp}_{SSM} = 6 \cdot 10^{10} \text{ cm}^{-2} \text{s}^{-1}$

$\phi^{Be}_{SSM} = 4.9 \cdot 10^{9}$ "

$\phi^{B}_{SSM} = 5.7 \cdot 10^{6}$ "

Then Luminosity (k) constraint is:

$$1 = 0.94 f_p + 0.075 f_{Be} + 5 \cdot 10^{-5} f_B$$

Similarly

$$R_{Cl} = 6.2 f_B + 1.2 f_{Be} + \ldots$$ in SNUS

$$R_{Ga} = 71 f_p + 36 f_{Be} + 14 f_B$$ "

$$R_{Ka} / R_{SSM} = f_B$$

Solve for f_{Be}

- $H_2O + {}^{37}Cl$: $f_{Be} = -0.73 \pm 0.4 - (pep + CNO)$
  (known since 1990)

- $\mathcal{L} + {}^{76}Ga + H_2O$: $f_{Be} = -0.43 \pm 0.2 - (\cdots)$

- $\mathcal{L} + {}^{76}Ga + {}^{37}Cl$: $f_{Be} = -0.38 \pm 0.3 - (\cdots)$

But $f_{Be} \geq 0$.

Furthermore $f_{Be} \neq 0$, otherwise no ${}^{8}B$.

This is the

${}^{7}Be$ Problem!

CONCLUSION:

EITHER (AT LEAST) TWO SOLAR ν EXPTS ARE WRONG

OR ν's OSCILLATE

OR DO SOMETHING FUNNY.

almost UNANIMOUS: Berezinsky, Parke, Castellini et al., Langacker et al., Schramm et al, KVL Sarma, Bahcall, Rosen, Fogli, ...

HELIOSEISMOLOGICAL DATA

⊕ ANALYSIS (Chitre) $\Longrightarrow$

$$T_c / T_c^{SSM} = 1 \pm 0.025$$

Q: How to confirm deficit of ^7Be ν's ?

A: With Borexino!!

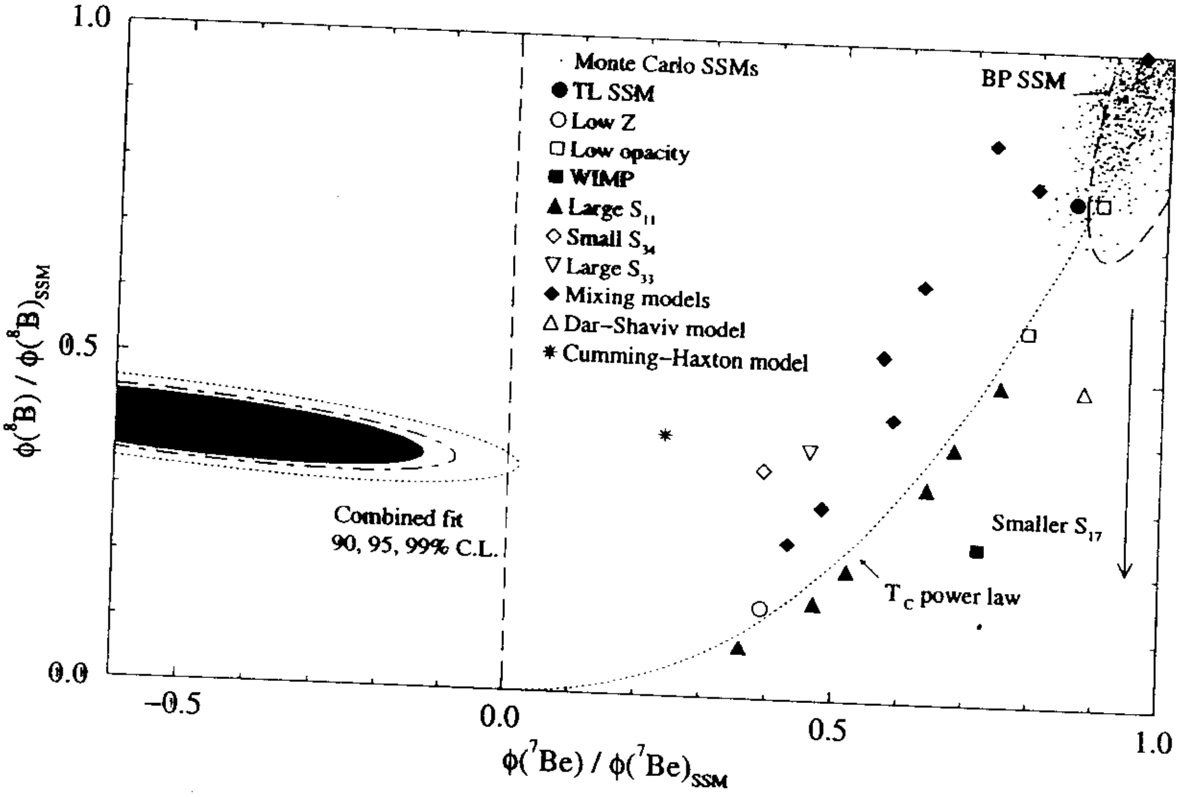


FIG. 2. The constraints from the combined Cl, Ga, and Čerenkov experiments at 90, 95, and 99% C.L. Also shown are the Bahcall-Pinsonneault SSM region at 90% C.L. [7], the core temperature power law and standard and nonstandard solar models including the recent ^{3}He diffusion model by Cunning and Haxton [34] (see Ref. [16] for references for the other models). A smaller S_{17} cross section moves the solar model predictions to a smaller ^{8}B flux as indicted by the arrow.

the BP No Diffusion model and the assumed mixing of the solar core (constant value of μ). We also show in Figure 3 the relatively tiny discrepancies found for the new standard model, OPAL EOS.

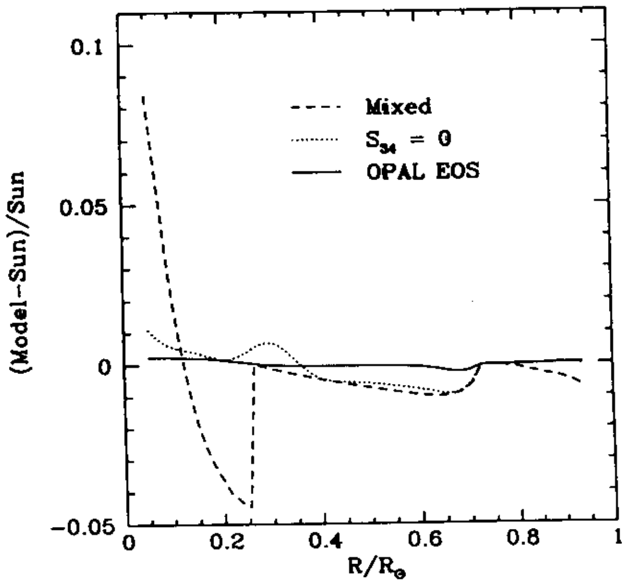


Figure 3: Non-standard solar models compared with helioseismology. This figure is similar to Figure 2 except that the vertical scale is expanded. The dashed curve represents the sound speeds computed for the mixed solar model of Cumming and Haxton [16] with ^{3}He mixing. The dotted line represents the sound speed for a solar model computed with the rate of the $^3He(\alpha,\gamma)^7Be$ reaction set equal to zero. For comparison, we also include the results for the new standard model labeled OPAL EOS in Figure 2.

More generally, helioseismology rules out all solar models with large amounts of interior mixing, unless finely-tuned compensating changes in the temperature are made. The mean molecular weight in the standard solar model with diffusion varies monotonically from 0.86 in the deep interior to 0.62 at the outer region of nuclear fusion ($R = 0.25 R\odot$) to 0.60 near the solar surface. Any mixing model will cause μ to be constant and equal to the average value in the mixed region. At the very least, the region in which nuclear fusion occurs must be mixed in order to affect significantly the calculated neutrino fluxes [35,36,37,38,39]. Unless almost precisely canceling temperature changes are assumed, solar models in which the nuclear burning region is mixed

TABLES

TABLE I. Solar neutrino data used in the analysis. The experimental results are given in SNU for all of the experiments except Kamiokande, for which the result is expressed the measured ^{8}B flux above 5 MeV in units of $cm^{-2}s^{-1}$ at the earth. The ratios of the measured values to the corresponding predictions in the standard solar model of ref. [5] are also given. The result cited for the Kamiokande experiment assumes that the shape of the ^{8}B neutrino spectrum is not affected by physics beyond the standard electroweak model.

E_{th}	Experiment	Result (1σ)	Exp. Result/Th. Calculation		Reference	# events
.8 MeV	HOMESTAKE	2.55 ± 0.17(stat) $\pm$ 0.18(syst)	0.27 ± 0.03	25 yr	[1]	1000
.2 MeV	GALLEX	71 [redacted]$\pm$ 8.5(stat) $\pm^{+4.4}_{-5.4}$ (syst)	0.56 ± 0.07	5 yr	[2]	150
.2 MeV	SAGE	69 ± 11(stat)$^{+5}_{-7}$(syst)	0.50 ± 0.09	5 yr	[3]	150
7.5 MeV	KAMIOKANDE	[$2.89\pm^{0.22}_{0.21}$ (stat) ±0.35 (syst)] $\times10^6$	0.44 ± 0.06	7 yr	[4]	500

Running Time

Bahcall - Krastev

Dec. 1995

Solutions based on Neutrino Properties

- MSW — $\delta m^2 \sim 10^{-5}\,eV^2$ θ sm, & l.
  $\sim 10^{-6}\,eV^2$ θ large

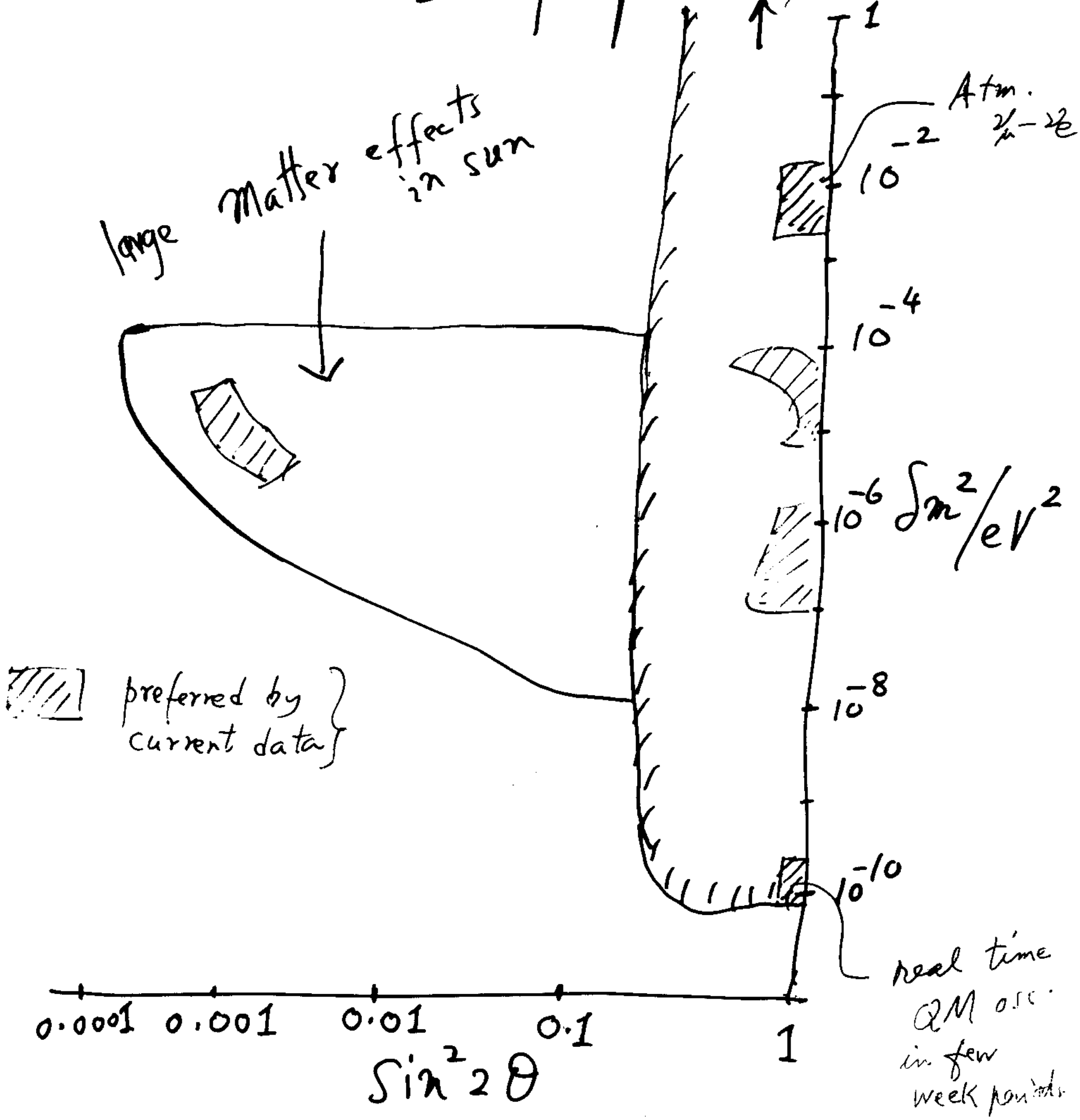
- Long Wavelength — $\delta m^2 \sim 10^{-10}\,eV^2$
  $\sin^2 2\theta \sim 0.8 - 1$

- Decay w. mixing — $\delta m^2 \sim 10^{-2}\,eV^2$
  $\sin^2 2\theta \sim 0.8 - 1$

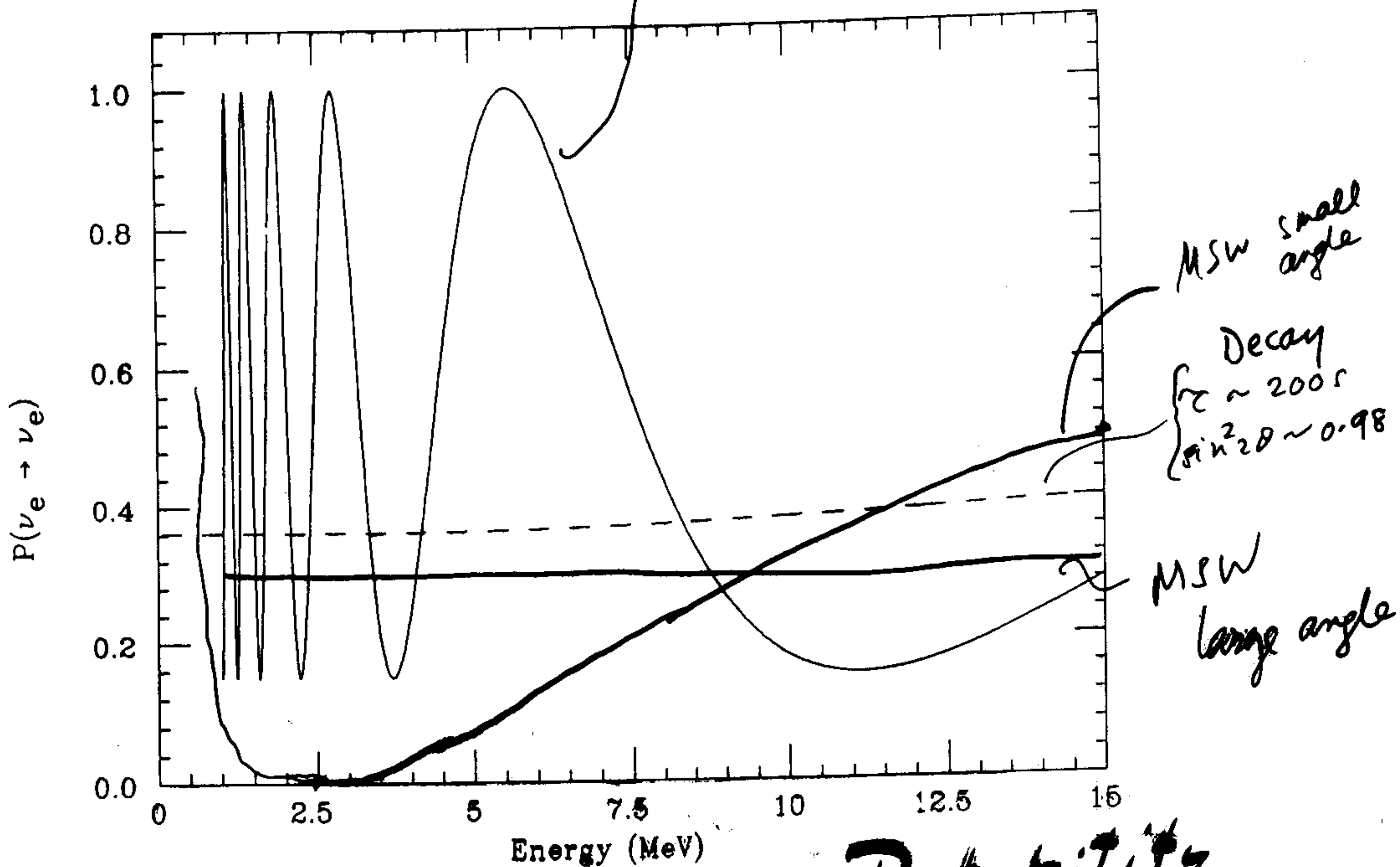
- "gravitational" or violation of equivalence principle — $\sin^2 2\theta \sim 1$

- For simplicity assume
  - 2 flavors
  - no sterile
  - B-P fluxes
  - ignore flavor violation

Sensitivity of Solar Neutrinos to ν properties



After Gallex



ν_e Survival Probability

Large Angle Long Wavelength

- $L_{osc} \sim d_{\odot} \Rightarrow \delta m^2 \sim 10^{-10} eV^2$
- Large Mixing $\Rightarrow \sin^2 2\theta \sim 0.8 - 1$
- Matter Effects negligible both in sun & in earth.

Signatures:

- Strong Spectrum Distortion
- Real Time Oscillations w. periods of days to months!!
  Esp. strong in ^{7}Be Line

Visible in Borexino

ν- Osc. in Matter

~~Forward~~ Coherent scattering

ν_e: $\delta H = \sqrt{2}\, G_F \left\{ \frac{1}{2} + 2x_w^2 \right\} n_e + \sqrt{2}\, G_F \left\{ \begin{array}{l} (\frac{1}{2} - 2x_w^2) n_p \\ - \frac{1}{2} n_{pn} \end{array} \right\}$

$= \sqrt{2} G_F \frac{1}{2} \cdot ((\nu_1 + s\nu_2)((\bar\nu_1 - \bar s\nu_2)$

$(c^2 \bar\nu_1 \nu_1 + s^2 \bar\nu_2 \nu_2$ $n_e = \#\, el/vol.$ etc

$+ sc\, \bar\nu_2 \nu_1 + h.c.)$.

$\bar\nu_e$: $\delta H = -\delta H_{\nu_e}$

ν_μ: $\delta H = \sqrt{2}\, G_F \left\{ -\frac{1}{2} + 2x_w^2 \right\} n_e + \sqrt{2}\, G_F \left\{ \begin{array}{l} (\frac{1}{2} - 2x_w^2) n_p \\ - \frac{1}{2} n_n \end{array} \right\}$

$= -\sqrt{2} G \frac{1}{2} \cdot (-s\nu_1 + c\nu_2)(-s\bar\nu_1 + c\bar\nu_2)$

$= (s^2 \bar\nu_1 \nu_1 + c^2 \bar\nu_2 \nu_2 - sc\, \bar\nu_2 \nu_1 \cdots)$

$\bar\nu_\mu$: $\delta H = -\delta H_{\nu_\mu}$.

2 - flavor Case

$\nu_e = c\nu_1 + s\nu_2$ | $\nu_1 = c\nu_e - s\nu_\mu$

$\nu_\mu = -s\nu_1 + c\nu_2$ | $\nu_2 = s\nu_e + c\nu_\mu$

. no matter

$i\dot\psi_j = $ ~~$m_j^2/2E\, \psi_j$~~ $=$ ~~(ignore common)~~ ϕ

$= (E - m_j^2/2E)\psi_j$

$c \cdot \underbrace{[c\psi_1 + s\psi_2]}_{\nu_e}$

In matter

$i\dot\psi_1 = (E - m_1^2/2E)\psi_1 + \sqrt{2} G N_e \left\{ \begin{array}{c} c^2 \\ -s^2 \end{array} \psi_1 + sc\, \psi_2 \right\}$

$+ \cdots$

$i\dot\psi_2 = (E - m_2^2/2E)\psi_2 - \sqrt{2} G N_e \left\{ \begin{array}{c} c^2 \\ -s^2 \end{array} \psi_2 - sc\, \psi_1 \right\}$

$+ - - - -$

Re-diagonalize the Hamiltonian

- ν_e (Matter) $= \cos\theta_m\, \nu_1(m) + \sin\theta_m\, \nu_2(m)$

  ν_μ ( ) $= -\sin\theta_m\, \nu_1(m) + \cos\theta_m\, \nu_2(m)$.

- $$\tan 2\theta_m = \frac{\sin 2\theta}{\cos 2\theta - l_v/l_M}$$

- $$\delta m(m)^2 = \delta m^2 \left[1 - 2(l_v/l_m)\cos 2\theta + (l_v/l_m)^2\right]^{1/2}$$

$$l_v = 4\pi E/\delta m^2 \qquad l_m = \frac{2\pi}{\sqrt{2}\, G_F\, n_e}.$$

$$= 2.5\, E/\delta m^2 \qquad = 1.8 \cdot 10^7\, N_A/N_e$$

E (MeV) $\qquad N_e \sim N/cm^3$

δm^2 (eV^2) $\qquad N_A \sim$ Av.

$$l = l_v\left[1 - 2(l_v/l_M)\cos 2\theta + (l_v/l_m)^2\right]^{-1/2}$$

- $l_v << l_M$. matter effects negligible

  $\theta_m \sim \theta$, $\delta m(m)^2 \sim \delta m^2$.

- if $l_\nu >> l_M$

  $\theta(M) \longrightarrow 0$

  matter effects damp out all mixing & osc.

- $l_\nu \sim l_M$. matter effects v. important

ν effects <u>diff</u>. from $\bar{\nu}$

- visible matter effects

  $L \sim$ good fraction of l_M.

in earth $E(\text{MeV}) \gtrsim 10^5\ (\delta m^2/eV^2)$

- $\theta(M) \longrightarrow \pi/4$ (max)

  even if θ v.v small.

MSW. If ρ_e changing slowly.

$$P_{\nu_e \to \nu_e}(t) = \frac{1}{2} + \left(\frac{1}{2} - P_{jump}\right) \cos 2\theta_m \cos 2\theta_v$$

(ν_e produced at $\rho > \rho_{res}$).

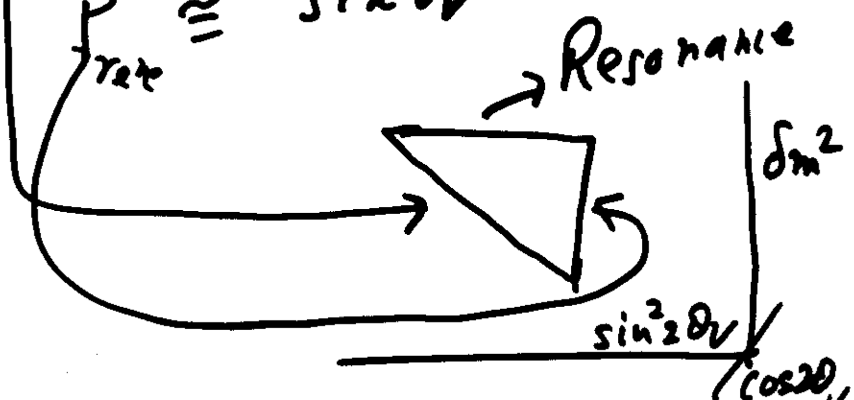
$$P_{jump} = \exp\left[-\{\ \}/E\right] \xrightarrow[\text{at res.}]{} 0$$

when $\rho >> \rho_{res}$:

$$P_{\nu_e \to \nu_e} \cong \sin^2\theta_v + P_{jump} \cos 2\theta_v$$

so if $\theta_v << 1 \Rightarrow$ $P_{\nu_e \nu_e} \cong P_{jump}$

θ_v large $P_{\nu_e \nu_e} \cong \sin^2\theta_v$.



MSW Diagram

Matter Effects in Earth

ρ_e nearly constant.

If near resonance. i.e.

$$E/\delta m^2 \sim \frac{10 \text{ MeV}}{10^{-6} \text{ eV}^2}.$$

get significant amount of conversion, e.g. $\nu_\mu \longrightarrow \nu_e$.

Hence Regeneration

& hence Day Night Effect

In presence of matter

$$\delta H = \pm \frac{\sqrt{2} G_F}{m_N} \rho \left(Y_e - \frac{1}{2} Y_n \right)$$

($+ \to \nu$, $- \to \bar{\nu}$)

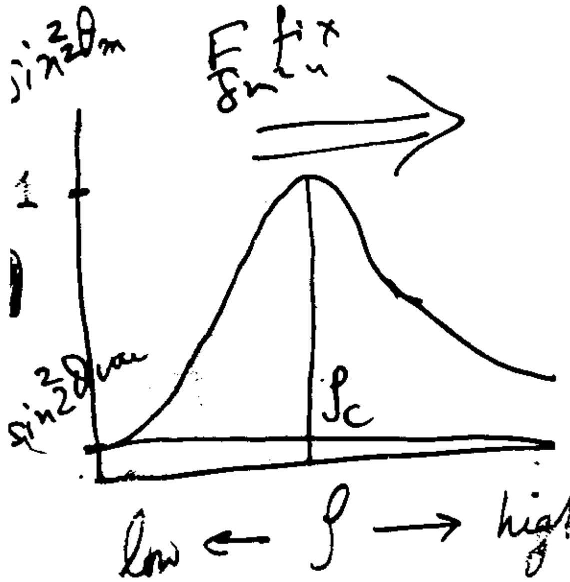
for ν_e.

$$\delta H = \pm \frac{\sqrt{2} G_F \rho}{m_N} \left(-\frac{1}{2} Y_n \right)$$

for ν_μ.

ρ = electron density
$Y_e = \# e / N$
$Y_n = \# n / N$

ν $m_2 > m_1$

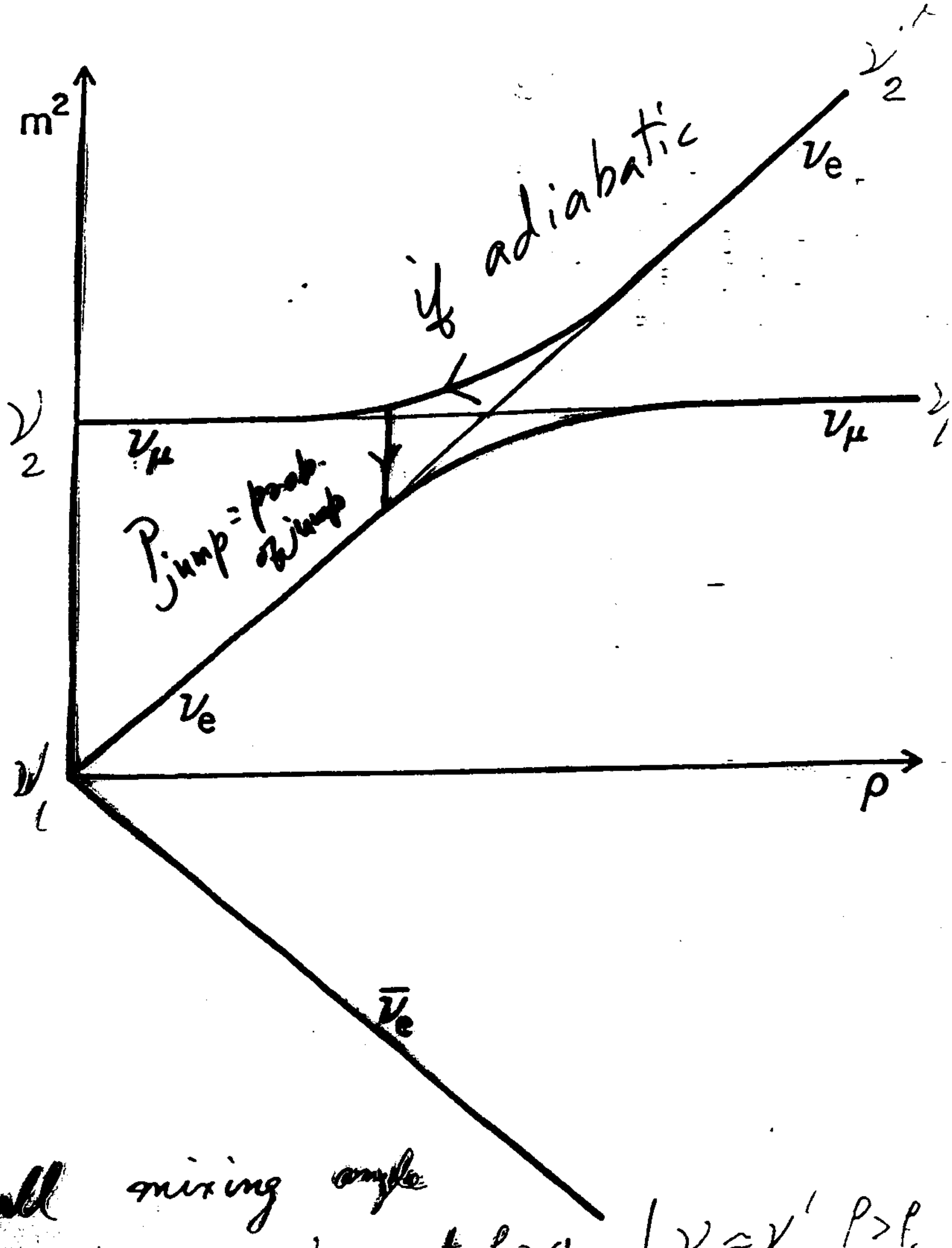


re-diagonalisation

$\theta_{e\mu}$ (vac) $\longrightarrow$ θ_m

$\left. \begin{matrix} m_1, m_2 \\ \delta m \end{matrix} \right\}$ $\longrightarrow$ M_1, M_2, δM

vac. matter.



Small mixing angle

then $\nu_e \approx \nu_1$ at $\rho = 0$

$\nu_\mu \approx \nu_2$ ″

$\nu_e \approx \nu_2'$ $\rho > \rho_c$

$\nu_\mu \approx \nu_1'$ $\rho > \rho_c$

Does $\delta m^2 \sim 10^{-10} eV^2$ & $\theta \sim 45°$ require fine tuning? Maybe Not. (C. W. Kim)

Example. (Akhmedov et al. 1992, Barbieri et al. 198?, Weinberg 1979).

Suppose Lepton # conserved until Planck scale. (no RH ν's).

Gravity induced terms:

$$g_{ij}^2 / m_{Pl} \quad \overline{\nu_{L_i}^c} \, \underline{\tau} \, \nu_{Lj} \cdot \bar{\phi} \, \underline{\tau} \, \phi$$

Neutrino Mass Matrix (let $g_{ij} \equiv g$) ~ O(1)

$$M_\nu \sim \frac{v^2}{m_{Pl}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

e.values $\quad m_1 = m_2 = 0 \quad m_3 = \frac{g v^2}{m_p} \sim 10^{-5} eV.$

Find $\quad P(\nu_e \to \nu_e, L) = 1 - \frac{8}{9} \sin^2 \frac{\delta m^2 L}{4E}$

$\Rightarrow \delta m^2 \sim 10^{-10} eV^2 \quad \sin^2 2\theta \sim 0.89.$

Also have to worry about renorm. of m_{ν_i} & θ_i from Planck scale to low energy. (Babu, Leung, Pantaleone 1993. Cheng, Gill, Hall (1993).

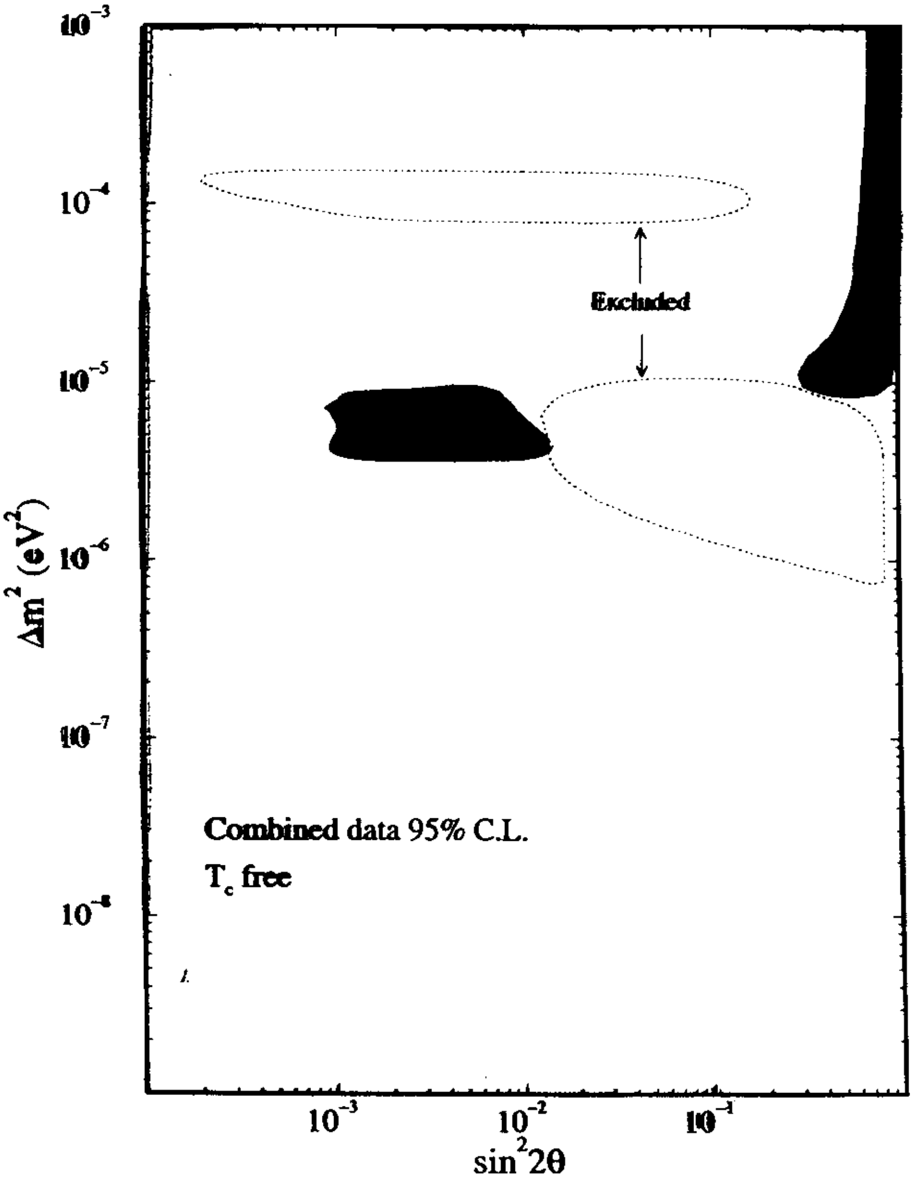


FIG. 16. The MSW parameter space allowed by the combined observations when the core temperature is used as a free parameter. The model independent exclusion regions by the Kamiokande spectrum and day-night data are also shown.

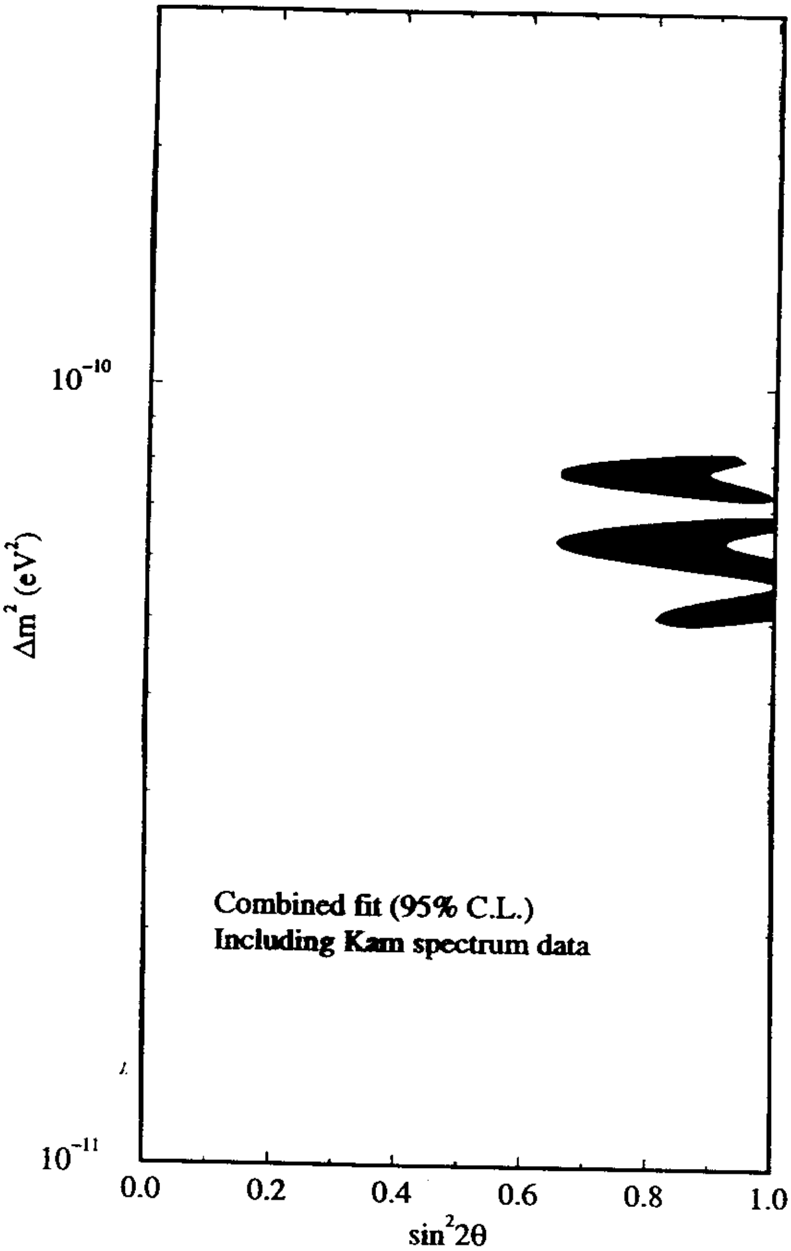
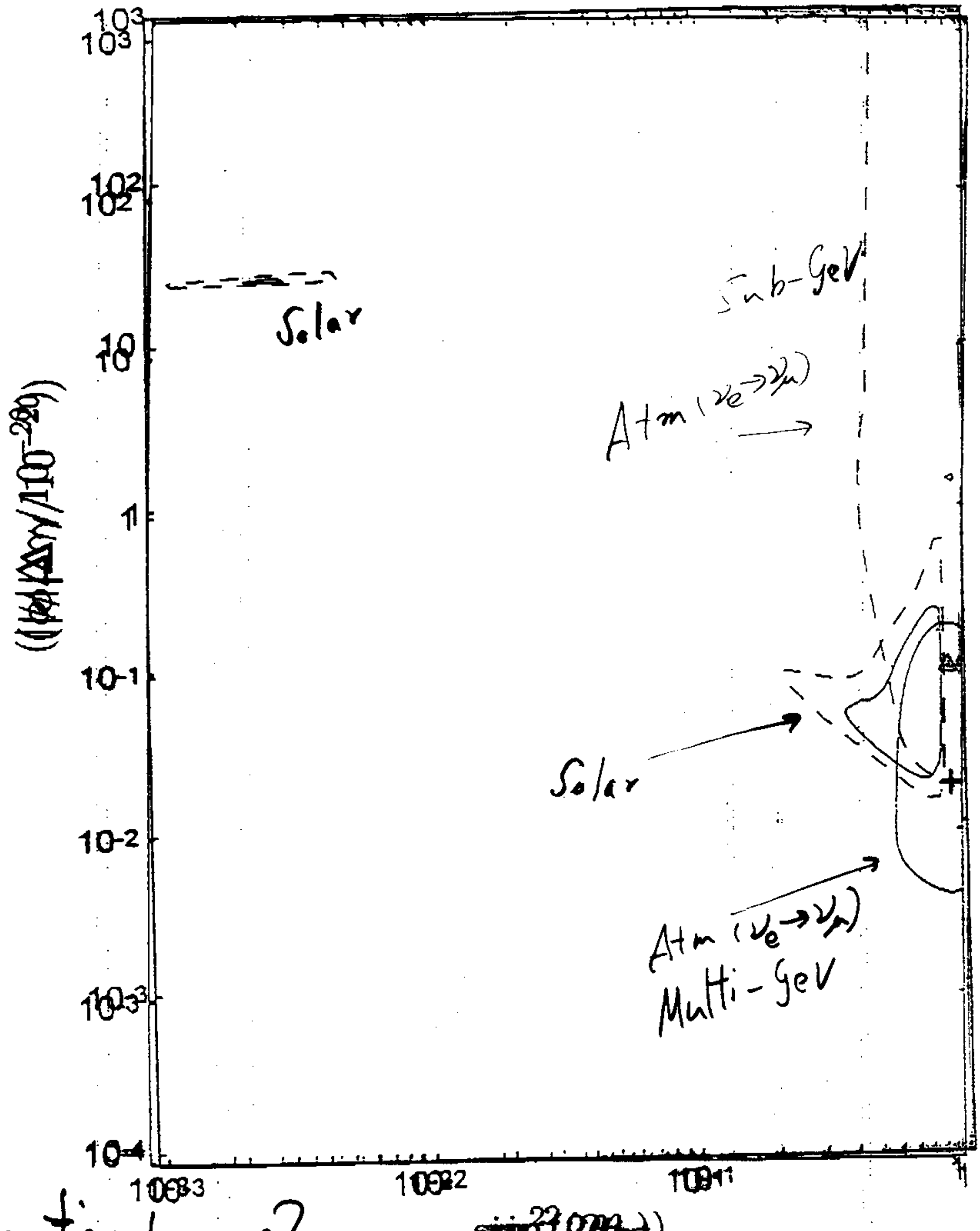


FIG. 20. The vacuum oscillation parameter space allowed by the combined observations including the Kamiokande spectrum data.

Future (Real & Virtual) Detector Characteristics

Status	Size (Fid.)	Radio ↓	Det.	E_{th}	Ev/yr	Reactions	Char. Features
Const. → ~~12/95~~ 6/96	1 KT	10^{-14}	SNO Č	5 MeV	10000	$\nu_e D \to e p p$	spectrum
					3000	$\nu_x D \to \nu_x p n$	NC
					1000	$\nu e \to \nu e$	
Const. → 4/96	22 KT		Super K Č	5 MeV	10000	$\nu e \to \nu e$	sp.
CTF → Tests; Full Det → '98	0.1 KT	10^{-15}	Borexino (LS)	0.25 MeV	15000	$\nu e \to \nu e$	^7Be Line
TPC Test	12 T		Hellaz	0.1 MeV	12000	$\nu e \to \nu e$	pp real time

Fig(4a)



- Interesting because same parameters explain Solar & atmosp. } Flavor Violating Gravity
- But grave theor. diff.] Halprin, Leung, Pantaleone '95

With high statistics, Real Time
Data from SNO, SuperK & Borexino:

- Presence of ν-osc can be established.
  - NC/CC
  - Spectrum Distortion

- Parameter Range can be determined.

MSW vs LWO
Real Time QM osc. over days/months

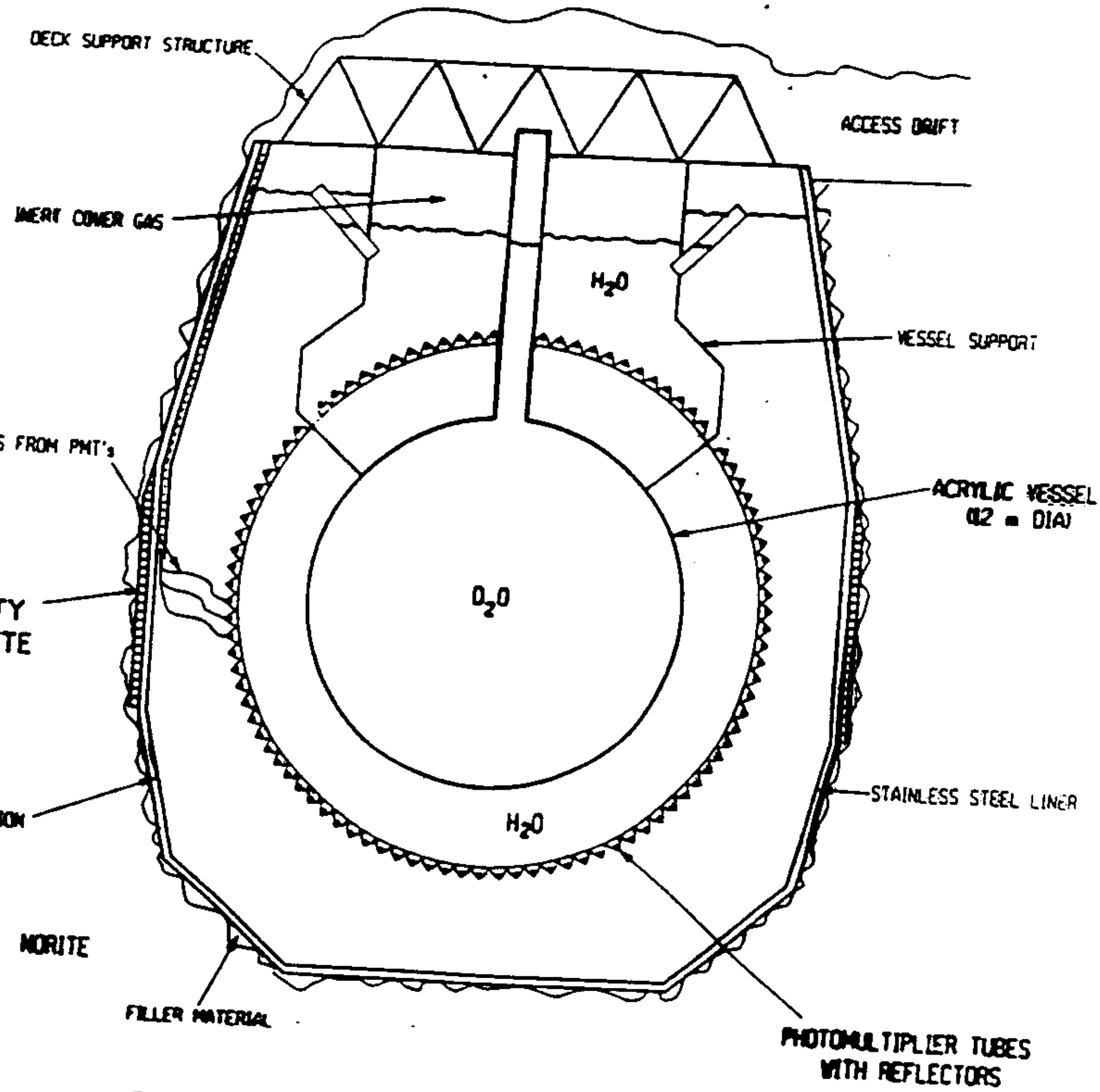
- precise amounts of suppression
- " distortion etc.

- lack or presence of day-night effect.

- Then can determine also the primary solar ν fluxes.

- The sun provides a free, high intensity ν_e flux — would be dumb not to use it!

SNO



CROSS SECTION OF NEUTRINO DETECTOR

Figure 1: Outline of the proposed neutrino detector. The detector would be located at a depth of 6800 feet in the Creighton mine near Sudbury.

Heavy water target - 1,000 tons
2070 meters underground
Creighton Mine, Sudbury, Ontario

Deuterium has unique properties –

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

$E_\nu = E_{e^-} + 1.442$ MeV ± Nuclear Effects

⇒ ~ Direct determination of energy spectrum of ν_e

if std model ⇒ ~ 10^4 events yr^{-1}

also, $\nu + d \rightarrow \nu + p + n$

threshold = 2.2 MeV

cross-section independent of neutrino flavor.

To detect, must capture neutron

NaCl $n + {}^{35}Cl \rightarrow 8.6$ MeV γ

^3He

⇒ $CC/NC|_{EXP} \,/\, CC/NC|_{Predicted} < 1$?

Data beginning late 1997

$\nu_e D \rightarrow ppe$ CC

$\nu_\alpha D \rightarrow np\nu_\alpha$ NC.

↳ To detect n. $MgCl_2$ or ^3He Bags.

Data Taking → July 96.

XMAS '95

Sequence

CC

⇒ ^8B flux

Spectrum > 7 MeV

· NC/CC

→ E_{th} > 5 MeV.

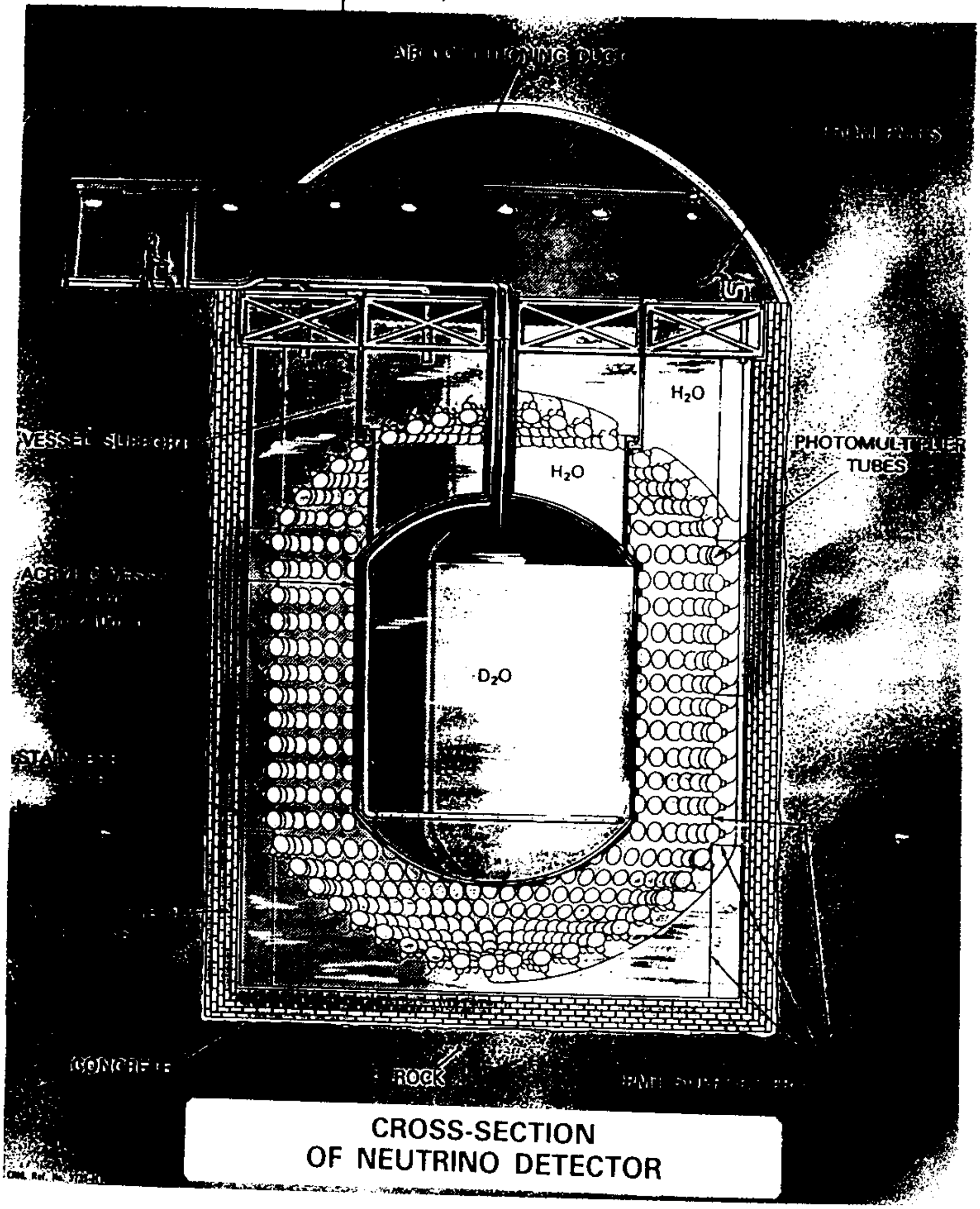
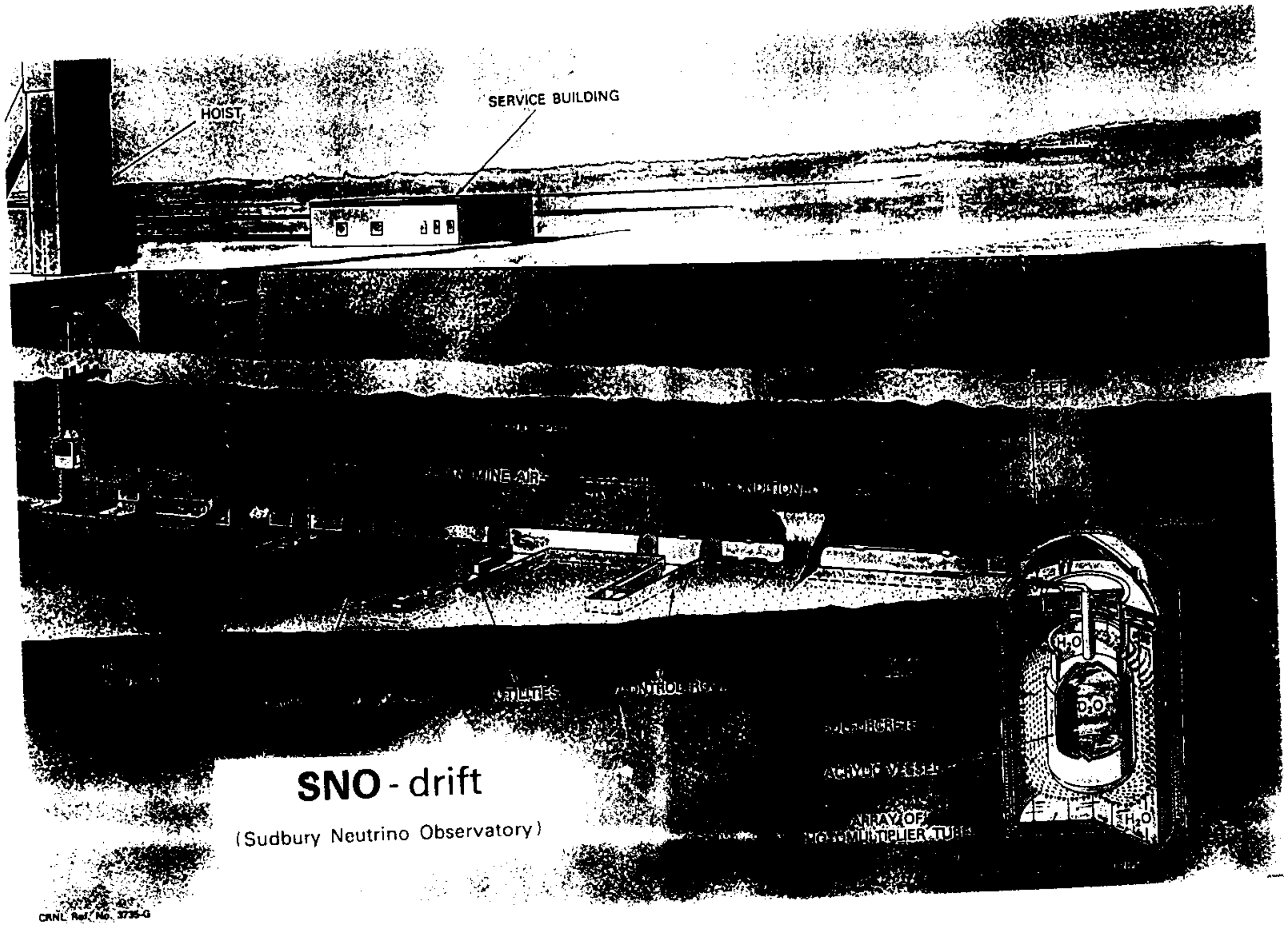


Figure1.1: Design of the Proposed Detector.
The diameter of the cylindrical rock cavity is 20 metres.

SNO



Artistic Conception of the Sudbury Neutrino Observatory at the Creighton Mine.

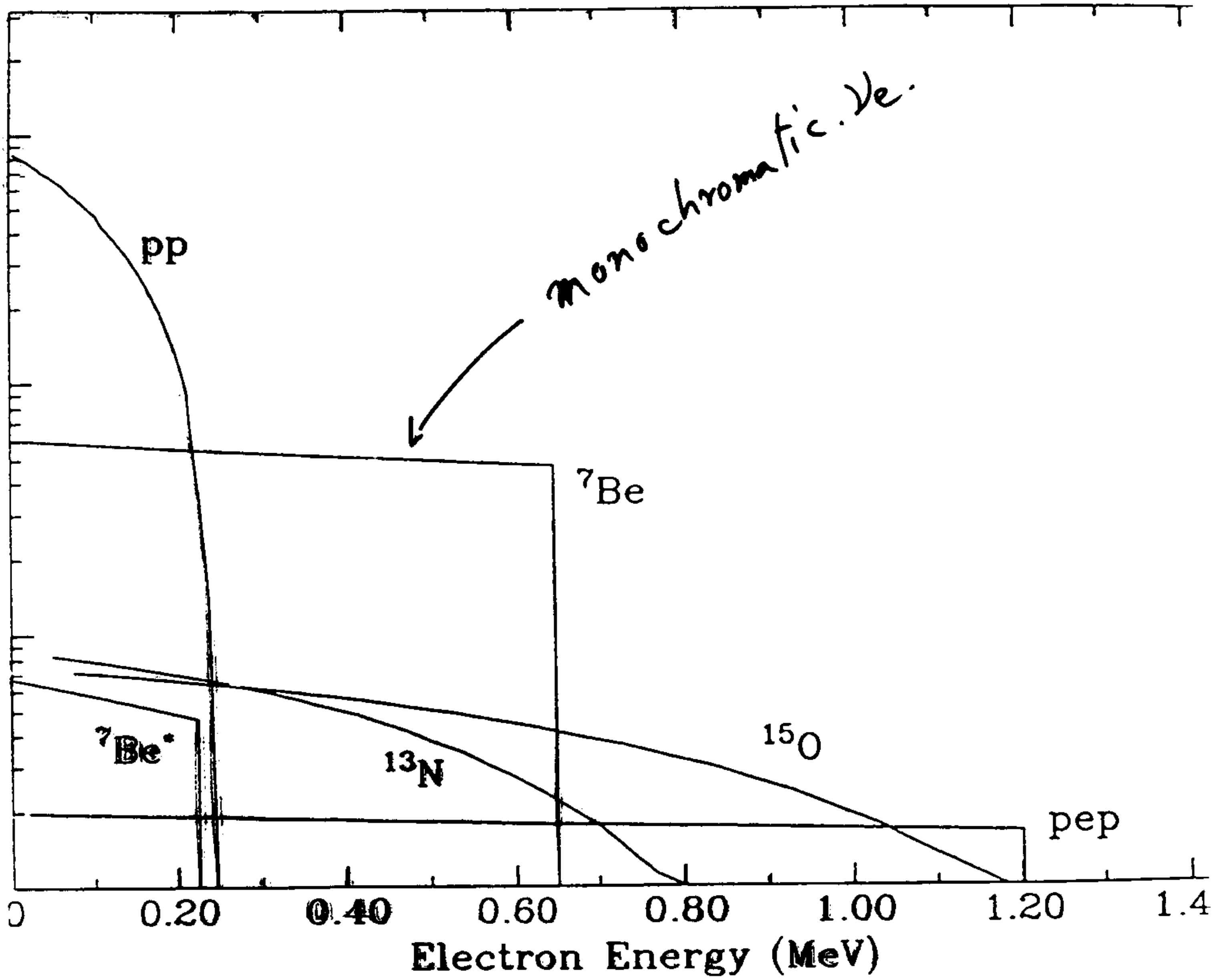
Figure 2.2 Plan of the Gran Sasso Laboratory: Artists perspective of the Borexino detector in Hall C of the Gran Sasso underground laboratory.

The electron spectrum due to p,p neutrinos has its endpoint at 0.25 MeV and in the interval 0.20 – 0.25 MeV their number is comparable with that due to ^{7}Be in the standard model. Neutrinos from ^{13}N and ^{15}O contribute about one third of that value. If the ^{14}C background can be reduced well below the present design target, the ability to detect a part of the p,p neutrino spectrum may be of value, especially in searching for diurnal variation of the rate.

Figure 2.4 shows Monte Carlo generated electron spectra expected in Borexino for the standard model and for complete ν_e to ν_μ conversion (MSW). The ^{7}Be spectrum is the main component of the signal. The sharp rise at 0.66 MeV provides a characteristic signature, distinguishing the signal from the principal background sources. The intensities of $\nu(pep)$, $\nu(^{13}\mathrm{N})$ and $\nu(^{15}\mathrm{O})$ above 0.66 MeV are probably too low for measurement. The rate of (ν, e) scattering of neutrinos from ^{8}B decay

$\int \phi_\nu \sigma_{\nu e} = C \cdot R.$

$\nu_e e \to \nu_e e$



re 2.3 The Electron Spectra: Calculated electron spectra in B

BOREXINO COLLABORATION

- GERMANY

a) Technical Univ. of Munich, Garching:
E. von Feilitzsch, T. Goldbrunner, T. Hagner, E. Kellner, G. Korschinek, J. Jochum

b) Max-Plank-Institute f. Kernphysik, Heidelberg:
G. Heusser   c) Heidelberg, T. Kirsten et al.

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b) University and I.N.F.N. of Genova:
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c) C.C.R. EURATOM - ISPRA:
P. Trincherini

d) University and I.N.F.N. of Milano:
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M. Deutsch, G. Fisher

c) Princeton University:
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d) University of Hawaii, Honolulu:
S. Pakvasa

(1) On leave of absence from the M.P.I., Heidelberg.
(2) On leave of absence from the University of Budapest, Hungary.
(3) On leave of absence from the Techn. Univ. Munich.

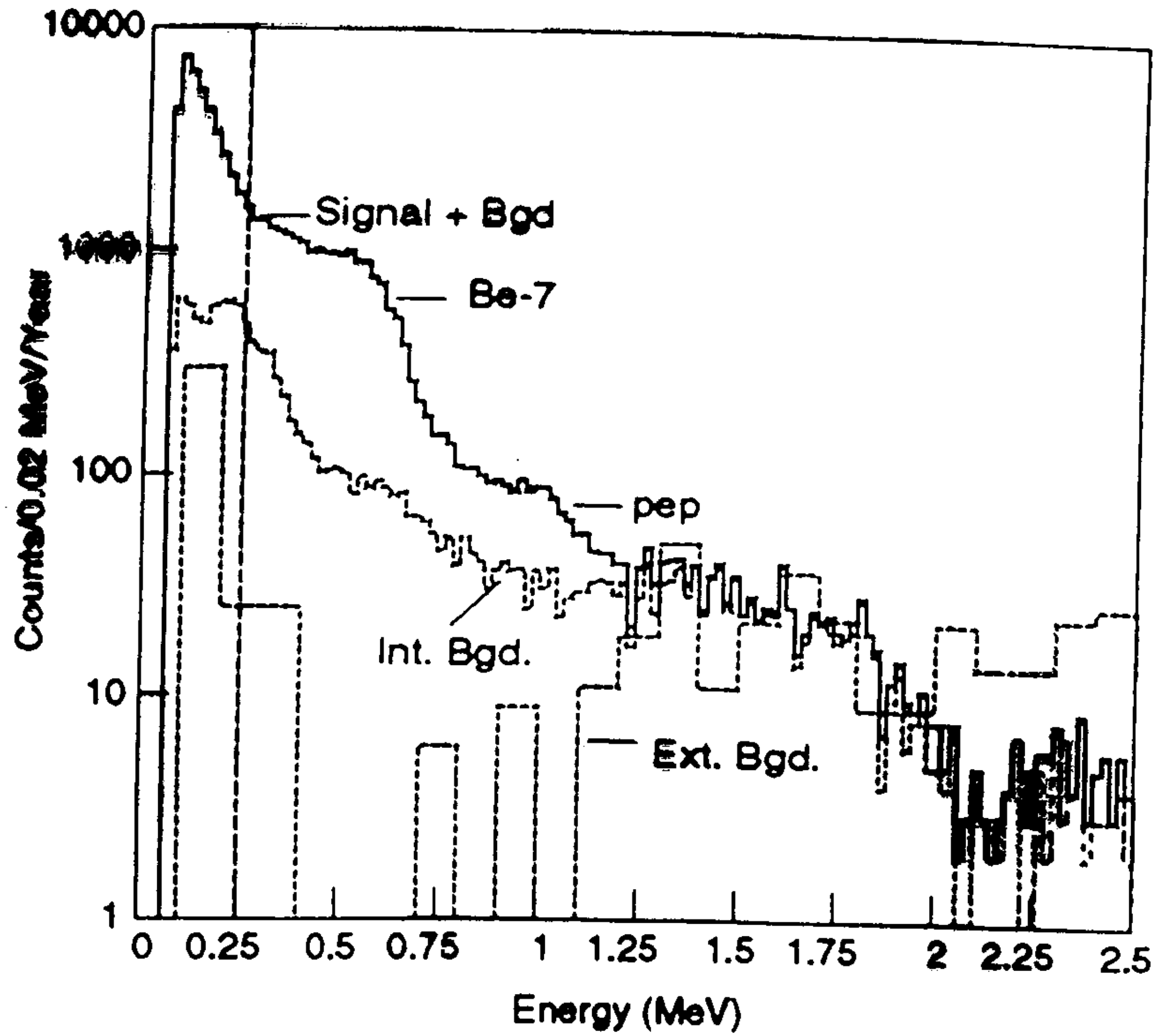


*Fig. 6 Design spectra of **BP**-predicted **signal** and background simulated for Borexino (Ref. 34).*

History of Borex (1987)
↓ (1997)

WHY BOREXINO

The measurement of ^{7}Be ν provides

- Measurement of N(^{7}Be ν)/N(^{8}B ν) (with Kamioka and SNO results)
- Npp=N(gallium)-N(^{7}Be)-N(^{8}B)-CNO
- ν,e$^-$ minimal rate from ^{7}Be ν ⟶ ν oscillation

BOREXINO DETECTOR

- Water tank: 16.5 m high, 16.5 m of diameter (<10^{-10} g/g U, Th)
- Stainless-steel sealed sphere, which supports the PMT's and concentrators: 12.5 m of diameter - filled with mineral oil (<10^{-13} g/g U, Th)
- 1650 PMT's
- Inner Vessel: 8.5 m of diameter, containing the scintillator
  300 tons of scintillator (~10^{-16} g/g U, Th)

Measured Quantities in Borexino

- Calorimetric measurement of energy
  Photomultiplier pulse heights
  Energy Resolution 45 KeV@0.5 MeV

- Position of event in space
  Light transit time to PMT's
    PMT time jitter ~1 ns
    Scint. decay time ~3 ns
  Position Resolution ~20 cm@0.5 MeV
  Important for External Backgrounds

- Particle identification (alphas vs betas)
    PMT pulse shape
    (different scint. decay time)
    α ID~ 99%
    Important for U, Th, backgrounds

- Time correlation between the events
  Very high resolution measurements (Δt~0.3 ns) of the time elapsed between adjacent events(in the time range up to 8 ms)
  Absolute time of each event with an absolute clock (Δt~1 μs)

THE PHYSICS PROGRAM

1. **Measure ν flux from ^{7}Be decay in the Sun** (0.86 MeV)

   reaction: $\nu + e \longrightarrow \nu + e$ $\qquad \sigma_{\nu_e} / \sigma_{\nu_\mu} = 4.54$

   E_{e^-} software threshold: 0.25 MeV (E_ν>0.4 MeV)

S.S.M.	50 c/d	F.V. ~ 100 tons 250-800 KeV
total conversion		
$\nu_e \rightarrow \nu_x$	10 c/d	

2. $1/R^2$ yearly variation ⟶ Sun origin (no directionality

3. Time variations

Also: appearance experiment; search for $\overline{\nu_e}$ in the Solar flux (sensitivity: 20 ev/year)

$\overline{\nu} + p \rightarrow n + e^{+}$ thresh. = 1.8 MeV

↓ 200 μs

$n + p \rightarrow {}^{2}_{1}H \cdot \gamma$ (2.2 MeV)

- Laboratory experiments with a source are also possible.

CTF PAST AND PRESENT

- 1993
  Installation of the water tank, barracks, general facilities. Radon control in the hall C. Installation of the water and liquid handling plants. Installation of the bottom clean room (class 100).

- January-November 1994
  Installation of the stainless steel support structure, PMT's, concentrators, laser control for time calibration of PMT's, etc. within the water tank. Installation of the water loop.
  Installation and tuning up of the read-out electronics.

- December 1994
  Run with air in the water tank (study of the air scintillation).
  Installation of the Inner Vessel in controlled atmosphere with reduced radon content.
  Water tank purged with nitrogen. Run with nitrogen in the tank.
  Rapid transport (2 days by the production) of 6 tons of pseudocumene.
  Start up of the water filling.

- January-March 1995
  Water tank filled with water. Nitrogen blanket maintained on the top of the tank.
  Run with water in the tank
  Installation of the clean room on the top of the tank.
  Filling of the Inner Vessel with 1 ton of scintillator.
  Run with the scintillator.
  Assembling of the purification plant.

CORRELATED EVENTS

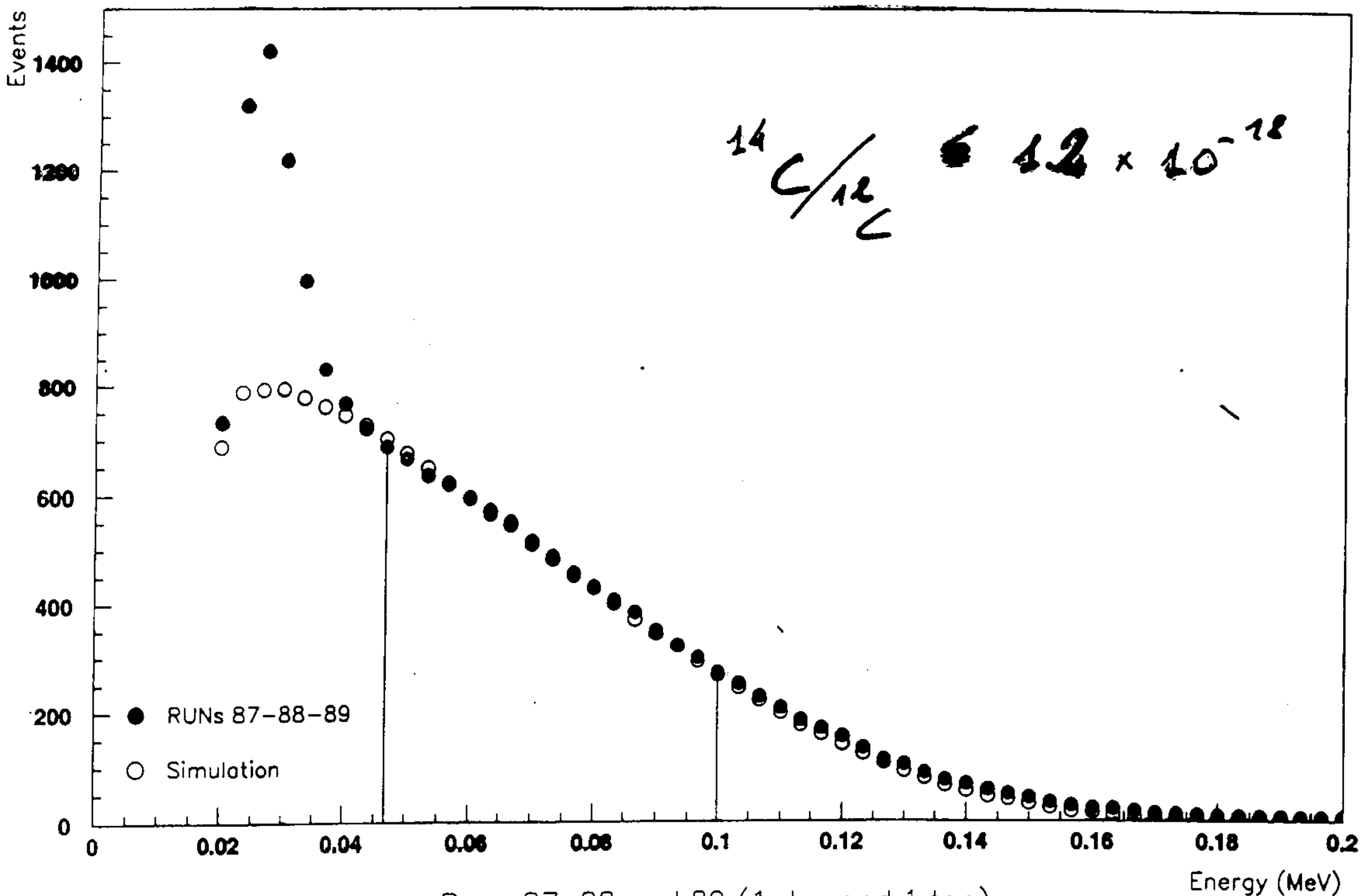
U^{238} $\quad {}^{214}Bi \xrightarrow{\beta} {}^{214}Po \xrightarrow{\alpha} {}^{210}Pb \quad T_{1/2} = 164\ \mu s$

${}^{232}Th$ $\quad {}^{212}Bi \xrightarrow{\beta} {}^{212}Po \xrightarrow{\alpha} {}^{208}Pb \quad T_{1/2} = 300\ ns$

EASILY DETECTABLE FOR THEIR SPECIFIC TEMPORAL SEQUENCE AND THE ENERGY ASSOCIATED TO THE SECOND α EVENT.

TAGS OF URANIUM AND THORIUM CONCENTRATION IN THE SCINTILLATOR

^{14}C β-spectrum (simulated and corrected measured spectra)



Runs 87, 88 and 89 (1 day and 1 ton)

CONCLUSIONS

During the R&D, the setting up, the running and the preliminary analysis of the data:

- We reached the Borexino goals for the constructing and shielding materials: low radioactivity level, good resistance to chemical corrosion, low radon permeability etc.

- **Preliminary** data analysis showed that the scintillator **radiopurity** is very good:

Th		1×10^{-16} g/g
	upper limit	$< 3.$[illegible]$\times 10^{-16}$ g/g (90% confidence level)
U	upper limit	$< 3 \times 10^{-15}$ g/g (84% confidence level)

  These results have been achieved before to purify the scintillator with the purification plant!

- The upper limit for ^{14}C has been measured:

  $< 1.2 \times 10^{-18}$ $^{14}C/^{12}C$

  At this limit the background contribution from ^{14}C upper our lower threshold of 250 KeV is completely negligible.

* These results have finally convinced the Collaboration (waiting in US) that Borexino experiment is feasible. → appr. in Italy, Germany,
Forthcoming proposal ⇒ ## ⇒ construction 98-99

^7Be Line BOREXINO

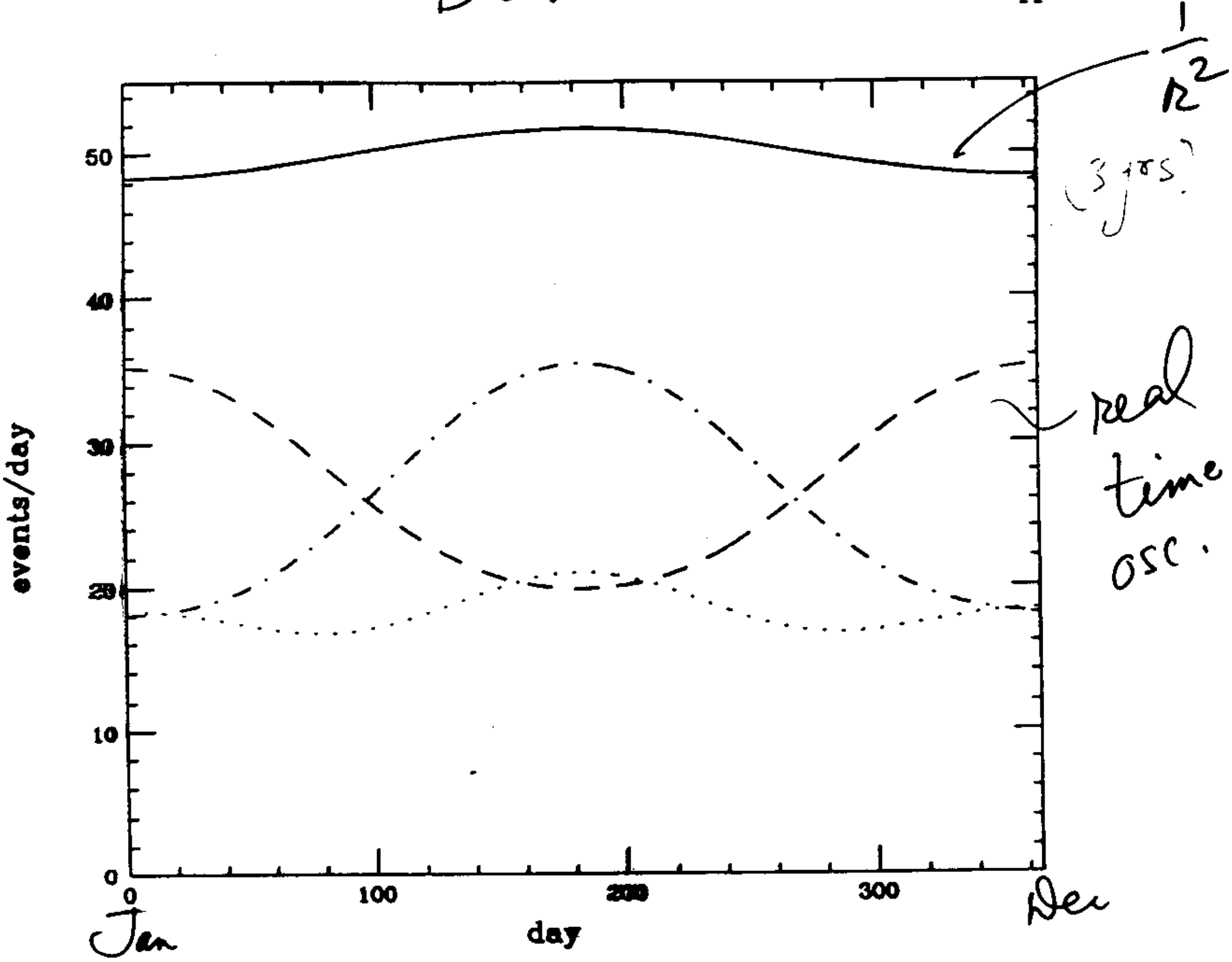


Figure 3.7: Seasonal variations in ^7Be neutrino flux. The solid line is the SSM prediction showing the $1/r^2$ effect. The dashed, dot-dashed and dotted lines represent 3 vacuum oscillation solutions to the solar neutrino problem with $\sin^2 2\theta = 0.8$ and $\delta m^2 = .81\times10^{-10}\ eV^2$, $.76\times10^{-10}\ eV^2$ and $.782\times10^{-10}\ eV^2$ respectively.

3.5.1 Theory

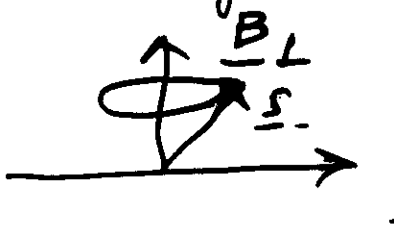
In the discussion of matter enhanced neutrino oscillations we will again limit the discussion to the simple case of oscillations of two neutrino flavors. Let us begin by writing the neutrino vacuum evolution equations in a form suitable for generalization to neutrino propagation in matter. Consider two neutrino flavor

Acker (Thesis)

If ν has mdm, μ,

$$\frac{d\underline{S}}{dt} = \mu \, \underline{S} \times \underline{B}.$$

and spin precesses around $\underline{B}_\perp$.



So ν no longer pure ν_L.

$$P(\nu_L \to \nu_L, t) = \cos^2(\mu B_\perp t).$$

For $B_\perp \sim 10^4$ G.
$ct \sim 10^{10}$ cm

$P \gtrsim \frac{1}{2}$ if $\underline{\mu \sim 10^{-11} \mu_B}$ $\left(\frac{e\hbar}{m_e c}\right)$.

Very Large mdm for ν.

Cisneros (1971)

Neutrino Spin Precession

{Voloshin, Vysotsky, Okun (1986)

Need $\mu_\nu B \sim 10^{-7} \mu_B G$ } $\rightarrow \mu B L \sim O(1)$

$L \sim 10^{10}$ cm }

$\delta m^2 << 10^{-9}$ eV^2 or $\theta \approx 0$

Dirac} Time Variation identical for ^{37}Cl, ^{71}Ga, K-II

NC, CC

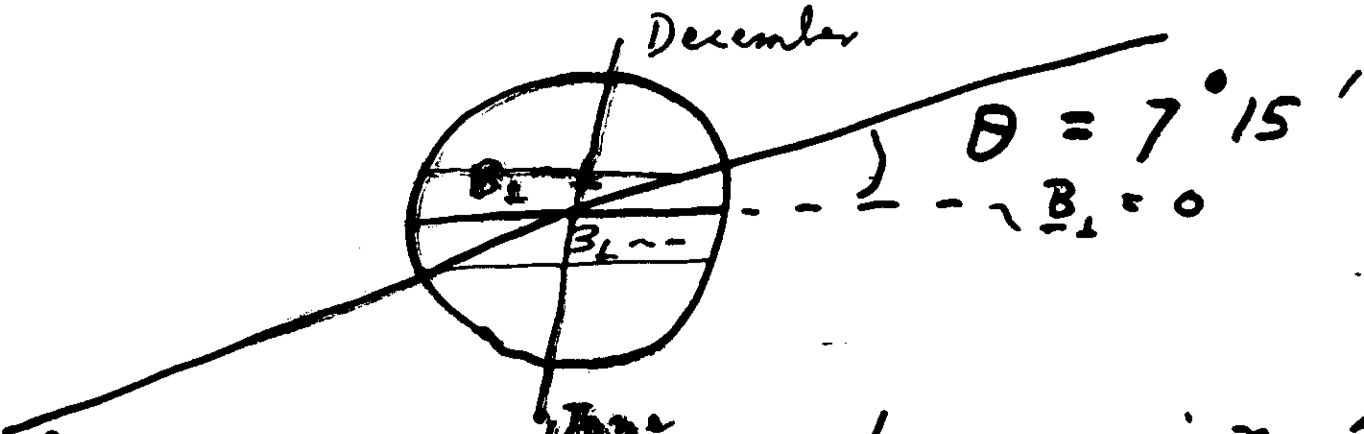
Majorana ⇒ { NC no variation/supp.

νe { 17% const; 83% varying

Semi Annual Variation for ^{8}B neutrinos

No Energy Dependence.

Semi Annual Variation



Earth's orbit

$\underline{B}_\perp$ changes sign a

the solar equator an

the "slit

$\simeq \pm 8 \cdot 10^9$ cm. >> size o

^8B producing region.

So at the nodes the flux i

maximum.

Period of Quiet Sun ⟹

No variation

Resonant Spin Flavor Precession

$\mu_\nu \sim \mu_{\nu_e \nu_\mu}$ (Majorana e.g.)

$\nu_{e_L} \to \bar{\nu}_{\mu R} \{\to \bar{\nu}_{eR}\}$

$\nu_{e_L} \to \nu_{\mu_L}$

To get factor 2 change in ^{37}Cl

favored region : $\begin{cases} \delta m^2 \sim 10^{-7}\, eV^2 \\ \sin^2 2\theta \sim 0.1 \end{cases}$

- Expect νe (K-II) change bet 0.46 & 0.78 (1.7)
- Expect ^{71}Ga change bet. 5 SNU & 10 SNUS
- $\bar{\nu}_e$ Signal.

NC no change or suppression

Schechter, Valle
Lim, Marciano
Akhmedov
Minakata, Nunokawa
Balantekin, Loretti
Smirnov, . . .

S. Pakvasa