NEW ENHANCEMENT MECHANISM OF THE TRANSITIONS OF SOLAR AND ATMOSPERIC NEUTRINOS CROSSING THE EARTH

S.T. PETCOV

SISSA/INFN - SEZIONE DI TRIESTE, TRIESTE, ITALY, AN
INRNE, BULGARIAN ACADEMY OF SCIENCES, SOFIA, BULGARIA

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SISSA 111/98/EP

M. Chizhov, M. Maris, S.T.P.
SISSA 53/98/EP, 31.7.'98
hep-ph/9810501.

See also: M. Maris, S.T.P. PR D56 ('97) 7444
PR D58 ('98)

(D-N effect) Q.Y. Liu, M. Maris, S.T.P., PR D56 ('97) 5991

$\nu_\odot$ - Oscillations in Vacuum

(Pontecorvo 1958; 1967 - relevance to $\nu_\odot$ - experiment

ν - Oscillations in vacuum are possible if ν_i's with $m(\nu_i) \neq 0$ ($m_i \neq m_j$, $i \neq j$) and nontrivial lepton (ν-) mixing exist in vacuum.

(idea of ν-osc. Pontecorvo, '5. Maki et al, '62)

Consider the simplest case:

$$\begin{cases} |\nu_e\rangle = |\nu_1\rangle \cos\theta + |\nu_2\rangle \sin\theta, \\ |\nu_x\rangle = -|\nu_1\rangle \sin\theta + |\nu_2\rangle \cos\theta. \end{cases}$$

in vacuum

$\vec{p}, E_1(m_1)$ $\quad$ $\vec{p}, E_2(m_2)$ $\quad$ $m_2 \neq m_1$, $\theta \neq \frac{\pi}{2}k$, $k = 0,1,2,\ldots$

$\nu_x = \nu_\mu$ or ν_τ - active, or

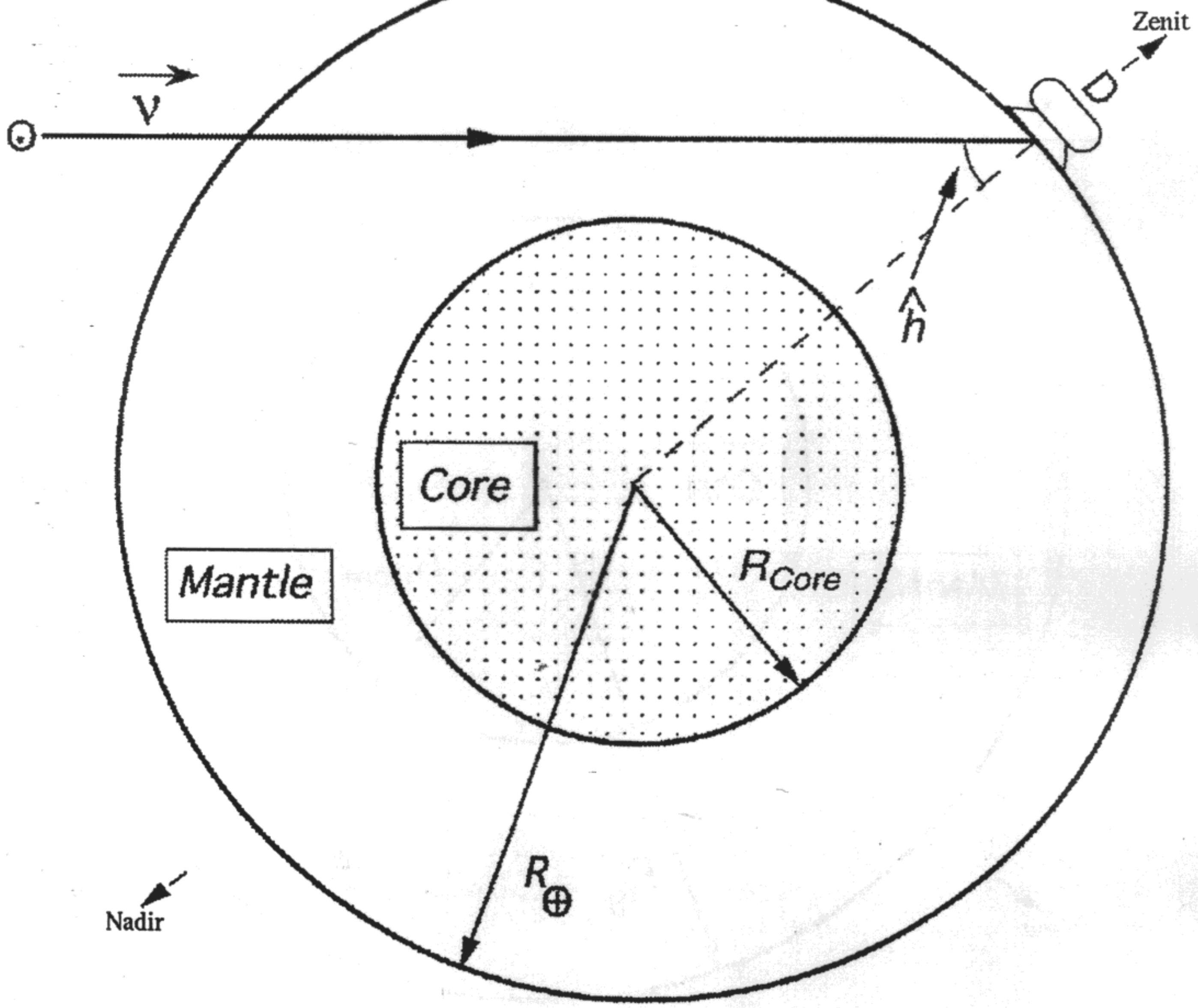
$\nu_x = \nu_s$ - sterile;

$$\boxed{\nu_e \rightleftarrows \nu_\mu \quad {\scriptstyle x=\mu}}$$ possible in vacuum.

θ - neutrino mixing angle in vacuum,

ν_1, ν_2 - neutrinos with definite mass in vacuum (vacuum mass-eigenstate ν's)

Figure 1



(M. MARAS)

- $\rho_c \cong (10 - 13)\, g/cm^3$ over a distance of $R_c = 3486\ km$

- $\rho_m \cong (3.3 - 5.5)\, g/cm^3$ over a distance of ~2885 km

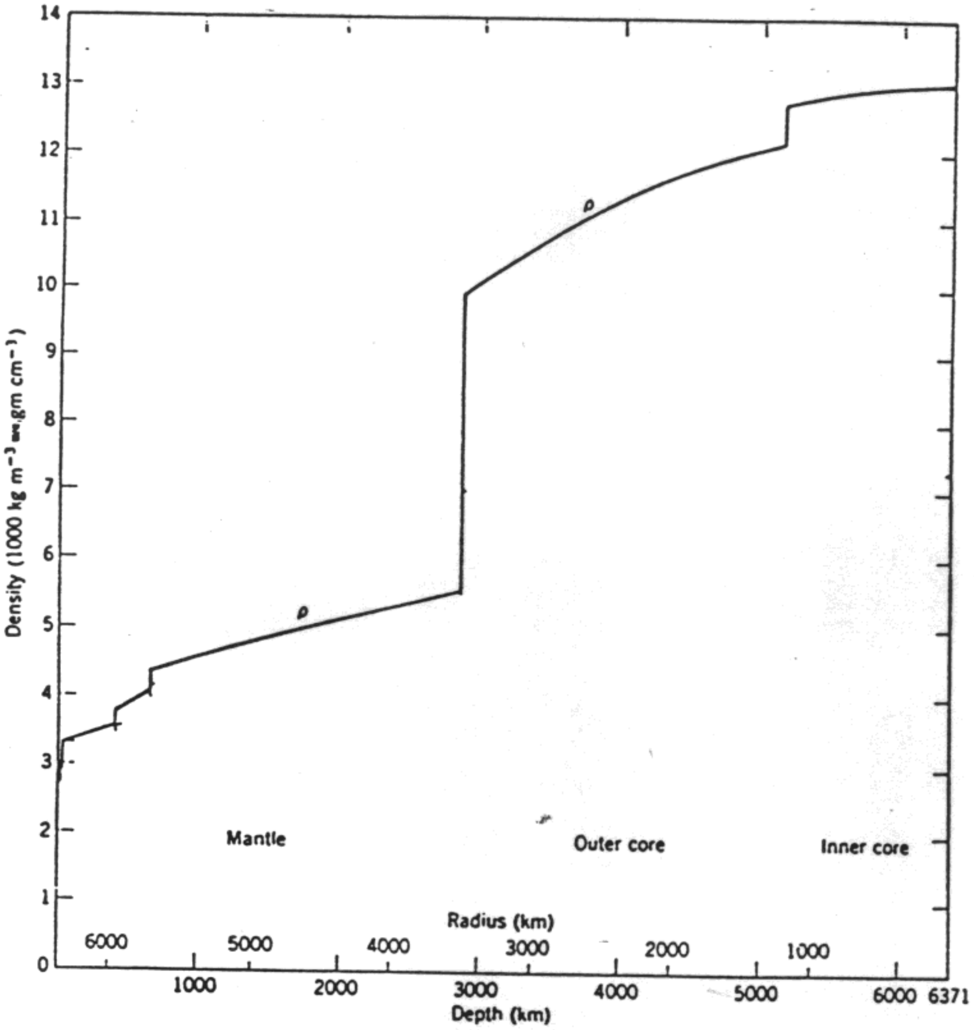


Figura 5.1: Distribuzione di densità della Terra (Stacey, 1977).

$P(\nu_{\mu(e)} \to \nu_{e(\mu;\tau;s)})$

"New Type" of RESONANCE IN $P_{e2} \equiv P(\nu_2 \to \nu_e)$:

(P_{e2}: accounts for the Earth Effect in $P_{\odot}(\nu_e \to \nu_e)$ in the case of 2-ν mixing MSW solution of the $\nu_{\odot}$-problem)

S.T.P.: PL B434
hep-ph/9809587
/9811205

- Not the MSW resonance
- Takes place when

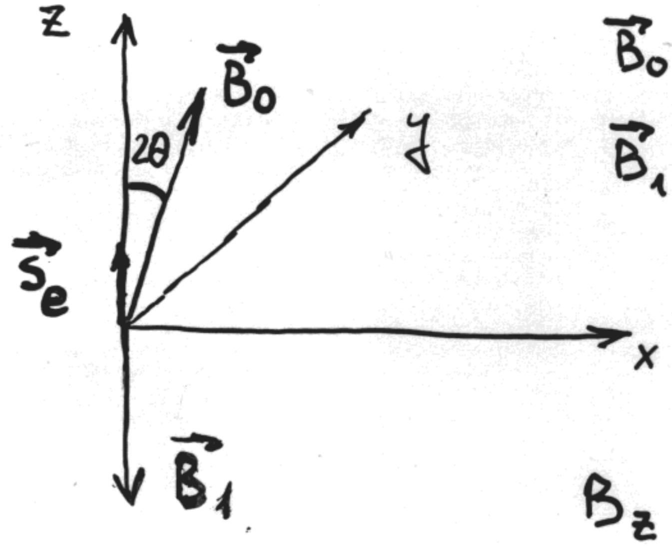
  L^{core}_{osc}, L^{man}_{osc} obey certain constraints

  hence, it is a

  "neutrino oscillation length resonance"
- Similar to the

  electron paramagnetic resonance

L. WOLFENSTEIN



$\vec{B}_0$: $B_{0y} = 0$, const;

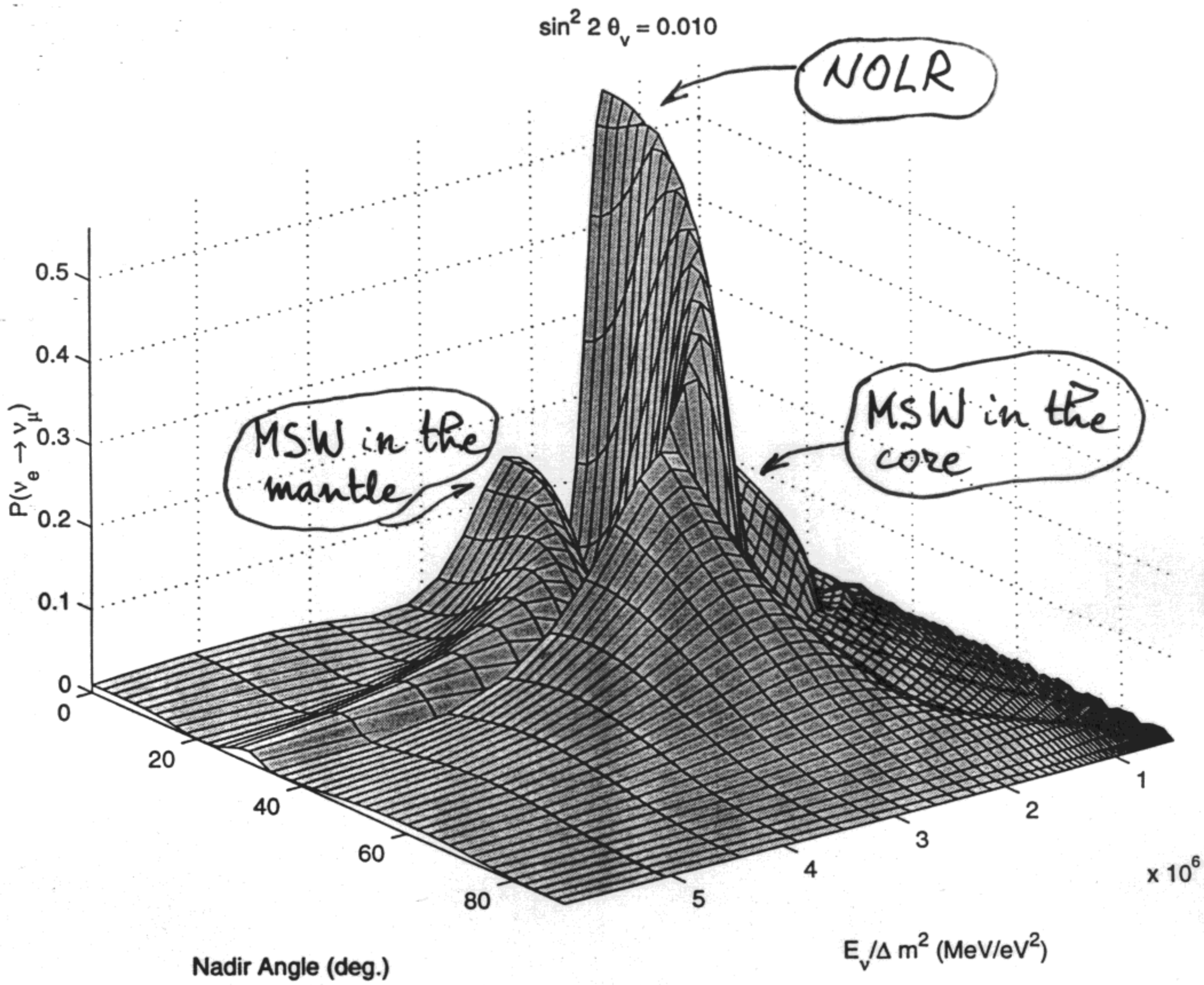
$\vec{B}_1$: $B_{1x} = B_{1y} = 0$, assumes (2) values; changes step-wise

$$B_z = \begin{cases} B_0 \cos 2\theta - B_1 > 0, & t < t_1 \\ & t_2 \leq t \leq t_3 \\ B_0 \cos 2\theta - B_1 < 0, & t_1 \leq t < t_2 \end{cases}$$

const.

(M. CHIZHOV, M. MARIS, S.T.P. '98)

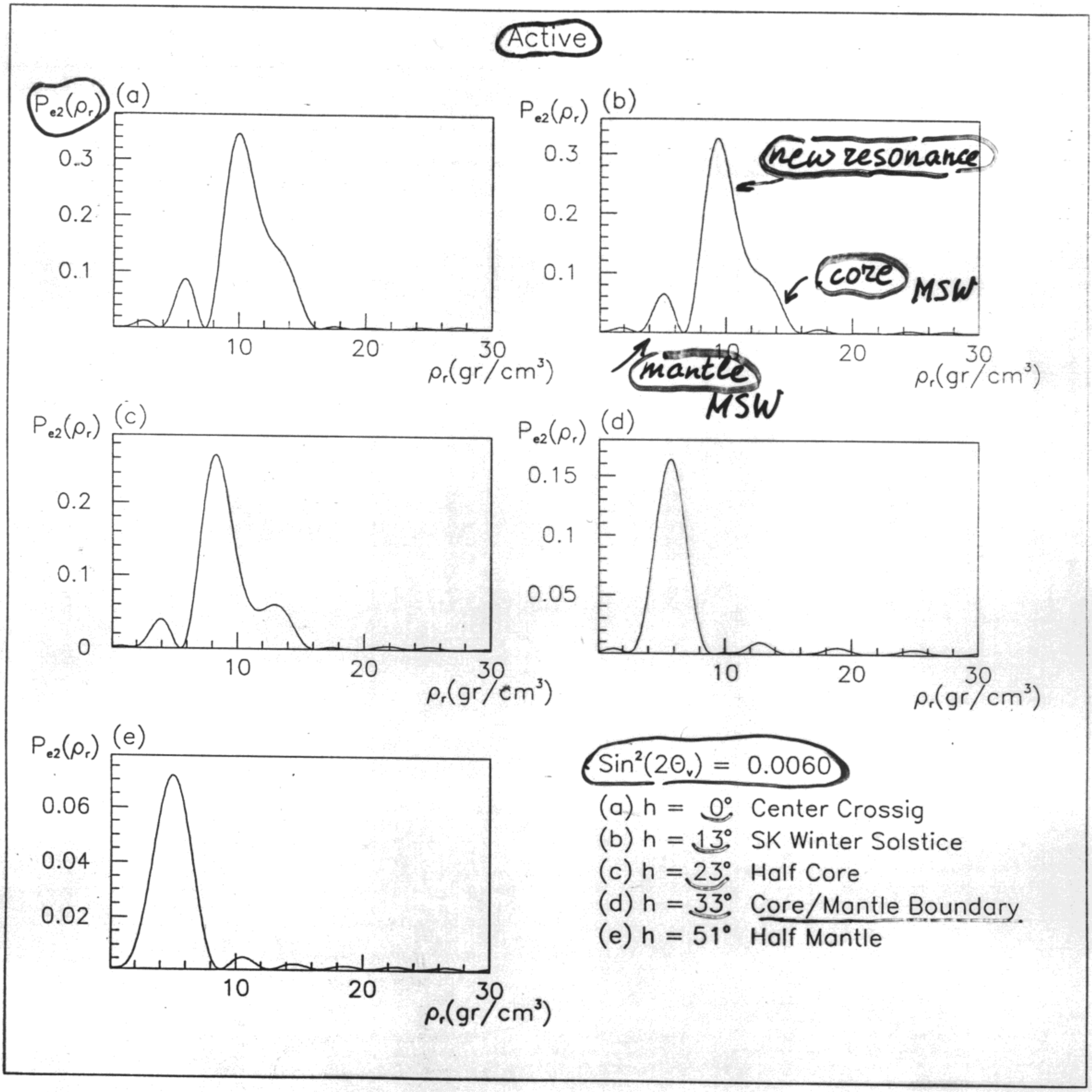
$\nu_\mu \to \nu_e\ ,\ \nu_e \to \nu_\mu(\tau)$



(MARIS, S.T.P., TCHIJOV, '98)

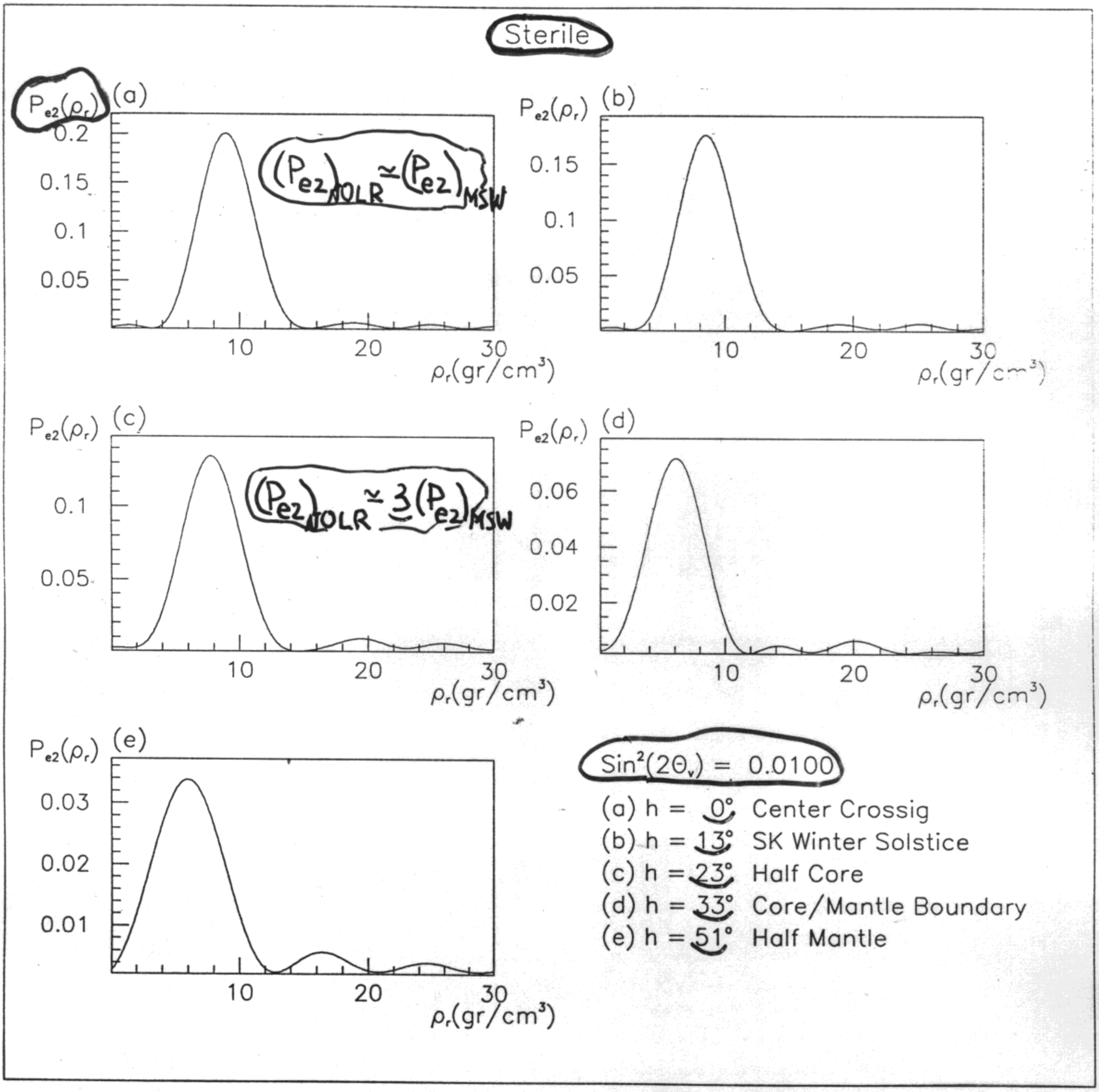
$\nu_2 \rightarrow \nu_e$

$$\boxed{E/\Delta m^2 = \frac{6.56 \times 10^6}{0.5\, \rho_2 [g/cm^3]} \cos 2\Theta \quad MeV/eV^2}$$



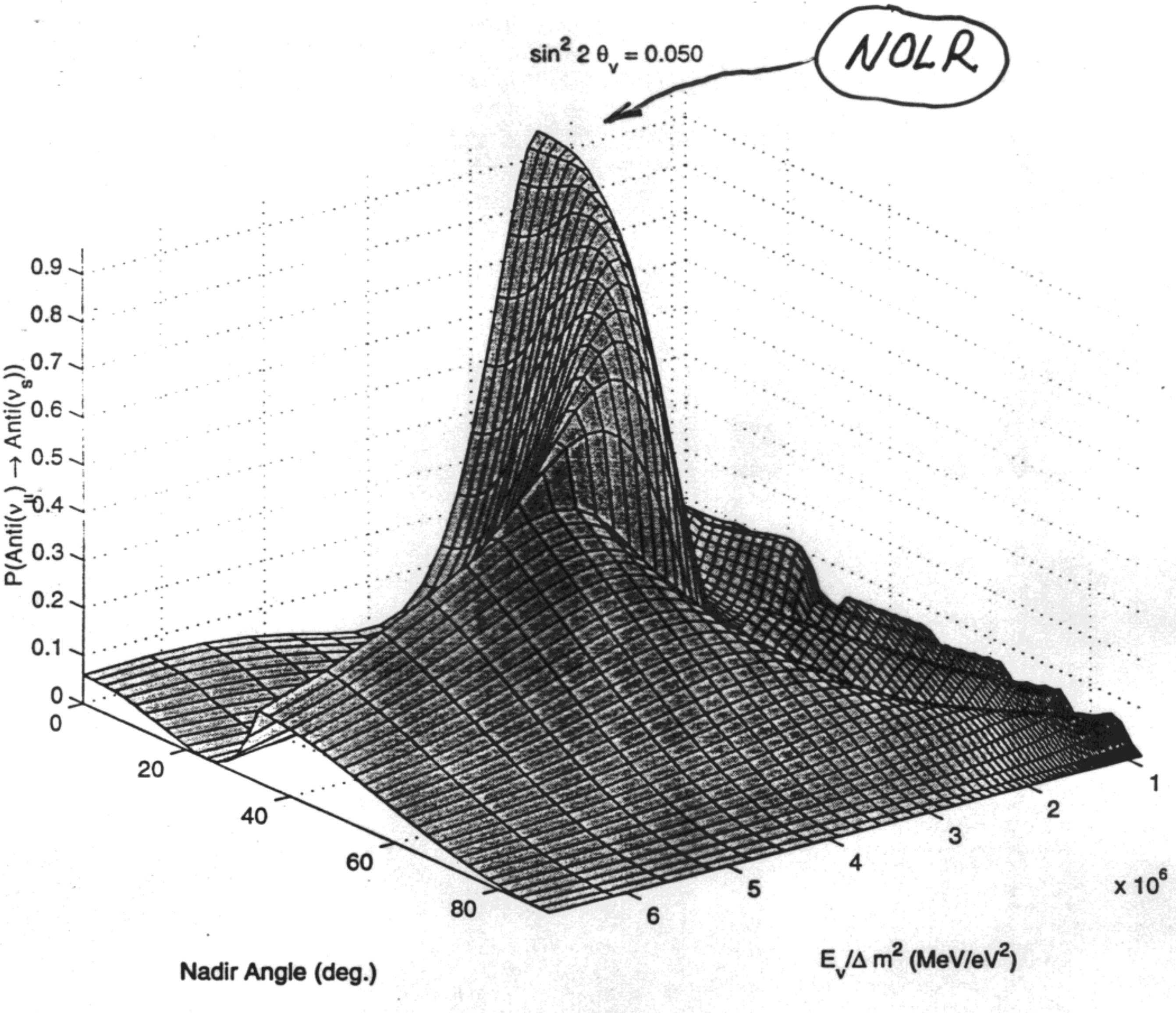
$\nu_2 \to \nu_e$ $(\nu_e \to \nu_s)$ (M. MARIS, S.T.P. '98)

$$\boxed{E/\Delta m^2 = \frac{6.56 \times 10^6}{0.25\, \rho_r [g/cm^3]}\ \mathrm{MeV/eV^2}}$$



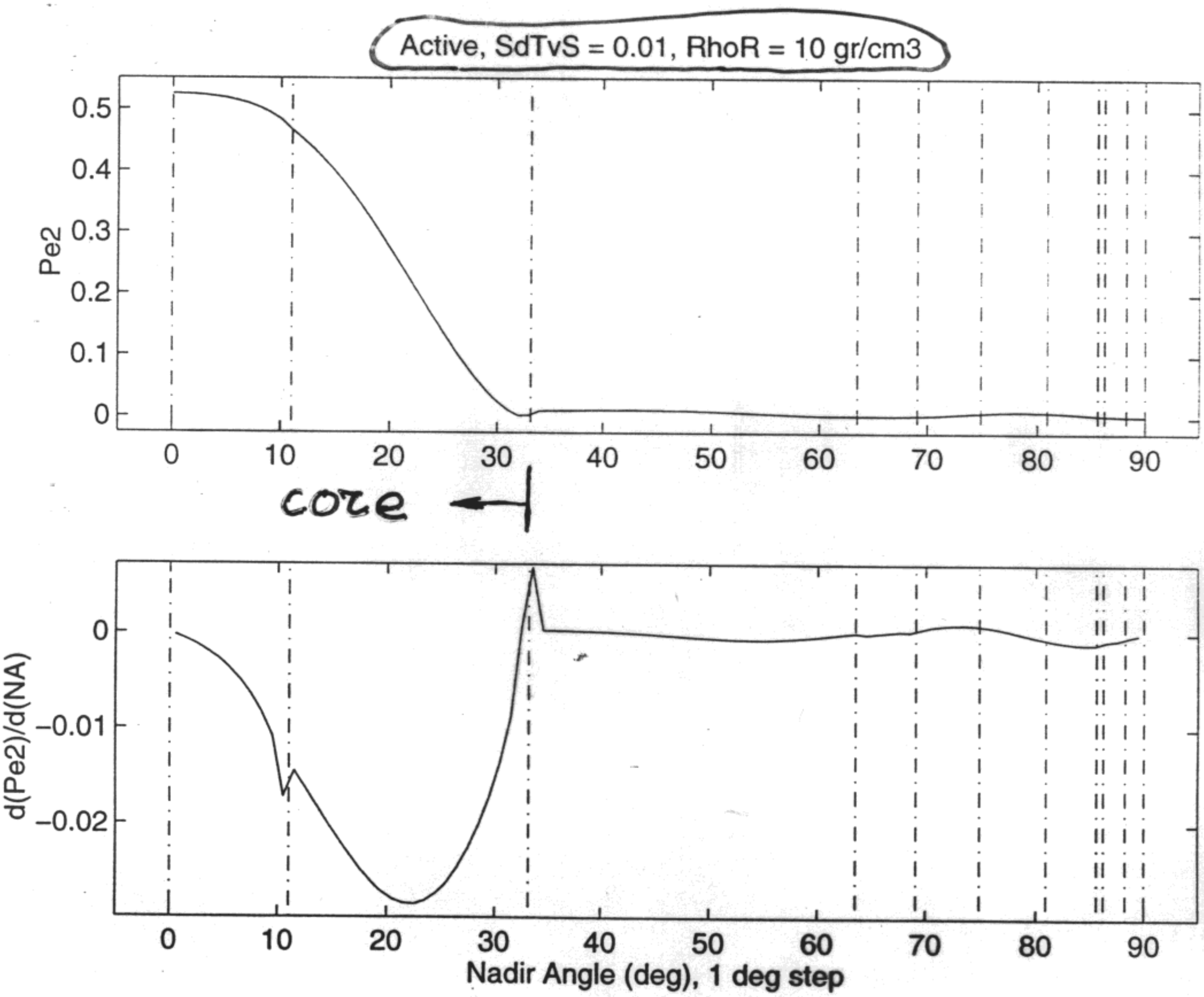
(CHIZHOV, MARIS, S.T.P., '98)

$\bar{\nu}_\mu \longrightarrow \bar{\nu}_s$



(M. MARIS, S.T.P., M.TCHIJOV '98)

$\nu_e \longrightarrow \nu_{\mu(\tau)}$



The neutrino oscillation length resonance in P_{e2}, $P(\nu_{\mu(e)} \to \nu_{e(\mu;\tau)})$

- exhibits strong dependence on E
- for Δm^2 from the SMA solution region takes place for $E \cong (5-12)$ MeV
- leads in the case of the SMA (MSW) $\nu_e \to \nu_{\mu(\tau)}$ solution to a ~6 times bigger D-N asymmetry in the "Core" sample of event in the SK detector than the asymmetry in the whole "Night" sample
- is sufficiently wide (it is wider than the MSW resonance) $\Delta E/E_{max} \cong (0.3-0.4)$ and is $\sin^2 2\theta$ independent at $\sin^2 2\theta \leq 0.05$

The resonance takes place in the $\nu_\mu \to \nu_e$ ($\nu_e \to \nu_\mu$) transitions of atmospheric neutrinos as well:

e.g., for $\begin{cases} \Delta m^2 \sim 10^{-3}\,\text{eV}^2, & \sin^2 2\theta_{e\mu} \sim (0.01-0.10) \\ h = 0^\circ \end{cases}$

max $P(\nu_\mu \to \nu_e)$ occurs at $E_\nu \cong 1.6$ GeV

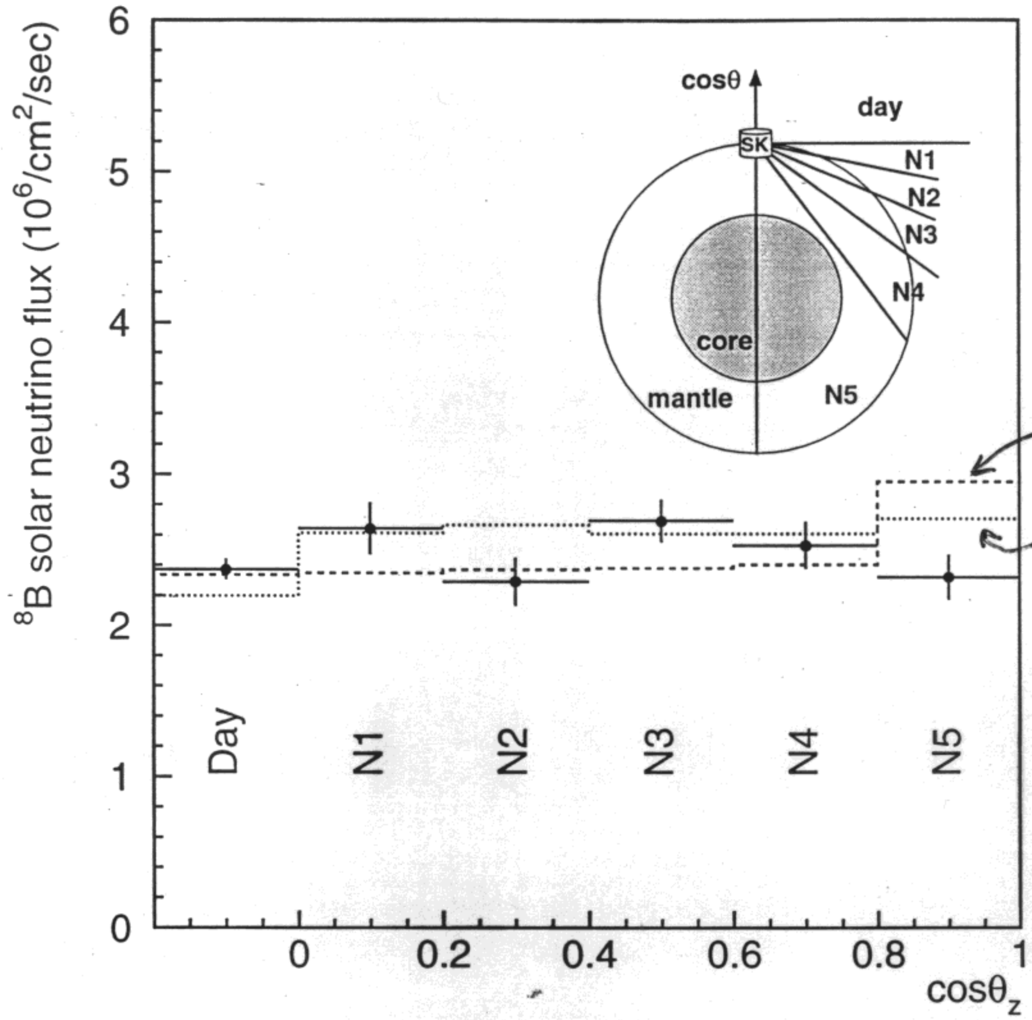
(M. MARIS, S.T.P. '97)

Table II. D - N Asymmetries for the Super - Kamiokande Detector.

N.	$\sin^2 2\theta_V$	Δm^2	f_B	$Y_e = 0.467$ $A^s_{D-N} \times 100$ Night	Core	Mantle	$\frac{\lvert A^C_{D-N}\rvert}{\lvert A^N_{D-N}\rvert}$	$Y_e = 0.500$ $A^s_{D-N} \times 100$ Night	Core	Mantle	$\frac{\lvert A^C_{D-N}\rvert}{\lvert A^N_{D-N}\rvert}$
1	0.0008	9.0e-6	0.4	-0.09	-0.54	-0.01	6.24	-0.12	-0.75	-0.01	6.25
2	0.0008	7.0e-6	0.4	-0.21	-1.26	-0.04	6.00	-0.22	-1.35	-0.04	6.14
3	0.0008	5.0e-6	0.4	-0.37	-1.29	-0.23	3.44	-0.35	-1.14	-0.23	3.26
4	0.0010	9.0e-5	0.4	3e-3	4e-3	3e-3	1.25	3e-3	4e-3	3e-3	1.33
5	0.0010	7.0e-6	0.4	-0.25	-1.50	-0.04	6.01	-0.26	-1.59	-0.04	6.12
6	0.0010	5.0e-6	0.4	-0.45	-1.52	-0.27	3.39	-0.43	-1.35	-0.27	3.14
7	0.0020	1.0e-5	0.5	-0.07	-0.41	-0.01	6.00	-0.10	-0.62	-0.01	6.20
8	0.0020	7.0e-6	0.5	-0.35	-2.10	-0.07	5.98	-0.36	-2.18	-0.07	6.06
9	0.0020	5.0e-6	0.5	-0.71	-2.30	-0.45	3.23	-0.67	-2.02	-0.45	3.01
10	0.0040	1.0e-5	1.0	0.15	0.79	0.04	5.42	0.22	1.28	0.04	5.82
11	0.0040	7.0e-6	0.7	-0.04	-0.12	-0.02	3.48	0.01	0.21	-0.02	21.00
12	0.0040	5.0e-6	0.7	-0.59	-1.36	-0.46	2.31	-0.56	-1.12	-0.47	2.00
13	0.0060	1.0e-5	1.5	0.72	3.98	0.17	5.56	1.05	6.20	0.17	5.90
14	0.0060	7.0e-6	1.0	1.06	6.46	0.17	6.13	1.26	7.60	0.17	6.03
15	0.0060	5.0e-6	0.7	0.47	2.93	0.06	6.19	0.46	2.82	0.06	6.13
16	0.0080	1.0e-5	1.5	1.63	8.93	0.37	5.47	2.36	13.59	0.37	5.76
17	0.0080	7.0e-6	1.5	3.04	17.00	0.53	5.59	3.39	19.10	0.53	5.63
18	0.0080	5.0e-6	1.0	2.55	10.26	1.22	4.02	2.44	9.54	1.22	3.91
19	0.0100	7.0e-6	1.5	5.72	29.85	1.05	5.22	6.28	32.85	1.05	5.23
20	0.0100	5.0e-6	1.0	5.60	19.84	3.03	3.54	5.36	18.38	3.03	3.43
21	0.0130	5.0e-6	1.5	11.69	36.33	6.89	3.11	11.21	33.72	6.89	3.01
22	0.3000	1.5e-5	2.0	10.73	13.25	10.31	1.24	11.03	15.29	10.30	1.39
23	0.3000	2.0e-5	2.0	7.64	9.60	7.31	1.26	7.79	10.66	7.31	1.37
24	0.3000	3.0e-5	2.0	4.74	5.54	4.61	1.17	4.78	5.85	4.61	1.22
25	0.3000	4.0e-5	2.0	3.29	3.93	3.18	1.20	3.31	4.07	3.19	1.23
26	0.4800	3.0e-5	1.5	5.95	6.81	5.81	1.15	5.99	7.08	5.81	1.18
27	0.4800	5.0e-5	1.5	2.98	3.50	2.89	1.17	2.99	3.57	2.89	1.19
28	0.5000	2.0e-5	1.5	9.48	10.97	9.24	1.16	9.60	11.79	9.23	1.23
29	0.5600	1.0e-5	1.5	23.65	34.9	21.64	1.48	27.50	40.77	25.11	1.48
30	0.6000	8.0e-5	1.0	1.42	1.64	1.38	1.15	1.42	1.65	1.38	1.16
31	0.7000	3.0e-5	1.0	6.54	7.26	6.41	1.11	6.56	7.43	6.41	1.13
32	0.7000	5.0e-5	1.0	3.37	3.90	3.29	1.16	3.38	3.95	3.29	1.17
33	0.7700	2.0e-5	1.0	9.89	10.27	9.83	1.04	9.94	10.59	9.83	1.07
34	0.8000	1.3e-4	0.7	0.57	0.69	0.55	1.21	0.57	0.69	0.55	1.21
35	0.9000	4.0e-5	0.7	4.53	5.12	4.42	1.13	4.53	5.17	4.42	1.14
36	0.9000	1.0e-4	0.7	1.15	1.33	1.13	1.15	1.15	1.33	1.13	1.16

SK '99

FIGURES



MSW:

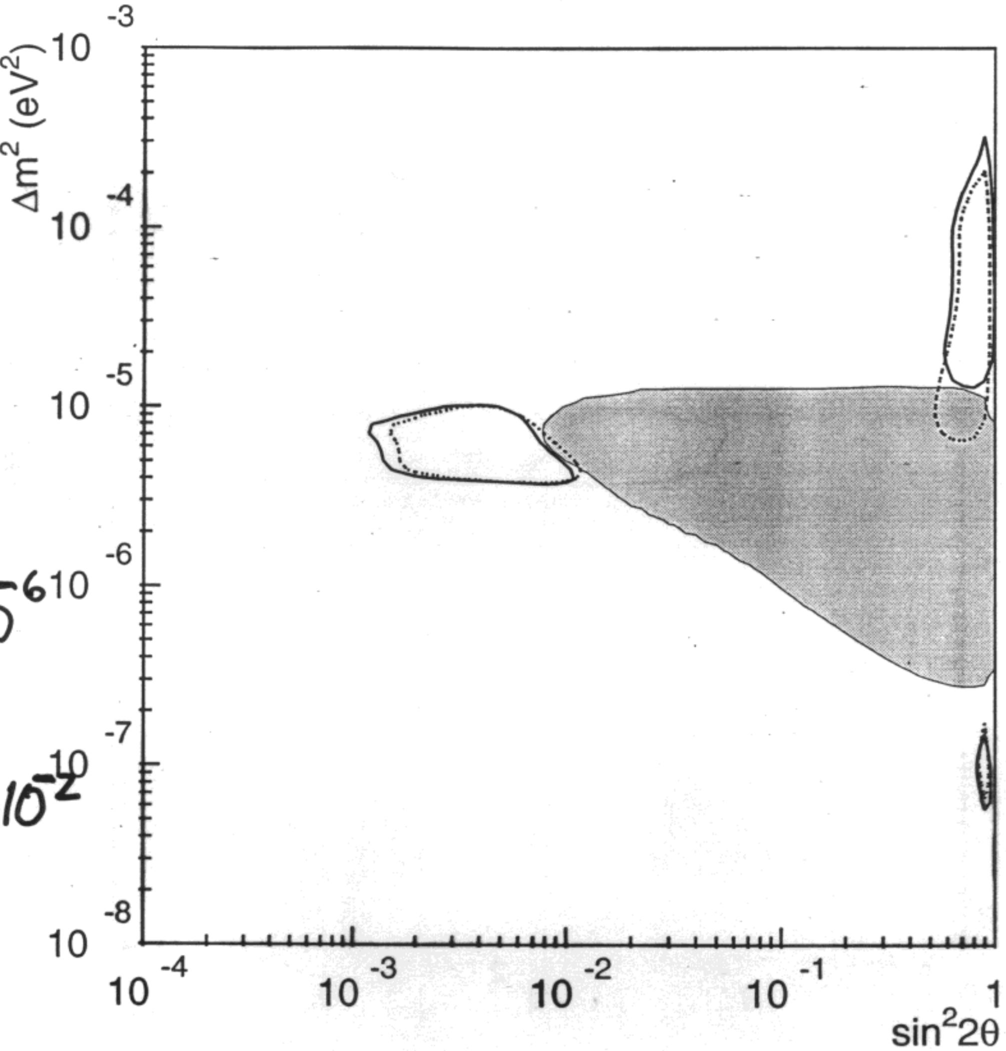
SMA

LMA

FIG. 1. Measured day/night solar neutrino fluxes as a function of the nadir of the Sun. Error bars represent statistical errors only. Night data is divided into 5 bins. Dotted histogram is the expected variation of a typical large angle solution and dashed histogram is that of a typical small angle solution.

(SK collaboration '98,

MSW $\nu_e \to \nu_{\mu(\tau)}$



LMA:

SMA

Δm^2

$(4 - 10)\cdot 10^{-6}$

$\sin^2 2\theta$

$(0.1 - 1.0)\cdot 10^{-2}$

(0.06)

LOW

FIG. 2. Flux independent exclusion region by SK day/night variation for $\nu_e \to \nu_{\mu.\tau}$ oscillations. Exclusion probabilities larger than 99% are shown in the shaded area. Regions inside of the dotted lines are allowed at the 99% C.L. from the combined rate analysis of Homestake, SAGE, Gallex and SK-flux in comparison with the BP98 SSM [6]. Regions inside of the thick solid lines are allowed at the 99% C.L. from the combined rate analysis of the rates and the SK D/N variation.

LMA: $\Delta m^2 \cong (0.2 - 30)\cdot 10^{-5}\,eV^2$ (99% C.L.

$\sin^2 2\theta \cong (0.6 - 0.96)$

(M. MARIS, S.T.P. '97)

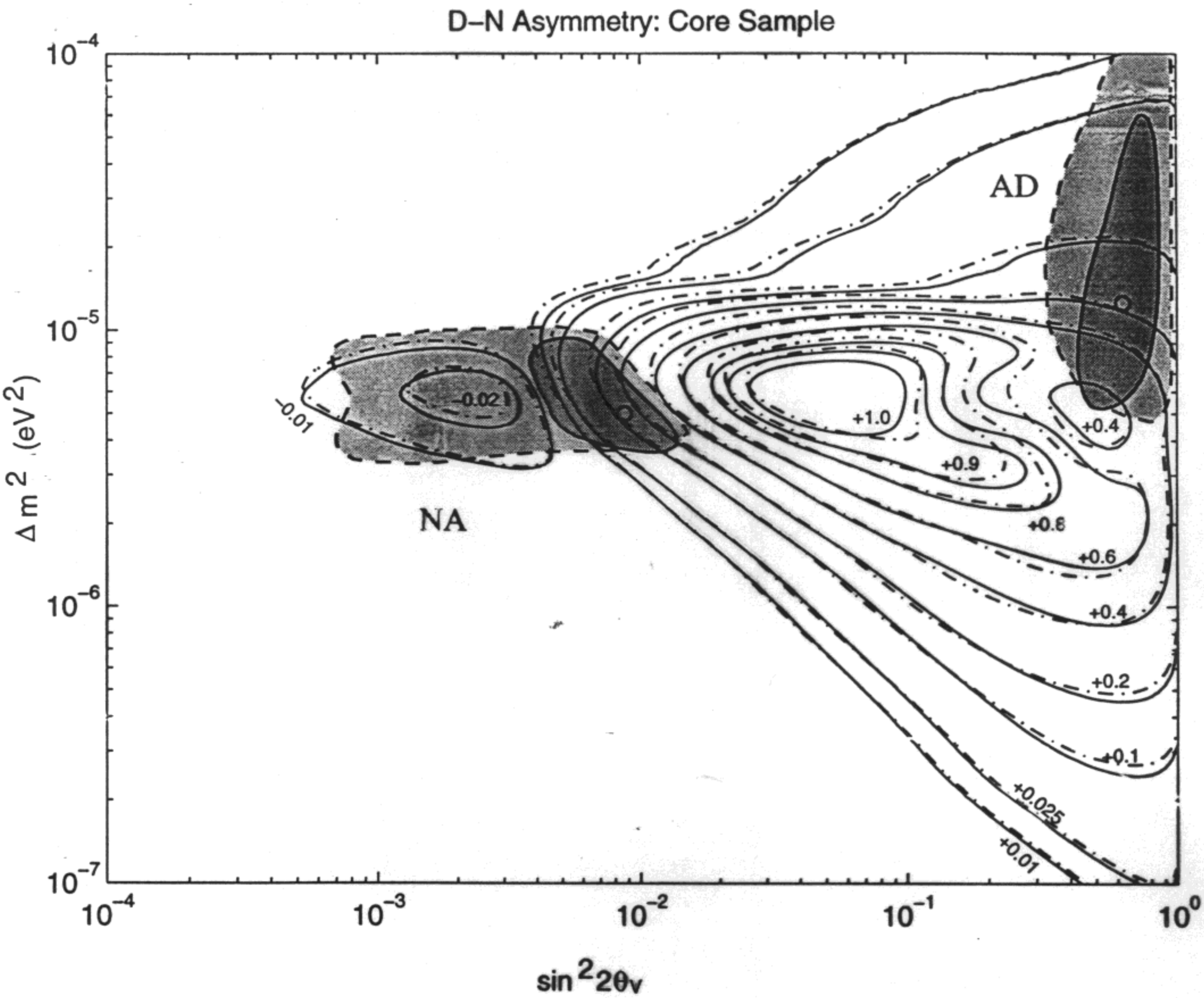


Figure 3c

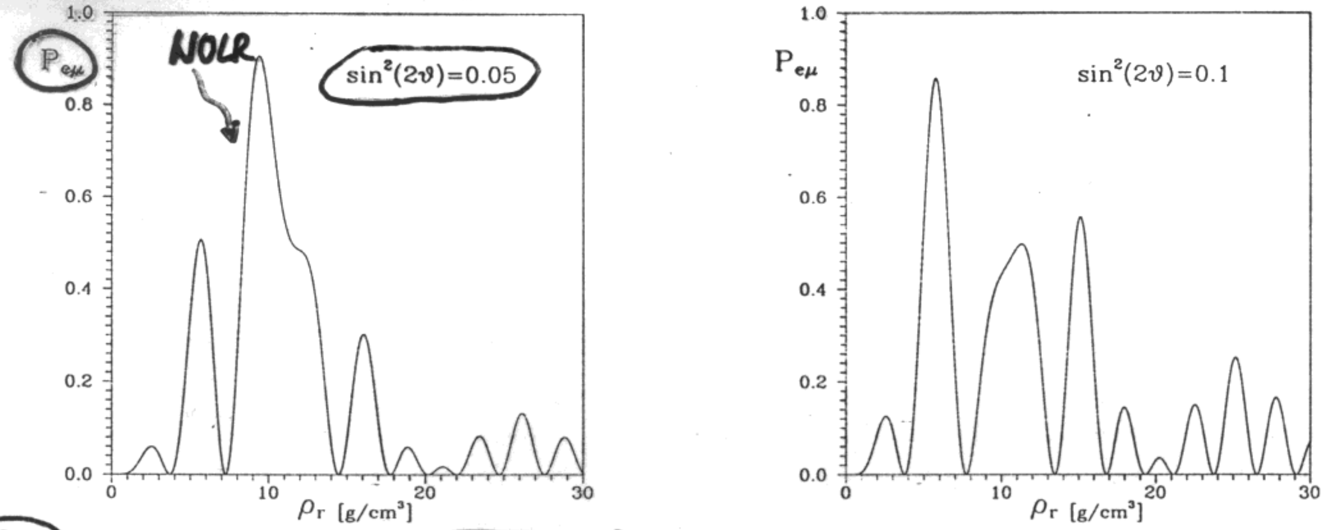
The same resonance is present in the

$$\nu_\mu \to \nu_e \,,\ \nu_e \to \nu_\mu$$

transitions of atmospheric neutrinos crossing the Earth core.

S.T.P., REPORT SISSA 31/98/EP
(hep-ph/9805262)
M. MARIS, S.T.P., M. TCHIJOV,
Report SISSA 53/98/EP
(to be released)

(M. MARIS, S.T.P., M. CHIZHOV '98)



$\Delta m^2_{atm} \cong$
$\cong 10^{-3} eV$ $\Big\{$ $E_{max} = 1.46$ GeV
$E_{sk} \cong 1.05$ GeV $\Big\}$ sub-GeV

sample of SK events

$\cong 5\times10^{-3} eV^2 \rightarrow$ $E_{max} \cong 7.3$ GeV $\}$ multi-GeV

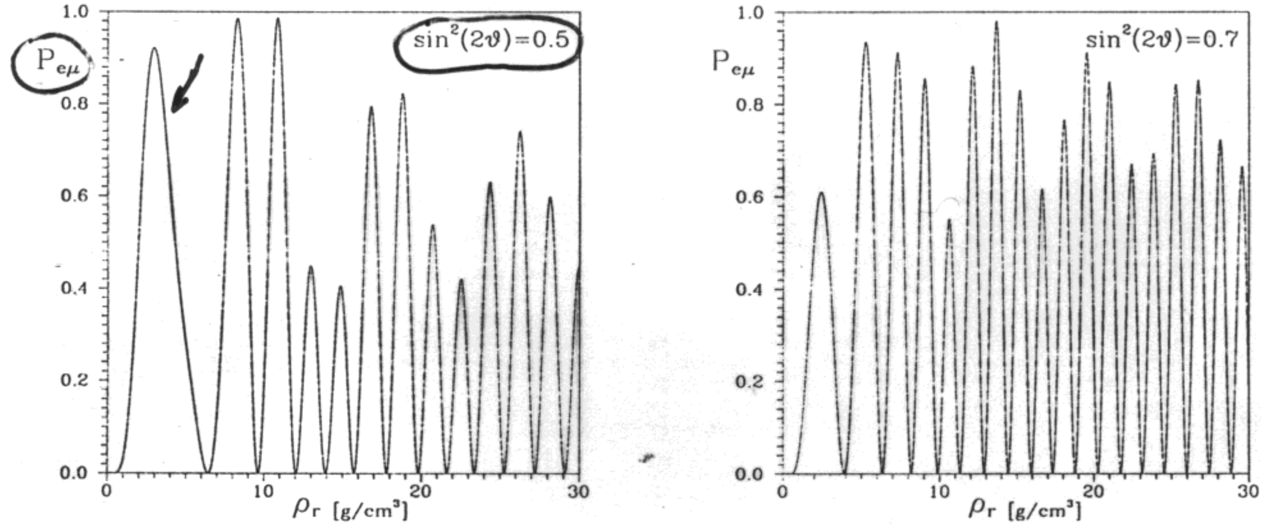


Figure 5a: h=0

ν_{ATM} : KAMIOKANDE, IMB, SOUDAN, SUPER-K

VERY STRONG EVIDENCES FOR $\overset{(-)}{\nu}_\mu$ - OSCILLATIONS FROM THE SK DATA ON

- Up - Down ASYMMETRY IN THE SUB-GeV AND MULTI-GeV SAMPLES OF μ-like EVENTS.
- ZENITH ANGLE DEPENDENCE OF THE RATES OF THE SUB-GeV AND MULTI-GeV μ-like EVENTS

NO SIMILAR EFFECTS WERE OBSERVED IN THE e-like SAMPLES OF EVENTS:

	$\nu_\mu \rightleftarrows \nu_\tau$ or	$\nu_\mu \rightleftarrows \nu_s$	DOMINATE!
$\Delta m^2 [eV^2]$	$10^{-3} - 8 \cdot 10^{-3}$	$2 \cdot 10^{-3} - 7 \cdot 10^{-3}$	90% C.L.
$\sin^2 2\theta$	$0.86 - 1.0$	$0.86 - 1.0$	

SK 736 days

L/E, PATH (i.e. ZENITH ANGLE) INDEPENDENT SUPPRESSION OF THE ATM. ν_μ - FLUX IS NOT COMPATIBLE WITH THE DATA.

Lipari, Lusignoli '99 : FCNC, ν - DECAY, GRAV. INDUCED OSCILLATIONS: DISFAVOURED

Let us assume 3-ν mixing:

$$|\nu_{lL}\rangle = \sum_{k=1}^{3} U^{*}_{lk} |\nu_{kL}\rangle, \quad \nu_k \text{ - Dirac or Majorana.}$$

$l = e, \mu, \tau$ $\qquad$ p, m_k

Two independent Δm^2: say, Δm^2_{21}, Δm^2_{31}

Assume further that:

(A) one Δm^2 - in the range of the MSW or VO solution of the $\nu_\odot$-problem

$$\Delta m^2 \lesssim 10^{-4}\ eV^2$$

(B) the second $\Delta m^2 \gtrsim 10^{-3}\ eV^2$

relevant to the ν_{ATM}-anomaly; (another option: LSND effect and Δm^2 can be in the range of reactor/accelerator ν-oscillation experiments...)

(?) (C) ν_k masses provide the "hot" DM component

$$\sum_{k=1}^{3} m_k \sim (4.5 - 6.0)\ eV$$

(~ 30% of DM)

S.T.P. '97

Assume, for example, that

- ν_{ATM} - ANOMALY DUE TO $\overset{(-)}{\nu}_\mu \rightleftarrows \overset{(-)}{\nu}_\tau$ $\quad \Delta m^2_{31} \gtrsim 10^{-3}\,\mathrm{eV}$
- $\nu_\odot$ - PROBLEM DUE TO $\nu_e \to \nu_{\mu,\tau}$ $\quad \Delta m^2_{21} \lesssim 10^{-4}\,\mathrm{eV}$

$m_1 \ll m_2 \ll m_3$; $m_1 \cong m_2 \ll m_3$; $m_1 < m_2 < m_3$,

$(m_1 \ll m_2 \cong m_3)$ $\quad m_1 \cong m_2 \cong m_3$

- the same ν - oscillation phenomenology

De Rujula et al., '80
Barger et al., '8
Bilenky et al., '9

$$P_{ATM}(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\tau) \cong 2|U_{\mu 3}|^2 |U_{\tau 3}|^2 \left[1 - \cos\frac{\Delta m^2_{31}}{2E} R\right]$$

$$P^{VAC}_{ATM}(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \cong 2|U_{\mu 3}|^2 |U_{e 3}|^2 \left[1 - \cos\frac{\Delta m^2_{31}}{2E} R\right]$$

$$\bar{P}_\odot(\nu_e \to \nu_e) = |U_{e3}|^4 + (1 - |U_{e3}|^2)^2 \, \bar{P}^{(2\nu)}_\odot(\nu_e \to \nu_e)$$

C.S. Lim '87
S.T.P. '88,
Smirnov, '

- MSW or VO solution of the $\nu_\odot$ - problem:

$|U_{e3}|^2 \lesssim \underset{0.05}{0.1}$, compatible with the CHOOZ result.

- $P^{(2\nu)}_\odot(\nu_e \to \nu_e)$: Δm^2_{21}, $\sin^2 2\theta_{12} \equiv 4\dfrac{|U_{e1}|^2 |U_{e2}|^2}{(|U_{e1}|^2 + |U_{e2}|^2)^2}$

$$\cos 2\theta_{12} \equiv \frac{|U_{e1}|^2 - |U_{e2}|^2}{|U_{e1}|^2 + |U_{e2}|^2}$$

More specifically, for $\Delta m^2_{21} \ll \Delta m^2_{31}$

$\nu_\odot$

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

ν_{ATM}

- "weak" connection via U_{e3}.
- CHOOZ + $\nu_\odot$: $|U_{e3}|^2 \lesssim 0.05$, $|U_{e3}| \lesssim 0.22$

  $(\Delta m^2_{31} \gtrsim 2 \cdot 10^{-3}\, eV^2)$

Fogli, Lisi et al.'9[illegible]
Yasuda '98
Barger et al., '9[illegible]
Bilenky, Giunti, Grimus '9[illegible]

- Perhaps, $|U_{e3}| \ll 1$:

  "very small"

LBLine: ICARUS, MINOS, K2K

$\nu_\mu \to \nu_e$ - high sensitivity to $|U_{e3}|$ (limit: $\sim 5 \cdot 10^{-2}$)

$$P_{LBL}(\nu_\mu \to \nu_e) \cong \frac{|U_{\mu 3}|^2}{1-|U_{e3}|^2} P^m_{2\nu}(\Delta m^2_{31}, \theta_{13})$$

$$\sin^2 2\theta_{13} = 4|U_{e3}|^2 (1-|U_{e3}|^2)$$

$$P^m_{2\nu}(\Delta m^2_{31}, \theta_{13}) = \frac{1}{2}\sin^2 2\theta^m_{13}\left[1-\cos \Delta E X\right]$$

$$\Delta E = \frac{\Delta m^2_{31}}{2E}\sqrt{\left(1-\frac{N_e}{N_e^{res}}\right)^2 \cos^2 2\theta_{13} + \sin^2 2\theta_{13}}$$

Interesting physics related to $|U_{e3}|$:

$|U_{e3}|$ drives the sub-dominant

$\nu_\mu \rightleftarrows \nu_e$, $\bar{\nu}_e \rightleftarrows \bar{\nu}_\tau$, $\bar{\nu}_e \rightleftarrows \bar{\nu}_\mu$

oscillations

of the atmospheric ν_μ, ν_e

which can be strongly enhanced by a new type of resonance ($\neq$ MSW) in the Earth

$$P^{VAC}_{ATM}(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \cong P^{VAC}_{ATM}(\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_{\mu(\tau)}) \sim |U_{e3}|^2 \text{ - suppressed!}$$

Consider $\nu_\mu \to \nu_e$ and $\nu_e \to \nu_{\mu,\tau}$ in the Earth: assume $\Delta m^2_{21} \ll \Delta m^2_{31}$

Then

S.T.P. '88

$$P^{3\nu}_E(\nu_\mu \to \nu_e) \cong P^{3\nu}_E(\nu_e \to \nu_\mu) \cong \frac{|U_{\mu 3}|^2}{1-|U_{e3}|^2} P^{2\nu}_E(\nu_e \to \nu'_\tau)$$

$$P^{3\nu}_E(\nu_e \to \nu_\tau) \cong \frac{|U_{\tau 3}|^2}{1-|U_{e3}|^2} \cdot \underbrace{P^{2\nu}_E(\nu_e \to \nu'_\tau)}_{\substack{\sin^2 2\theta = 4|U_{e3}|^2(1-|U_{e3}|^2) \\ \Delta m^2 = \Delta m^2_{31}}}$$

enhanced by NOLR

Consider transitions of ν's crossing the Earth core:

$$-1 \leq \cos\theta_z \lesssim -0.8$$

S.T.P. '98; CHIZHOV, MARIS, STP

E_ν - fixed:

$$\Phi(\nu_e) = \Phi^0(\nu_e)\left[1 + \left(r\frac{|U_{\mu 3}|^2}{1-|U_{e3}|^2} - 1\right)P^{2\nu}_E(\nu_e \to \nu'_\tau)\right]$$

$r s^2_{23}$

$$r \equiv \frac{\Phi^0(\nu_\mu)}{\Phi^0(\nu_e)} = \begin{cases} 2.0 - 2.5, & \text{sub-GeV} \\ 3.5 - 4.0 \ (4.5), & \text{multi-GeV} \end{cases}$$

$$\Phi(\nu_e) \cong \Phi^0(\nu_e)\left[1 + \left\{\begin{matrix} 0.0 - 0.25 \\ -(0.60) \\ 0.75 - 1.0 \end{matrix}\right\} P_E^{2\nu}(\nu_e \to \nu_\tau)\right]$$

sub-GeV

multi-GeV

If, for example

$|U_{e3}|^2 \cong 0.013$, $\sin^2 2\theta \cong 0.05$,

$\underline{\max}\ P_E^{2\nu}(\nu_e \to \nu_\tau) \cong 0.94$

$\underline{\text{at } 1/2\text{-width}}$ $\cong 0.45$

<u>e-like</u>

<u>sub-GeV</u> : $\underline{\lesssim 10\%}$ excess - small

<u>multi-GeV:</u> $< (30-40)\%$ excess - can be relatively large!

If the predictions for $\Phi^0(\nu_e)$ and $\Phi^0(\nu_\mu)$ are correct, the NOL resonance can produce sizeable excess of e-like events in the multi-GeV sample of SK data, provided $\Delta m^2_{31} \gtrsim (2-3) \times 10^{-3}\ eV^2$.

If an excess due to NOL resonance is observed in the sub-GeV sample of e-like events, then $\tau \gtrsim 3$, $\Delta m^2_{31} \lesssim 2 \cdot 10^{-3}\ eV^2$.

Similar analysis for $\Phi(\nu_\mu)$:

$$\Phi(\nu_\mu) \cong \Phi^0(\nu_\mu)\left[1 + s_{23}^4\left((s_{23}^2 r)^{-1} - 1\right)P_E^{2\nu} - 2c_{23}^2 s_{23}^2\left(1 - \mathrm{Re}\left(e^{-i\varkappa}A^{2\nu}\right)\right)\right]$$

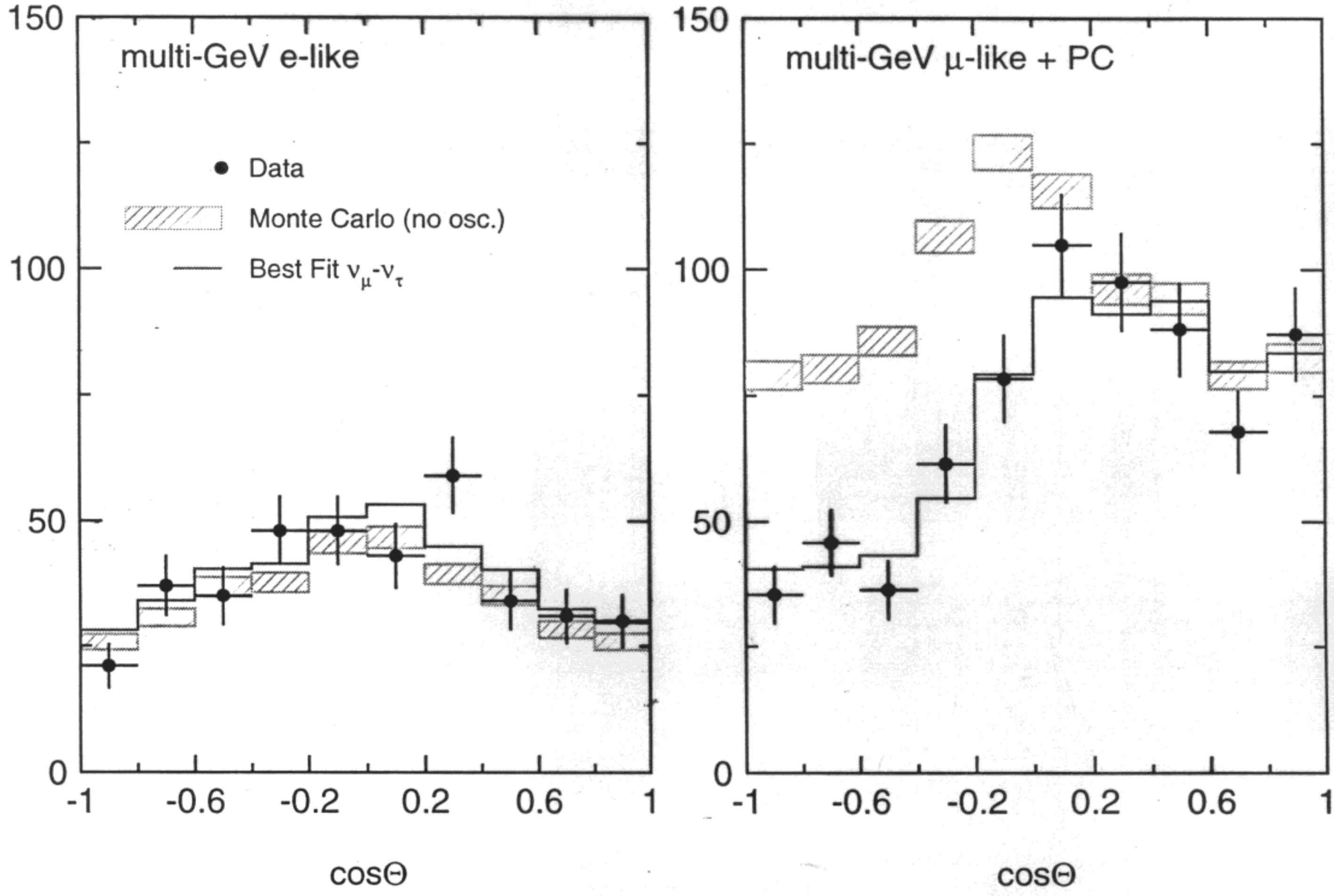
$$s_{23}^2 \equiv |U_{\mu 3}|^2/(1-|U_{e3}|^2),\quad c_{23}^2 = 1 - s_{23}^2$$

$\varkappa$, $A^{2\nu}$ - known

$$0.25 \leq s_{23}^4 \lesssim 0.5$$

$$s_{23}^4\left[\frac{1}{s_{23}^2 r} - 1\right] = \begin{cases} 0.0 \text{ to } (-0.22), & \text{sub-GeV} \\ s_{23}^2 = 0.5;\ 0.7 & \\ (-0.1) \text{ to } (-0.39), & \text{multi-GeV} \end{cases}$$

Thus, if the predictions for $\Phi^0(\nu_\mu; E, \theta_z)$ and $\Phi^0(\nu_e; E, \theta_z)$ are correct, the NOLR can contribute to the θ_z-dependence of the μ-like multi-GeV signal for $s_{23}^2 \cong 0.6-0.7$, and $\Delta m_{31}^2 \gtrsim (2-3)\cdot 10^{-3}$ eV^2



multi-GeV e-like
Data
Monte Carlo (no osc.)
Best Fit ν_μ-ν_τ
multi-GeV μ-like + PC
150
100
50
0
-1
-0.6
-0.2
0.2
0.6
1
cosΘ
cosΘ

THE NATURE OF THE NOLR:

$$A_E(\nu_\mu \to \nu_e) = A^{man}(\nu_\mu \to \nu_e)\, A^{core}(\nu_e \to \nu_e)\, A^{man}(\nu_e \to \nu_e)$$
$$+ A^{man}(\nu_\mu \to \nu_\mu)\, A^{core}(\nu_\mu \to \nu_\mu)\, A^{man}(\nu_\mu \to \nu_e)$$
$$+ A^{man}(\nu_\mu \to \nu_\mu)\, A^{core}(\nu_\mu \to \nu_e)\, A^{man}(\nu_e \to \nu_e)$$
$$+ A^{man}(\nu_\mu \to \nu_e)\, A^{core}(\nu_e \to \nu_\mu)\, A^{man}(\nu_\mu \to \nu_e)$$

CHIZHOV, S.T.P. '98

MSW: terms in $P(\nu_\mu \to \nu_e)$

$$\sim |A^{man}(\nu_\mu \to \nu_e)|^2, \quad \rho^{res} \sim \bar{\rho}^{man}$$

or

$$\sim |A^{core}(\nu_\mu \to \nu_e)|^2, \quad \rho^{res} \sim \bar{\rho}^{core}$$

dominate!

NOLR: $\sim 2\,\mathrm{Re}\left[A^{man}(\nu_\mu \to \nu_e)\,(A^{core}(\nu_\mu \to \nu_e))^* \ldots\right]$

dominates!

NOLR: constructive interference effect

$$\bar{\rho}^{man} < \rho^{res} < \bar{\rho}^{core}$$

S.T.P., PL B434

CHIZHOV, S.T.P. '98

$$\boxed{(A) + (B) \equiv \cos(2\Theta_m'' - 4\Theta_m' + \Theta) < 0}$$

The "maximum" (supplementary) conditions are satisfied for

$\sin^2 2\Theta \lesssim 0.05$ $\quad \bar{\rho}_m < \rho^{res} < \bar{\rho}_c$ $\quad$ SMA

$\rho^{res} < \bar{\rho}_m$ $\quad$ LMA

MSW solutions

$$\boxed{\Delta E'^{('')} = \frac{\Delta m^2}{2E}\left[\left(1 - \frac{\bar{\rho}_{m(c)}}{\rho^{res}_{m(c)}}\right)^2 \cos^2 2\Theta + \sin^2 2\Theta\right]^{1/2}}$$

$\Delta E' X' = \pi(2k+1)$, $\quad \Delta E'' X'' = \pi(2k'+1)$, $\quad \Delta E'^{('')} = \frac{2\pi}{L_{osc}^{man(c)}}$

$k = k' = 0$ $\qquad \sin^2 2\Theta \lesssim 0.02$

$$\boxed{\pi\left\{\frac{1}{X'} + \frac{1}{X''}\right\} \cong \sqrt{2}\, G_F \,(\underbrace{\bar{\rho}_c Y_e^c}_{\bar{N}_e^c} - \underbrace{\bar{\rho}_m Y_e^m}_{\bar{N}_e^m})}$$

For a given trajectory X' and X'' are fixed: the resonance conditions are constraints on L_{osc}^{man}, L_{osc}^{c}

The NOLR can be observed in the present and/or future $\nu_\odot$ and/or ν_{atm} experiments. Detectors located at lower geographical latitudes are better suited for that.

A NEW ATMOSPHERIC NEUTRINO EXPERIMENT WITH BETTER E- AND Θ_Z-RESOLUTION IS HIGHLY DESIRABLE.

Ermilova et al., 1986 :

$$\rho(\tau) = \overset{\text{const.}}{\bar{\rho}} + \rho_1 \cos\omega\tau , \quad \tau = \pi x / l_\nu$$

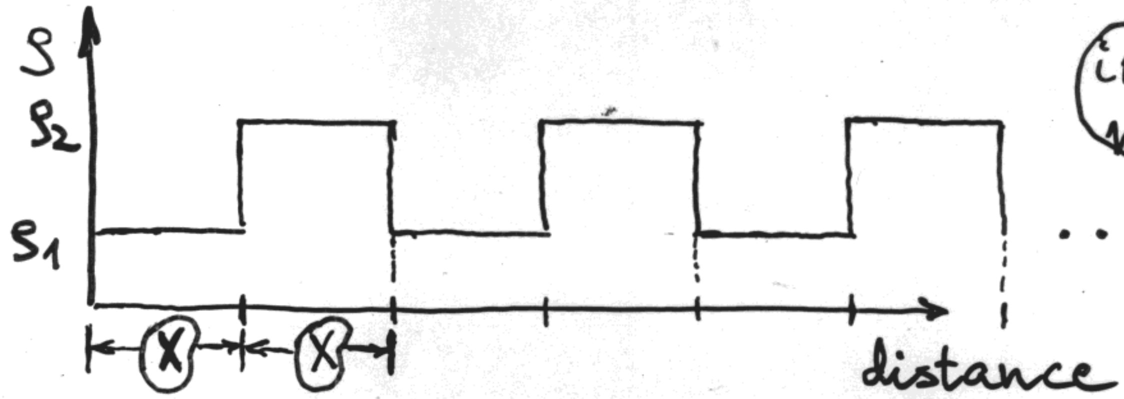
"... periodic dependence of ρ on the distance along the ν path."

True parametric resonance:

$$\bar{\omega} = \frac{n}{2}\omega , \quad \bar{\omega} = \cos 2\theta - \frac{l_\nu}{\bar{l}_0} = \cos 2\theta \left(1 - \frac{\bar{N}_e}{N_e^{res}}\right)$$

Akhmedov, '88 : the case considered by Ermilova et al. +

"periodic step function" (1 page)



...

interger number of periods

Looked for parametric resonance: specific case

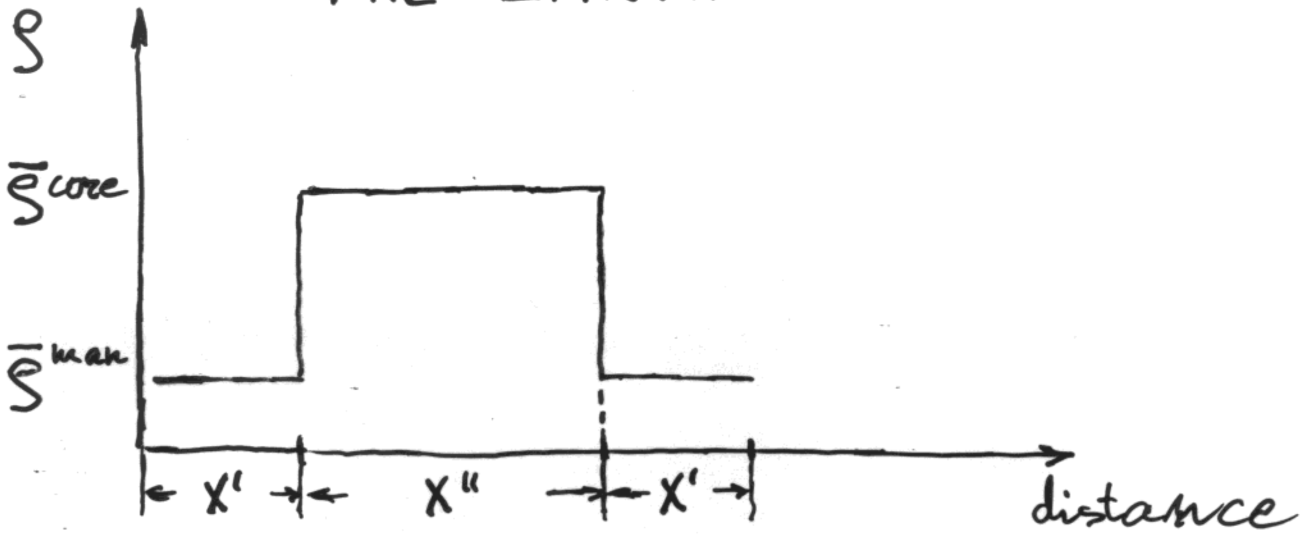
$\sin^2 2\theta \ll 1$

$\rho_{1,2} \ll \rho_{res}$

no MSW resonance!

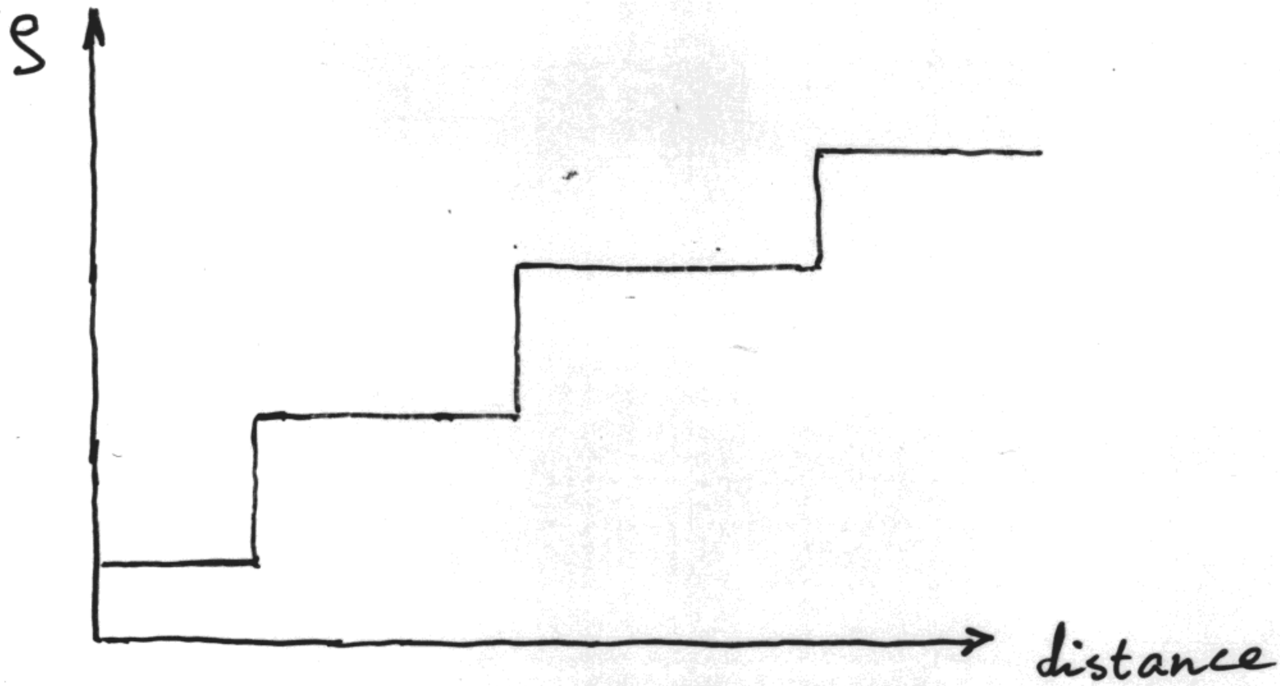
The Earth does not "look" like that!

THE EARTH



Not even 1+ ½ periods.

THE NOLR possible even if, e.g.,



Liu + Smirnov '98

(Liu + Mikheyev + Smirnov '98):

$\bar{\nu}_\mu \to \bar{\nu}_s$

$\sin^2 2\theta \cong 1.0$

$\Delta m^2 / 2E << V_{\bar{\mu}\bar{s}} = \sqrt{2} \cancel{G_F} \frac{1}{2} \bar{N}_n$

$h \cong 28^\circ$

$P(\bar{\nu}_\mu \to \bar{\nu}_s) \cong 1$

$X' V_{\bar{\mu}\bar{s}}^{man} \cong \pi$

$X'' V_{\bar{\mu}\bar{s}}^{core} \simeq \pi$

The authors claimed:

- No similar effect in $\nu_{\mu(e)} \to \nu_{e(\mu)}$