# ENHANSING MECHANISMS OF NEUTRINO TRANSITIONS IN THE EARTH AND ATMOSPHERIC NEUTRINO OSCILLATIONS

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2002 WAS EXCEPTIONAL FOR THE STUDIES OF $\nu$'S:

- SNO : NC DATA $\Rightarrow \overset{(-)}{\nu}_{\mu,\tau}$ IN $\Phi(\nu_\odot)$
- KAMLAND:
  - FIRST EVIDENCE FOR $\nu$-OSCILLATIONS IN AN EXPERIMENT WITH "TERRESTRIAL" $\nu$'S
  - EVIDENCE FOR $\nu$-MIXING IN VACUUM
  - $\nu_\odot$ : LMA SOLUTION (CPT)
  - KAMLAND "MASSACRE": SMA, LOW, QVO, VO, RSFP, FCNC, ...
  - DETERMINES THE PRIORITIES OF THE FUTURE RESEARCH
- SK IS OPERATIONAL AGAIN
- MINIBOONE STARTED
- THE ACHIEVEMENTS IN THE FIELD ($\nu_\odot$ - ASTRONOMY, SN $\nu$'S DETECTION) AND THE FUNDAMENTAL CONTRIBUTIONS MADE BY R. DAVIS AND M. KOSHIBA HONORED BY THE NOBEL PRIZE FOR PHYSICS.

EVIDENCES FOR $\nu$- OSCILLATIONS:

- $\nu_{ATM}$ : SK UP - DOWN ASYMMETRY (ZENITH ANGLE DEPENDENCE) MULTI-GeV $\mu$-LIKE SAMPLE

  DOMINANT $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\tau$

  K2K; MINOS, CNGS.

- $\nu_\odot$ : HOMESTAKE, KAMIOKANDE, SAGE, GALLEX/GNO, SUPER-KAMIOKANDE, SNO

  DOMINANT $\nu_e \rightarrow \nu_{\mu,\tau}$

  KamLAND; BOREXINO, ...

- LSND

  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ MiniBOONE

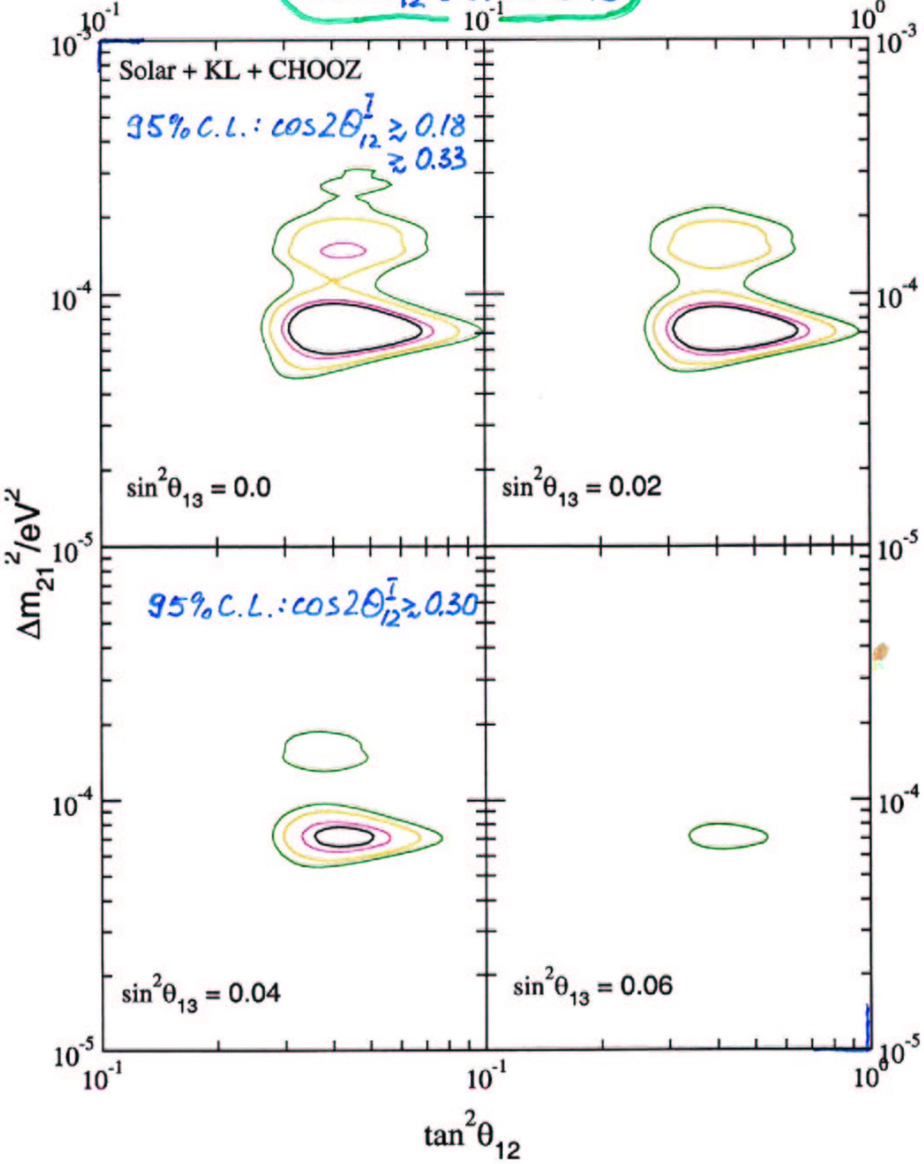
$$\nu_{\ell L} = \sum_{j=1} U_{\ell j}\, \nu_{jL}, \quad \ell = e, \mu, \tau$$

$\nu$- FACTORIES : 3-$\nu$ MIXING, LMA MSW

L ~ (3000 - 7000) km.

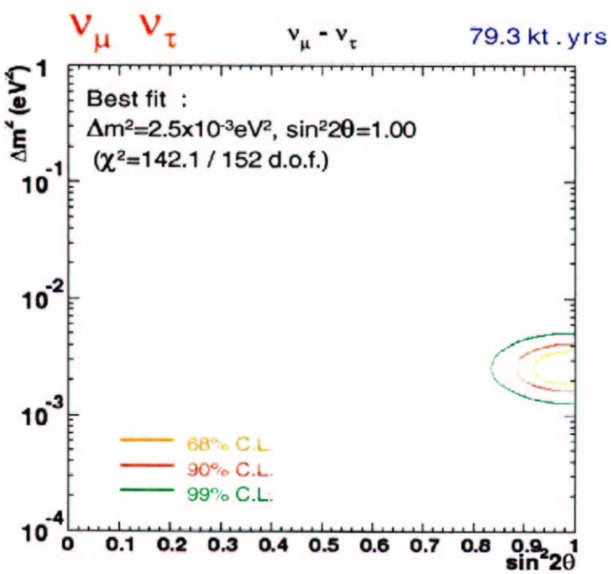
BEST FIT: $\Delta m^2_{21} \simeq 7 \cdot 10^{-5}\, eV^2$, $\tan^2\theta_{12} \cong 0.42 - 0.45$

S. CHOUBEY ET AL.



Allowed region

(FC + PC + UP-thru + UP-stop)




SK combined result

$\Delta m^2 = (1.7 \sim 4) \times 10^{-3} eV^2$

$\sin^2 2\theta > 0.89$ (90% C.L.)

SIGN$(\Delta m^2)$ - UNDETERMINED

3-ν MIXING : $m_1 < m_2 < m_3$ - NH

CHOOZ : $\bar{\nu}_e \to \bar{\nu}_e$

~ 1 km

$\bar{E}_\nu \sim 2$ MeV

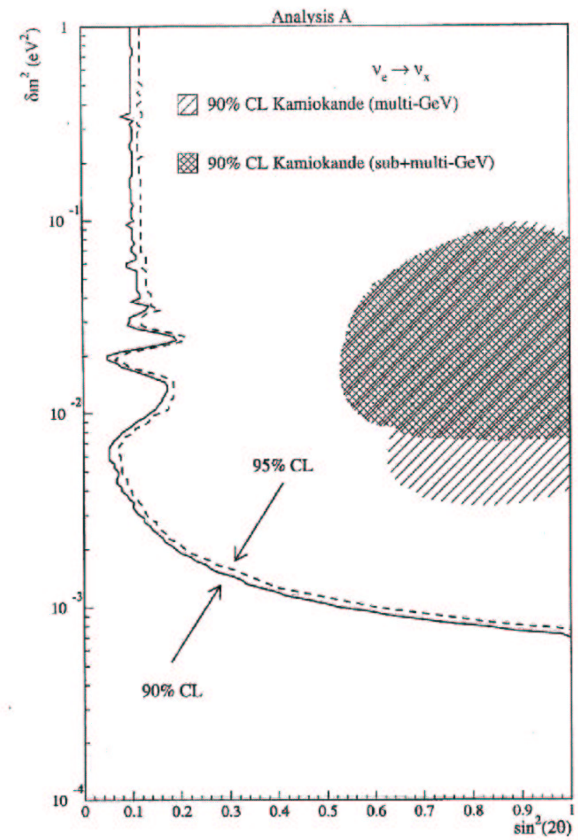



Figure 9: Exclusion plot for the oscillation parameters based on the absolute comparison of measured vs. expected positron yields.

16

## 3-$\nu$ MIXING:

$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix}$$

$U_{PMNS}$

**PARAMETERS:** $U_{PMNS}$ – $n \times n$

| | | $n$ | 2 | 3 | 4 |
|---|---|---|---|---|---|
| ANGLES | | $\frac{n(n-1)}{2}$ | 1 | 3 | 6 |
| CP-VIOLATING PHASES: | $\nu_j$ – DIRAC | $\frac{(n-1)(n-2)}{2}$ | 0 | 1 | 3 |
| | $\nu_j$ – MAJORANA | $\frac{n(n-1)}{2}$ | 1 | 3 | 6 |

BILENKY, HOSEK, PETCOV '80; DOI ET AL., '81.

## STANDARD PARAMETRIZATION:

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13}e^{i\alpha_{21}/2} & U_{e3}\,e^{i(\frac{\alpha_{31}}{2}+\delta)} \\ -s_{12}c_{23}-c_{12}s_{23}U_{e3}^{*} & (c_{12}c_{23}-s_{12}s_{23}U_{e3}^{*})e^{\frac{i\alpha_{21}}{2}} & s_{23}c_{13}e^{i(\alpha_{31}/2+\delta)} \\ s_{12}s_{23}-c_{12}c_{23}U_{e3}^{*} & (-c_{12}s_{23}-s_{12}c_{23}U_{e3}^{*})e^{\frac{i\alpha_{21}}{2}} & c_{23}c_{13}e^{i(\alpha_{31}/2+\delta)} \end{pmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$. $0 \le \theta_{12}, \theta_{13}, \theta_{23} \le \pi/2$

$U_{e3} = s_{13} e^{-i\delta}$, $\delta \in [0, 2\pi]$ – DIRAC CP-VIOLATING PHASE

$\alpha_{21}, \alpha_{31}$ – MAJORANA CP-VIOLATING PHASES

IF $\nu_j$ ARE MAJORANA PARTICLES, CP-SYMMETRY CAN BE VIOLATED EVEN IN THE CASE OF $n = 2$ FAMILIES OF LEPTONS: (S.M. BILENKY, J. HOSEK, S.T.P. '80)

$$n^{M}_{CP} = \frac{n(n+1)}{2} - n = \frac{n(n-1)}{2}$$

$\alpha_{21}, \alpha_{31}$: DO NOT APPEAR IN $P(\overset{(-)}{\nu}_{\ell} \rightarrow \overset{(-)}{\nu}_{\ell'})$

- AFFECT THE $(\beta\beta)_{0\nu}$-DECAY RATE
- IN SUSY SEE-SAW MODELS, THE RATES OF THE LFV DECAYS.

$\nu_\odot$, $\nu_{ATM}$, CHOOZ DATA:

$$\theta_\odot = \theta_{12} \cong \pi/6, \quad \theta_{ATM} = \theta_{23} \cong \pi/4, \quad \theta_{CHOOZ} \equiv \theta = \theta_{13} < \frac{\pi}{12} \div \frac{\pi}{15}$$

$$U_{PMNS} \cong \begin{pmatrix} \cong \frac{1}{2} & \cong \frac{\sqrt{3}}{2} & \varepsilon \\ U_{\mu 1} & U_{\mu 2} & \cong \frac{1}{\sqrt{2}} \\ U_{\tau 1} & U_{\tau 2} & \cong \frac{1}{\sqrt{2}} \end{pmatrix}$$

"PARAMETERS":

$\theta_{12}, \theta_{13}, \theta_{23}$

$\nu_j$: DIRAC — $\delta$; MAJORANA — $\delta, \alpha_{21}, \alpha_{31}$

$m_1, m_2, m_3$

$m_{1,2,3}$: MEASURED IN $\nu$-OSCILLATION EXPERIMENTS

$$\Delta m^2_\odot = \Delta m^2_{21} > 0, \quad |\Delta m^2_{ATM}| = |\Delta m^2_{31}|$$

(A) $m_1 < m_2 < m_3$ OR $m_3 < m_1 < m_2$

(B) $m_1 < m_2 < m_3$:

$$m_1, m_2, m_3 \Rightarrow m_1, \Delta m^2_{21} > 0, \Delta m^2_{32} > 0$$

$$m_2 = \sqrt{m_1^2 + \Delta m^2_{21}}$$

$$m_3 = \sqrt{m_1^2 + \Delta m^2_{21} + \Delta m^2_{32}}$$

$$\Delta m^2_{ATM} = \Delta m^2_{31} = \Delta m^2_{21} + \Delta m^2_{32}$$

TWO POSSIBILITIES:

$$\left.\begin{array}{l} \Delta m^2_\odot = \Delta m^2_{21} - NH \\ \Delta m^2_\odot = \Delta m^2_{32} - IH \end{array}\right\} - \text{"DISCRETE" PARAMETER}$$

THE MAIN PROBLEMS IN THE STUDIES OF $\nu$-MIXING:

- DETERMINATION OF $\Delta m^2_{\odot}$, $\theta_{\odot}$, $\Delta m^2_{atm}$, $\theta_{atm}$ WITH A HIGH PRECISION
- MEASURE, OR IMPROVE BY AT LEAST A FACTOR OF ~10 THE EXISTING LIMITS ON, $|U_{e3}|^2 = \sin^2\theta_{13}$
- DETERMINE THE TYPE OF $\nu$-MASS SPECTRUM

  $m_1 << m_2 << m_3$, NH

  $m_1 << m_2 \cong m_3$, IH

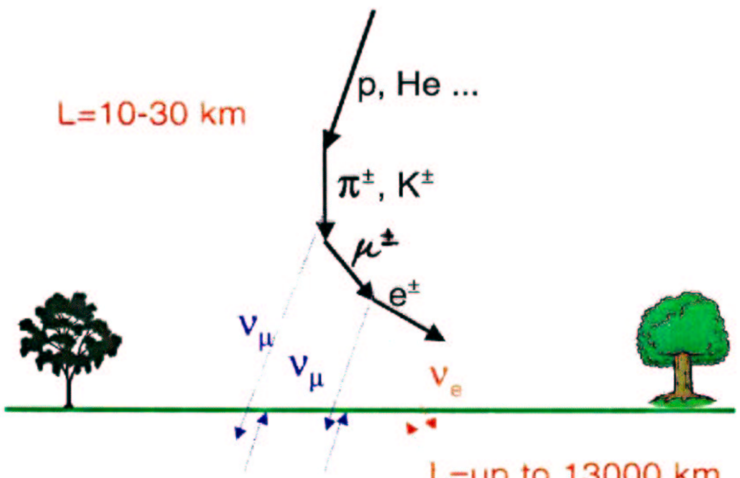
  $m_1 \cong m_2 \cong m_3$, $m_j^2 >> \Delta m^2_{atm}$, QD
- DETERMINE, OR OBTAIN CONSTRAINTS ON, THE ABSOLUTE $\nu$-MASS SCALE (LIGHTEST $\nu$ MASS)
- DETERMINE THE NATURE OF $\nu_j$ (DIRAC VS MAJORANA)
- ESTABLISH WHETHER CP-SYMMETRY IS VIOLATED IN THE LEPTON SECTOR
  1. DUE TO THE DIRAC PHASE, $\delta$,
  2. DUE TO THE MAJORANA PHASES $\alpha_{21}$, $\alpha_{31}$, IF $\nu_j$ - MAJORANA
- FIND A THEORY WHICH EXPLAINS THE DATA (THE THEORY)

FURTHER STUDIES OF $\nu_A$-OSCILLATIONS BY SK (OR OTHER WATER-Č DETECTOR) CAN PRODUCE INFORMATION ON

- $\sin^2\theta_{13}$
- $\sin^2 2\theta_{23}$ ($\sin^2 2\theta_{23} \neq 1$, $\cos 2\theta_{23} > 0$ or $\cos 2\theta_{23} < 0$)
- SIGN OF $\Delta m^2_{31}$, i.e., TYPE OF THE NEUTRINO MASS SPECTRUM NH vs IH

Y. TOTSUKA, SK

## Atmospheric neutrinos




$$\frac{\nu_\mu+\overline{\nu_\mu}}{\nu_e+\overline{\nu_e}} = \sim 2$$ @ low energy ($E_\nu < 1$ GeV)

$$\frac{\nu_\mu+\overline{\nu_\mu}}{\nu_e+\overline{\nu_e}} \nearrow$$ @ high energy

Error in absolute flux~20%, but $\nu_\mu/\nu_e$ ratio~5%

Neutrino oscillations :

$$\Rightarrow \left(\frac{\nu_\mu+\overline{\nu_\mu}}{\nu_e+\overline{\nu_e}}\right)_{\text{data}} \Big/ \left(\frac{\nu_\mu+\overline{\nu_\mu}}{\nu_e+\overline{\nu_e}}\right)_{\text{MC}} < 1$$

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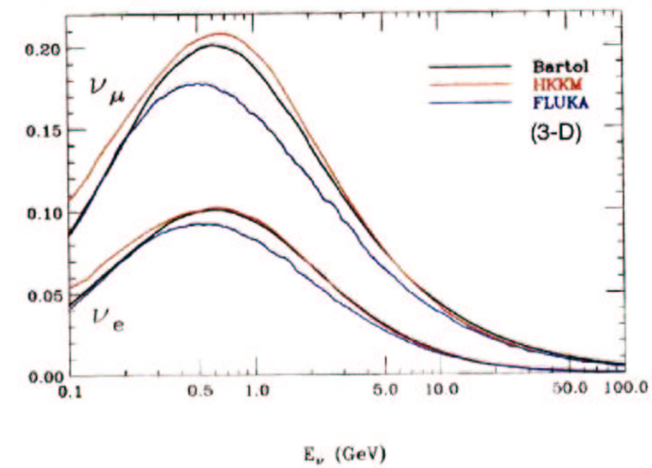
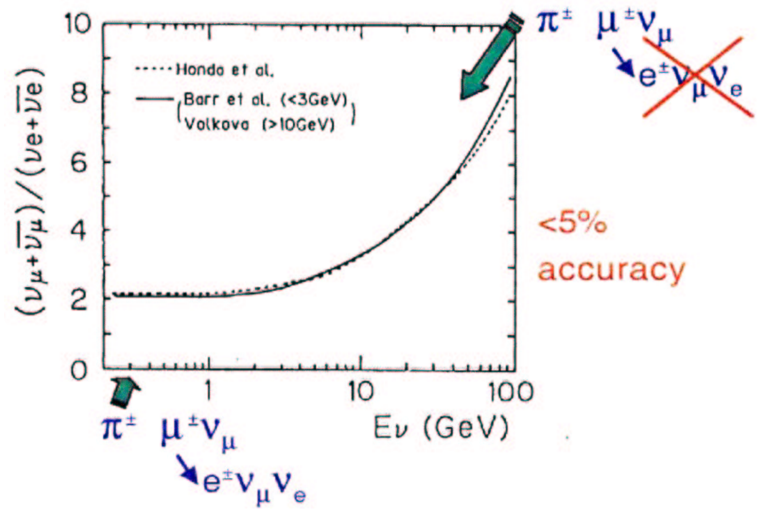
## Atmospheric neutrino spectrum

MODEL dependence of ENERGY spectrum (P.Lipari)



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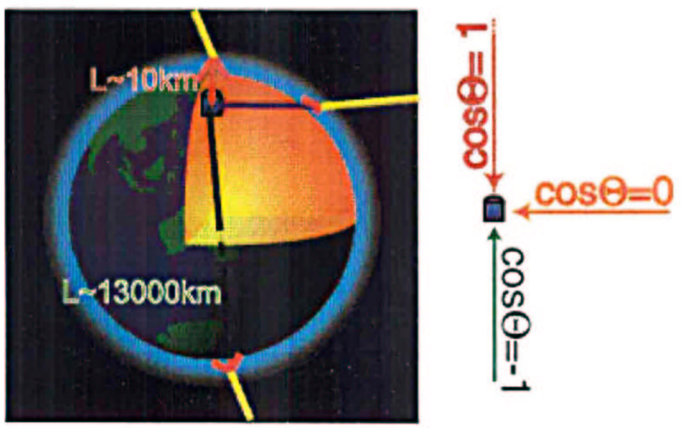
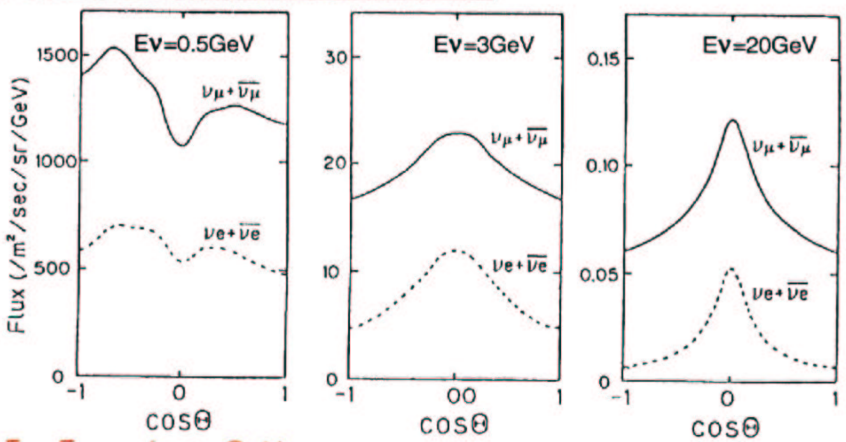
## Zenith angle distribution(1D)




Calculated zenith angle distribution




For $E_\nu$ > a few GeV.

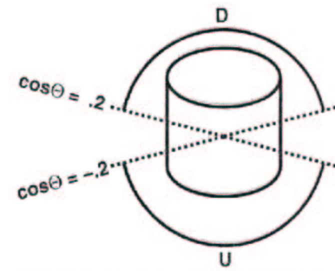
Upward / downward = 1 (within a few %)

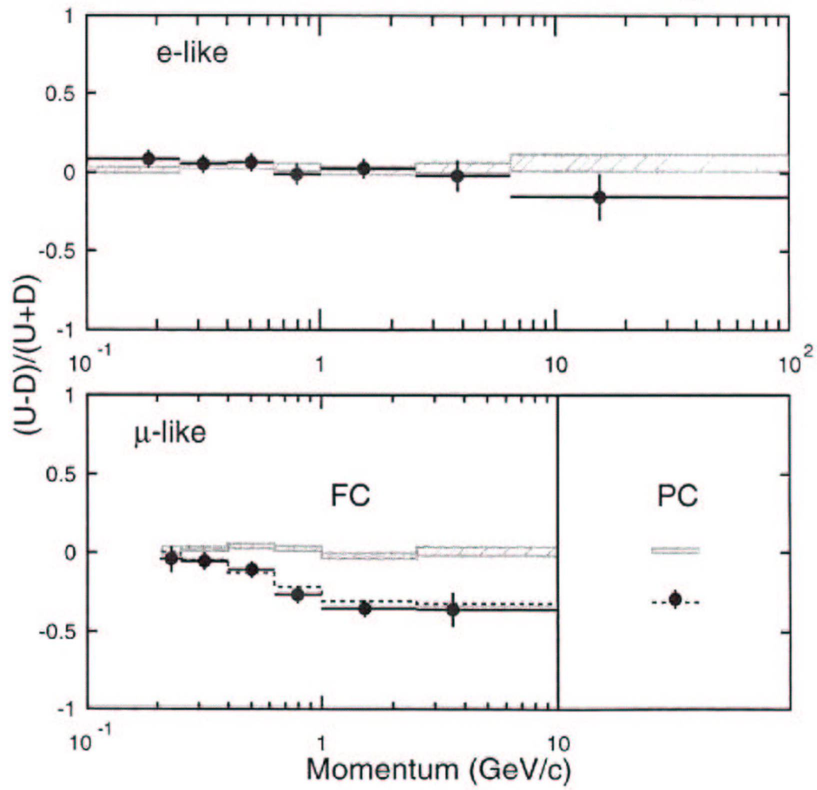
Up/Down asymmetry for neutrino oscillations

SK : MESSIER et al., '99

## Zenith Angle Asymmetry

$$A = (U-D)/(U+D)$$




$$A_{\text{multi-GeV}\,\mu} = -0.311 \pm 0.043 \pm 0.01 > 7\sigma \text{ from } 0$$

- 3-$\nu$ OSCILLATIONS OF $\nu_A$:

$$\Delta m^2_{21} \equiv \Delta m^2_{\odot} << \Delta m^2_A \equiv \Delta m^2_{31}$$

$$P_{3\nu}(\nu_e \to \nu_\mu) = P_{3\nu}(\nu_\mu \to \nu_e) \cong s^2_{23}\, P_{2\nu}(\Delta m^2_{31}, \theta_{13}; E, \theta_n)$$

$$P_{3\nu}(\nu_e \to \nu_\tau) = P_{3\nu}(\nu_\tau \to \nu_e) \cong c^2_{23}\, P_{2\nu}(\ldots\ldots)$$

$$P_{3\nu}(\nu_e \to \nu_e) = 1 - P_{2\nu}(\ldots\ldots)$$

$$P_{3\nu}(\nu_\mu \to \nu_\mu) \cong 1 - s^4_{23} P_{2\nu} - 2c^2_{23} s^2_{23}\left[1 - Re\left(e^{-i\varkappa} A_{2\nu}(\nu_\tau \to \nu_\tau)\right)\right]$$

$$P_{3\nu}(\nu_\mu \to \nu_\tau) = 1 - P_{3\nu}(\nu_\mu \to \nu_\mu) - P_{3\nu}(\nu_\mu \to \nu_e)$$

- $P_{2\nu}(\Delta m^2_{31}, \theta_{13}; E, \theta_n)$ - 2-$\nu$ OSCILLATION PROBABILITY

$$P_{2\nu} = P_{2\nu}(\nu_e \to \nu'_\tau),\quad \nu'_\tau = s_{23}\nu_\mu + c_{23}\nu_\tau$$

- $\varkappa$, $A_{2\nu}(\nu_\tau \to \nu_\tau)$ - KNOWN

- SIMILAR FOR ANTI-$\nu$'S:

$$P_{2\nu} \to \bar{P}_{2\nu},\quad \varkappa \to \bar{\varkappa},\quad A_{2\nu} \to \bar{A}_{2\nu}$$

- $\Phi_{\nu_e}(E, \theta_n)$, $\Phi_{\nu_\mu}(E, \theta_n)$:

$$\Phi_{\nu_e} \cong \Phi^0_{\nu_e}\left[1 + \left(s^2_{23}\,r(E, \theta_n) - 1\right) P_{2\nu}\right]$$

$$\Phi_{\nu_\mu} \cong \Phi^0_{\nu_\mu}\left[1 + s^4_{23}\left(\frac{1}{s^2_{23}\, r} - 1\right) P_{2\nu} - 2c^2_{23} s^2_{23}\left(1 - Re\left(e^{-i\varkappa} A_{2\nu}\right)\right)\right]$$

$\Phi^0_{\nu_e, \nu_\mu}(E, \theta_n)$

$$r \equiv \frac{\Phi^0_{\nu_\mu}(E, \theta_n)}{\Phi^0_{\nu_e}(E, \theta_n)}$$

- $\cos\theta_n \sim (0.40 - 1.0)$:

- SUB-GeV: $r \cong 2.0$

$$(s^2_{23} r - 1) \cong \begin{cases} 0, & s^2_{23} = 0.5 \\ 0.28, & s^2_{23} = 0.64 \end{cases}$$

- MULTI-GeV: $r \cong (2.6 - 4.5)$

$$(s^2_{23} r - 1) \cong \begin{cases} 0.3, & r = 2.6 \\ 1.25, & r = 4.5 \end{cases}$$

$s^2_{23} = 0.5$

OSCILLATION EFFECTS

- LARGER FOR LARGER $s^2_{23}$
- LARGER IN THE MULTI-GeV SAMPLE THAN FOR THE SUB-GeV SAMPLE ($R^{MULTI} > R^{SUB}$)
- MULTI-GeV SAMPLE:

LEAD TO INCREASE OF $\Phi^0_{\nu_e}$ ($N_e$)

DECREASE OF $\Phi^0_{\nu_\mu}$ ($N_\mu$)

SHOULD CONSIDER $N_\mu / N_e$.

ALL THE ABOVE RESULTS CAN BE DERIVED USING THE CPT-INVARIANCE, CPT-TRANSFORMATION PROPERTIES AND WORKING WITH AMPLITUDES OF THE PROCESSES:

CPT:

B. KAYSER, B. KAYSER, A. GOLDHABER, ...

$$U_{CPT}\,|\chi(t,p)\rangle = \eta_{CPT}(\chi)\,|\chi(-t,p)\rangle .$$

$$U_{CPT}\,|\psi(t,p)\rangle = \eta_{CPT}(\psi)\,|\tilde{\psi}(-t,p)\rangle$$

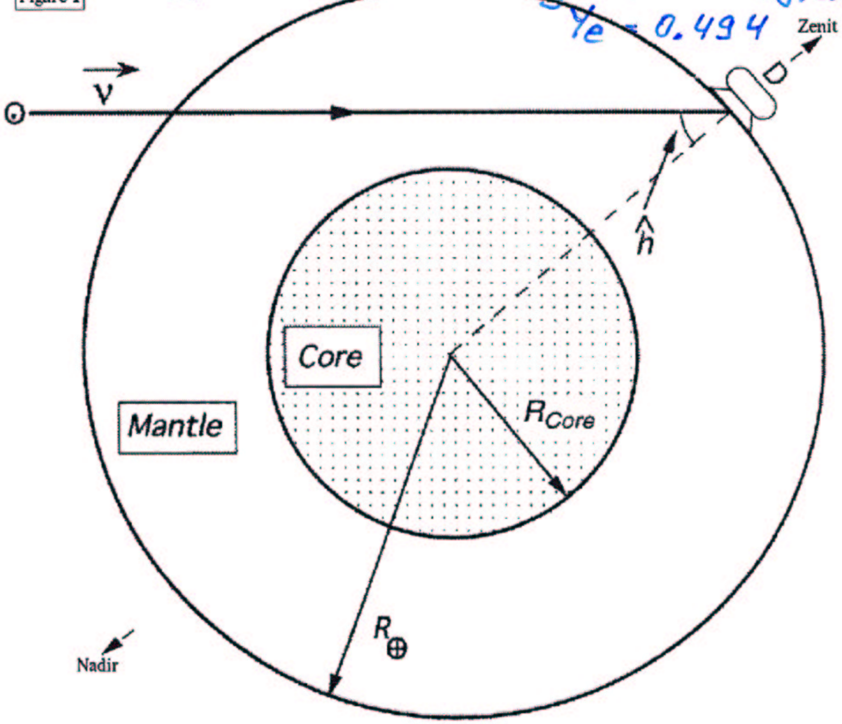
UNPHYSICAL

WHEN THE $\nu$'S CROSS ONLY THE EARTH MANTLE:

$$L = 2R_E \cos h, \quad R_E = 6371\ km$$
$$h \geq 33^\circ, \quad L \leq 10600\ km$$

$$L = 10^3 - 10^4\ km: \quad \bar{\rho} \simeq (2.9-4.8)\ g/cm^3$$
$$Y_e = 0.494$$

Figure 1




(M. MARIS)

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

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

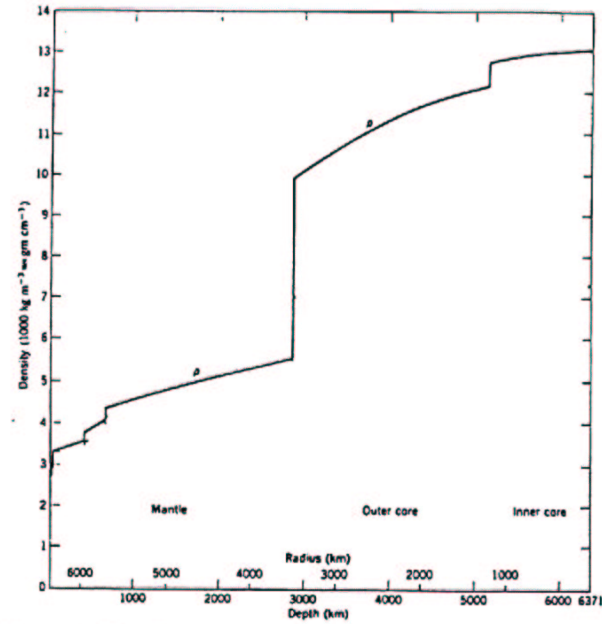



Figura 5.1: Distribuzione di densità della Terra (Stacey, 1977).

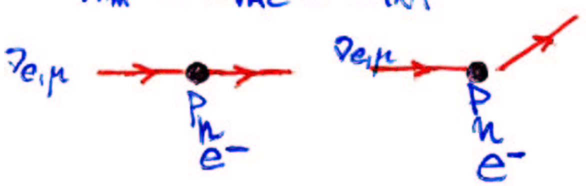
## NEUTRINO OSCILLATIONS IN MATTER

$$|\nu_e\rangle = |\nu_1\rangle\cos\theta + |\nu_2\rangle\sin\theta$$

$$|\nu_\mu\rangle = -|\nu_1\rangle\sin\theta + |\nu_2\rangle\cos\theta$$

$\vec{p}, m_1$ $\quad$ $\vec{p}, m_2$ $\quad$ $m_1 \neq m_2$

$$H_m = H_{VAC} + H_{INT}$$




$\varkappa(\nu_e)$, $\varkappa(\nu_\mu)$:

$$\varkappa(\nu_e) - \varkappa(\nu_\mu) = -\frac{1}{p}\sqrt{2}\,G_F N_e$$

$\langle\nu_1|H_m|\nu_2\rangle \neq 0$ :

$$\left.\begin{array}{l}\nu_{1,2}\\ E_{1,2}\\ \theta\\ L_v\end{array}\right\} \begin{array}{l}\nu^m_{1,2}\\ E^m_{1,2}\\ \theta_m\\ L_m\end{array}$$

$$|\nu_e\rangle = |\nu_1^m\rangle\cos\theta_m + |\nu_2^m\rangle\sin\theta_m$$

$$|\nu_\mu\rangle = -|\nu_1^m\rangle\sin\theta_m + |\nu_2^m\rangle\cos\theta_m$$

$$\sin^2 2\theta_m = \frac{tg^2 2\theta}{\left(1 - \frac{N_e}{N_e^{res}}\right)^2 + tg^2 2\theta}$$

$$N_e^{res} = \frac{\Delta m^2\cos 2\theta}{2E\sqrt{2}\,G_F}$$

For $\sin\theta \ll 1$, $\quad |\nu_e\rangle \cong |\nu_1^m\rangle$, if $N_e \ll N_e^{res}$

$|\nu_e\rangle \cong |\nu_2^m\rangle$, if $N_e \gg N_e^{res}$

$$P(\nu_e \to \nu_\mu) = \frac{1}{2}\sin^2 2\theta_m\left[1 - \cos 2\pi\frac{R}{L_m}\right]$$

$2\pi L_m^{-1} = \Delta E'$

$\Delta E' \equiv E_1^m - E_2^m$

$\Delta m^2 = m_2^2 - m_1^2 > 0$

$$L_m = \frac{L_v}{\sqrt{\left(1 - N_e/N_e^{res}\right)^2\cos^2 2\theta + \sin^2 2\theta}}, \quad L_v = 4\pi\frac{p}{\Delta m^2}$$

$$\boxed{L_m^{res} = \frac{L_v}{\sin 2\theta}}; \qquad L_m \begin{cases} \ll L_v, & N_e \gg N_e^{res} \\ \cong L_v, & N_e \ll N_e^{res} \end{cases}$$

So, for $N_e \ll N_e^{res}$ – $\nu_e \rightleftarrows \nu_\mu$ like in vacuum

$N_e \gg N_e^{res}$ – $\nu_e \rightleftarrows \nu_\mu$ damped

$N_e \cong N_e^{res}$ – the oscillations can be resonantly enhanced

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\left(1 - \frac{N_e}{N_e^{res}}\right)^2\cos^2 2\theta + \sin^2 2\theta}, \quad N_e^{res} = \frac{\Delta m^2\cos 2\theta}{2p\sqrt{2}\,G_F}$$

$\max P(\nu_e \to \nu_\mu) = \sin^2 2\theta_m$, $\Delta E' R = \pi(2k+1)$

$\max P(\nu_e \to \nu_\mu) \cong 1$, $\sin^2 2\theta \ll 1$, $\Delta E' R = \pi(2k+1)$

$\nu_A$ PASSING THROUGH THE EARTH MANTLE:

$$\bar{N}_e^{MAN} \simeq \text{CONST.} \cong (2.0 - 2.4)\, N_A\, cm^{-3}$$

$(\cos\theta_n \gtrsim 0.4)$

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

$$\sin^2 2\theta_{13} < 0.2$$

$\nu_e \to \nu_{\mu(\tau)}$, $\nu_\mu \to \nu_e$ :

$$E_R \simeq 6.6\, \frac{\Delta m^2_{31}}{10^{-3}\, eV^2}\, \frac{1\, N_A\, cm^{-3}}{\bar{N}_e^{MAN}} \cos 2\theta_{13}\ \text{GeV}$$

$$\cong 10\ \text{GeV}.$$

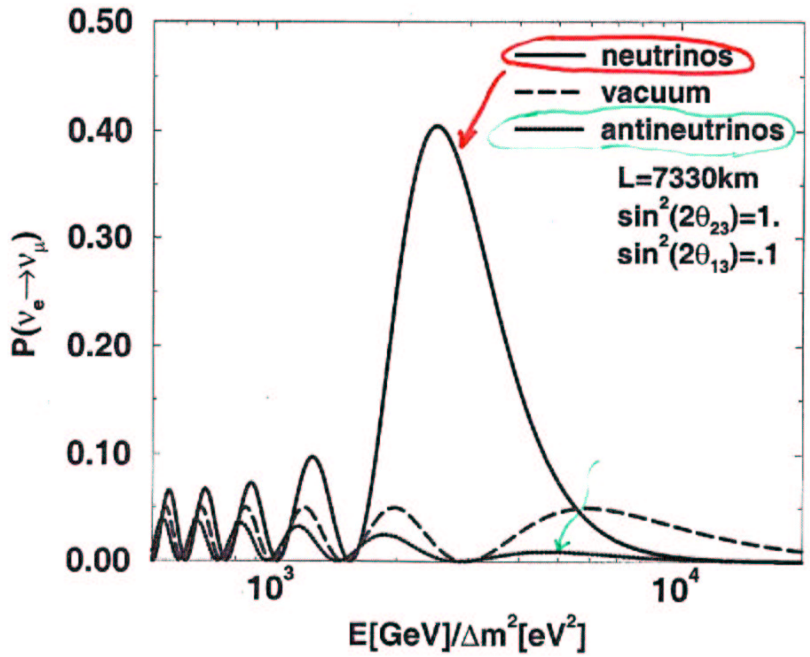
$\cos \Delta E' L = -1$ :

$$\Delta E'_{RES} L \simeq 1.23 \tan 2\theta_{13}\, \frac{\bar{N}_e^{MAN}}{1\, N_A\, cm^{-3}}\, \frac{L}{10^4\, km}\, \pi$$

$$\sin^2\theta_{13} = 0.05 : \quad L \simeq 8000\, km$$

$$= 0.025 : \quad L \simeq 10\,000\, km$$

MOCIOIU, SHROCK, '00



SK MULTI-GeV :

$$N_{e(\mu)} \cong \underbrace{\tfrac{2}{3} N_{e(\mu)}}_{\text{DUE TO } \nu_e\ (\nu_\mu)} + \underbrace{\tfrac{1}{3} N_{e(\mu)}}_{\text{DUE TO } \bar{\nu}_e\ (\bar{\nu}_\mu)}$$

$\cos 2\theta_{13} > 0$;

$\Delta m^2_{31} > 0$: $\nu_e \rightarrow \nu_{\mu(\tau)}$, $\nu_\mu \rightarrow \nu_e$

RESONANTLY ENHANCED

$P_{2\nu} \simeq 1$

AFFECTS $\frac{2}{3} N_{e(\mu)}$

$\Delta m^2_{31} < 0$: $\bar{\nu}_e \rightarrow \bar{\nu}_{\mu(\tau)}$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

RESONANTLY ENHANCED

$\bar{P}_{2\nu} \simeq 1$

AFFECTS $\frac{1}{3} N_{e(\mu)}$

THE EFFECTS OF THE OSCILLATIONS ARE LARGER FOR $\Delta m^2_{31} > 0$ THAN FOR $\Delta m^2_{31} < 0$:

SENSITIVITY TO THE TYPE OF $\nu$-MASS SPECTRUM.

NEW TYPE OF RESONANCE-LIKE ENHANCEMENT

OF $P(\nu_e \rightarrow \nu_{\mu(\tau)})$, $P(\nu_\mu \rightarrow \nu_e)$, S.T.P. '98

$P(\nu_e \rightarrow \nu_s)$, $P(\nu_\mu \rightarrow \nu_s)$ CHIZOV, S.T.P. '99

$P_{e2} \equiv P(\nu_2 \rightarrow \nu_e)$

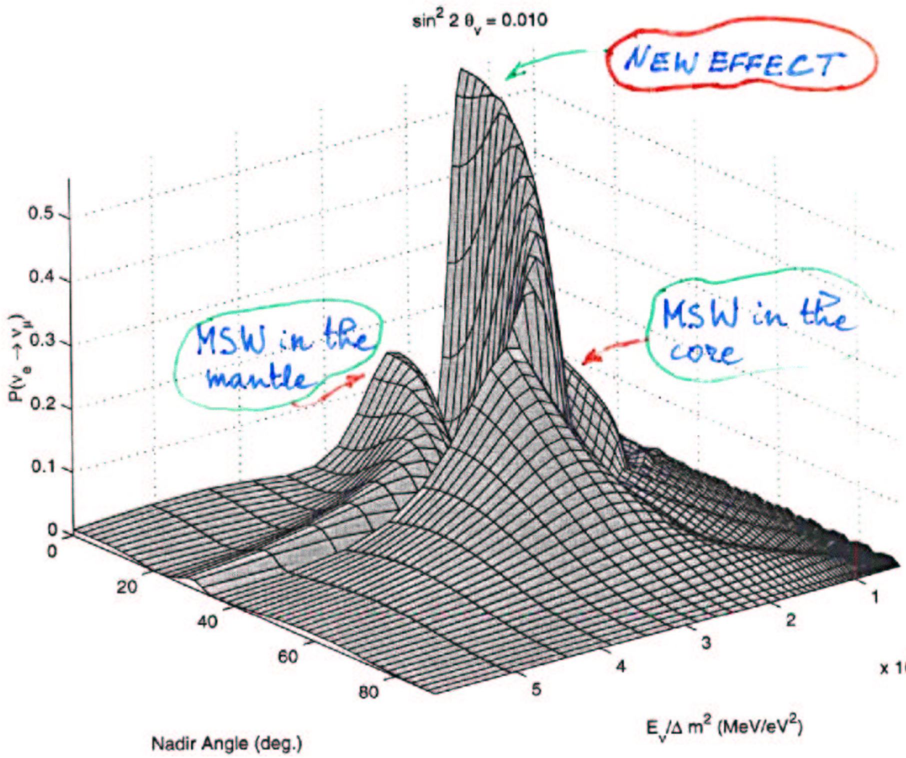
- NOT THE MSW RESONANCE
- TAKES PLACE WHEN

$L^{CORE}_{OSC}$ , $L^{MANTLE}_{OSC}$ OBEY CERTAIN CONSTRAINTS

"NEUTRINO OSCILLATION LENGTH RESONANCE" (NOLR)

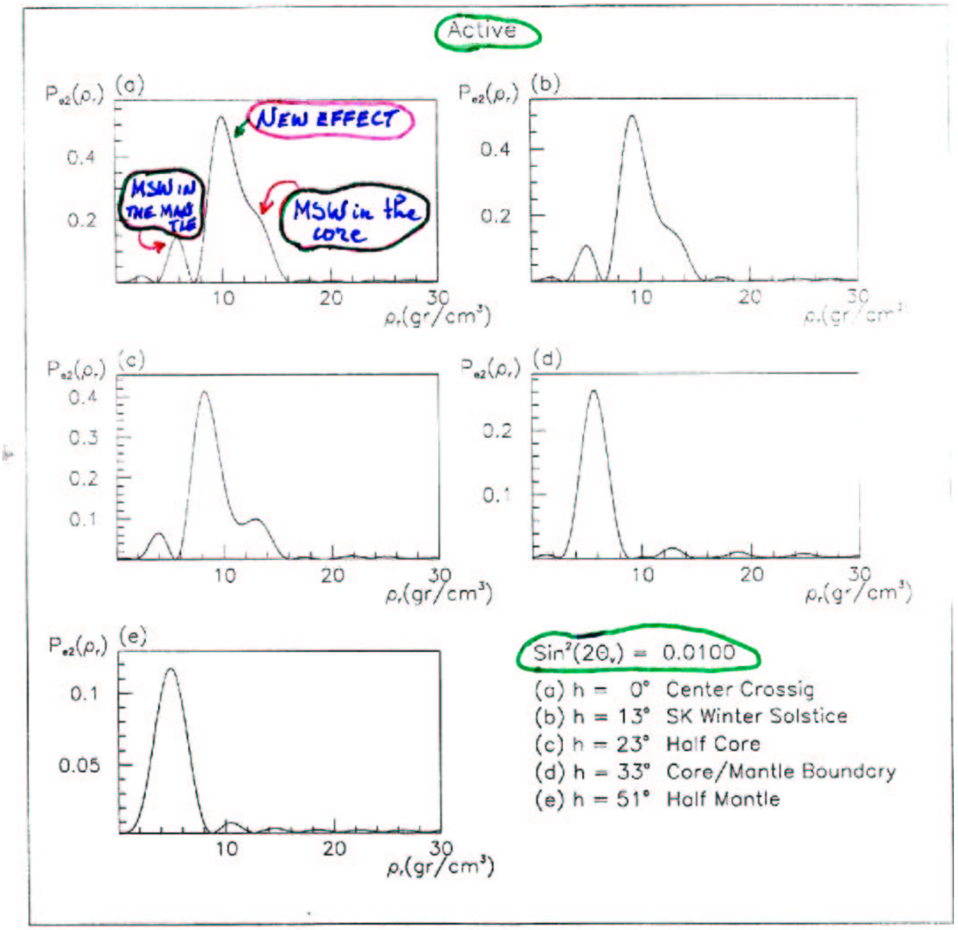
(M. Chizhov, M. Maris, S.T.P. '98)

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

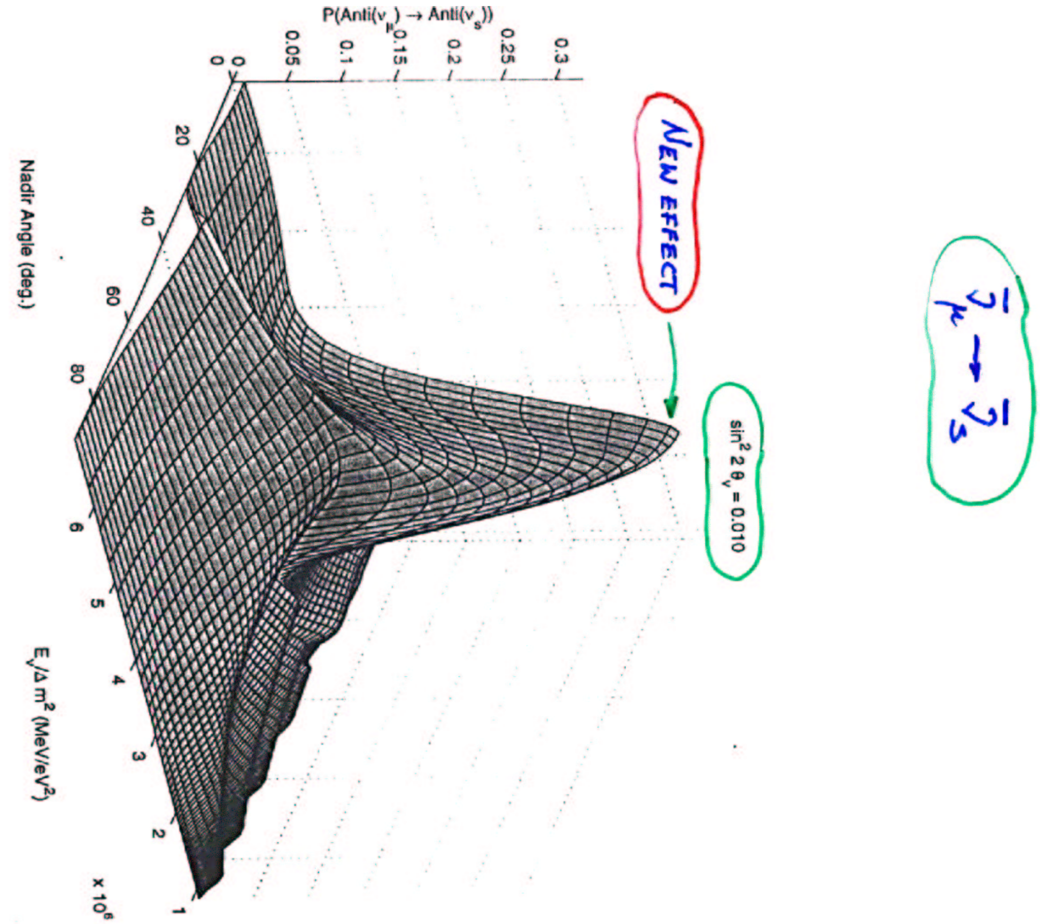



(Liu, Maris, S.T.P. '97)

$\nu_2 \to \nu_e\,,\ \nu_e - \nu_{\mu(\tau)}$ MIXING




$$\rho_R = \frac{\Delta m^2}{2E}\,\frac{\cos 2\theta}{\sqrt{2}\,G_F}\,\frac{1}{0.5}\cdot m_N$$




THE NEW EFFECT OR RESONANCE-LIKE ENHANCEMENT OF $P(\nu_e \to \nu_{\mu(\tau)})$, $P(\nu_\mu \to \nu_e)$, ETC.

- EXHIBITS STRONG DEPENDENCE ON E
- IS SUFFICIENTLY WIDE (IT IS WIDER THAN THE MSW RESONANCE)

$\frac{\Delta E}{E_{MAX}} \cong (0.3-0.4)$ AND IS $\sin^2 2\theta$ INDEPENDENT FOR $\sin^2 2\theta \lesssim 0.05$

THE "RESONANCE" TAKES PLACE IN THE $\nu_\mu \to \nu_e$ AND $\nu_e \to \nu_{\mu(\tau)}$ TRANSITIONS OF ATMOSPHERIC NEUTRINOS:

FOR $\Delta m^2 = 3 \cdot 10^{-3}\,eV^2$, $\sin^2 2\theta \simeq (0.01-0.10)$

MAX $(P(\nu_{\mu(e)} \to \nu_{e(\mu)})$ OCCURS AT $E \cong 4.8$ GeV

BASED ON: S.T.P., PL B434 ('98) 321
HEP-PH/9809587 (v'98)
9811205

M. CHIZHOV, S.T.P.
PHYS. REV. LETT. 83 ('99) 1306
HEP-PH/9903399
PHYS. REV. D63 ('01) 073003
HEP-PH/9903424

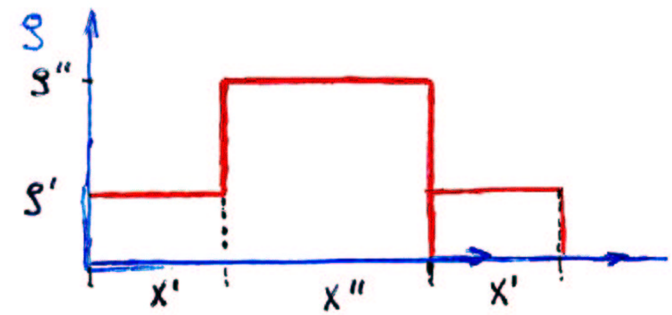
APPLICATIONS:

M. CHIZHOV, M. MARIS, S.T.P.
HEP-PH/9810501

M. MARIS, S.T.P., PR D62, 093006
HEP-PH/0003301

SEE ALSO: M. MARIS, S.T.P., PR D56, 7444
HEP-PH/
PR D58,
HEP-PH/
Q.Y. LIU, M. MARIS, S.T.P.,
PR D56, 5991
HEP-PH/

TRANSITIONS IN A ~~TWO~~ THREE CONSTANT-DENSITY LAYER MEDIUM




$\theta'_m$, $2\phi'_m = \Delta E' X'$ $\quad$ $\theta''_m$, $2\phi''_m = \Delta E'' X''$ $\quad$ $\theta'_m$, $2\phi'_m$

EARTH: MANTLE-CORE-MANTLE

$0 \leq V'_{\alpha\beta} < V''_{\alpha\beta}$

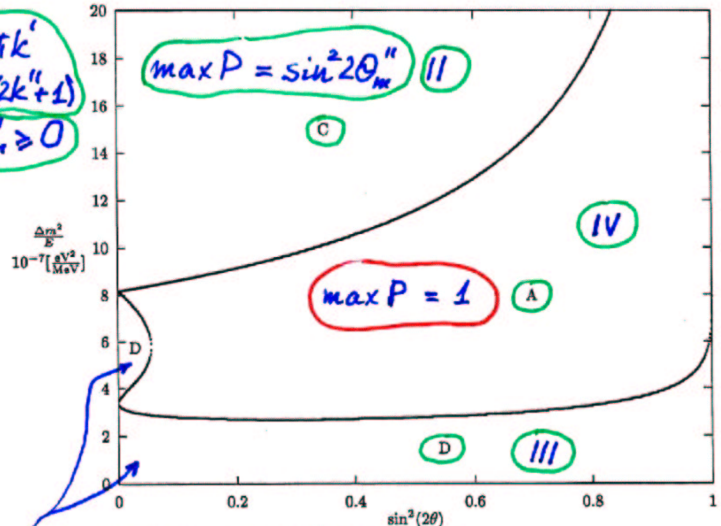
(M. Chizhov, S.T.P. '99)

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

$2\phi'_m = 2\pi k'$

$2\phi''_m = \pi(2k''+1)$

$\cos 2\theta''_m \geq 0$




$\max P = \sin^2(2\theta''_m - 4\theta'_m)$

$2\phi'_m = \pi(2k'+1)$

$2\phi''_m = \pi(2k''+1)$

$\cos(2\theta''_m - 4\theta'_m) \leq 0$

SOLUTION A: $\tan\phi'_m = \pm\sqrt{\dfrac{-\cos 2\theta''_m}{\cos(2\theta''_m - 4\theta'_m)}}$

$\tan\phi''_m = \pm \dfrac{\cos 2\theta'_m}{\quad}$

are provided by the solutions of eq. (52), which can be found explicitly:

$P_{\alpha\beta} = 1$:

$$\text{solution } A: \quad \text{IV} \quad \begin{cases} \tan\phi' = \pm\sqrt{\dfrac{-\cos 2\theta''_m}{\cos(2\theta''_m - 4\theta'_m)}}, \\ \tan\phi'' = \pm\dfrac{\cos 2\theta'_m}{\sqrt{-\cos(2\theta''_m)\cos(2\theta''_m - 4\theta'_m)}}, \end{cases} \qquad (54)$$

$2\phi' = 2\pi \dfrac{X'}{L^{man}_{osc}}$

$2\phi'' = 2\pi \dfrac{X''}{L^{core}_{osc}}$

where the signs are correlated.

The probability $P_{\alpha\beta}$ ($P_{\bar\alpha\bar\beta}$) exhibits a system of of maxima which is similar to that in the two layer case. Under the conditions (5), (18) and if $V'_{\alpha\beta} > 0$ (i.e., for the $\nu_\mu$ ($\nu_e$) $\to \nu_e$ ($\nu_{\mu;\tau}$), $\nu_e \to \nu_s$ and $\bar\nu_\mu \to \bar\nu_s$ transitions in the Earth), solutions (54) are realized in the region $A$ (Figs. 3 - 5),

$$\text{region } A: \quad \begin{cases} \cos(2\theta''_m) \leq 0, \\ \cos(2\theta''_m - 4\theta'_m) \geq 0. \end{cases} \qquad (55)$$

On the [redacted] line belonging to region $A$,

$$\text{region } B: \quad \cos 2\theta'_m = 0, \qquad (56)$$

we have

$$\text{case } B: \quad \max P_{\alpha\beta} = \sin^2 2\theta'_m = 1, \qquad (57)$$

provided

$$\text{solution } B: \quad \text{I} \quad \begin{cases} \cos 2\phi' = 0, \ or \ 2\phi' = \frac{\pi}{2}(2k'+1), \ k' = 0,1,..., \\ \sin\phi'' = 0, \ or \ 2\phi'' = 2\pi k'', \ k'' = 0,1,... \end{cases} \qquad (58)$$

Besides these *absolute* maxima, there exist two regions,

$$\text{region } C: \quad \cos(2\theta''_m) \geq 0, \qquad (59)$$

and

$$\text{region } D: \quad \cos(2\theta''_m - 4\theta'_m) \leq 0, \qquad (60)$$

with maxima

$$\text{case } C: \quad \max P_{\alpha\beta} = \sin^2 2\theta''_m, \qquad (61)$$

and

$$\text{case } D: \quad \max P_{\alpha\beta} = \sin^2(2\theta''_m - 4\theta'_m), \qquad (62)$$

which correspond to the solutions

$$\text{solution } C: \quad \text{II} \quad \begin{cases} \sin\phi' = 0, \ or \ 2\phi' = 2\pi k', \ k' = 0,1,..., \\ \cos\phi'' = 0, \ or \ 2\phi'' = \pi(2k''+1), \ k'' = 0,1,..., \end{cases} \qquad (63)$$

and

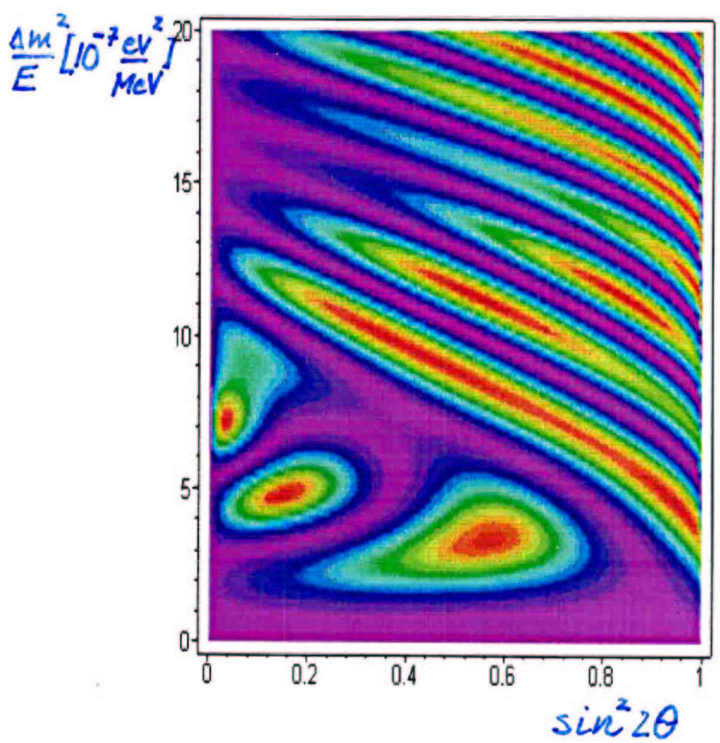
$$\text{solution } D: \quad \text{III} \quad \begin{cases} \cos\phi' = 0, \ or \ 2\phi' = \pi(2k'+1), \ k' = 0,1,..., \\ \cos\phi'' = 0, \ or \ 2\phi'' = \pi(2k''+1), \ k'' = 0,1,..., \end{cases} \qquad (64)$$

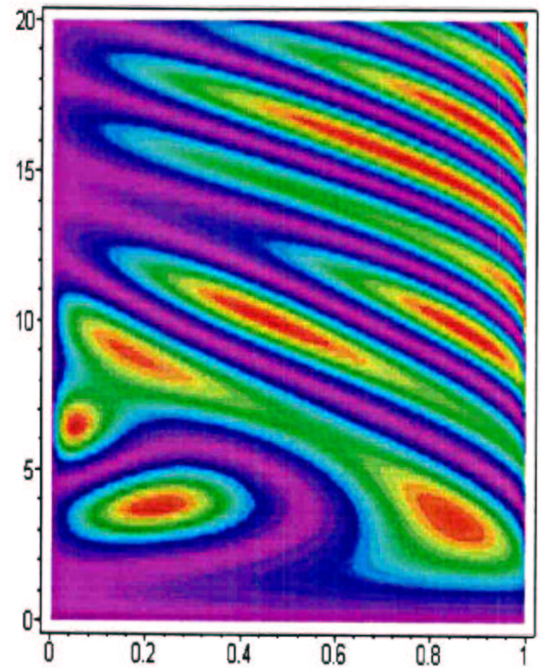
S.T.P.'99

13

(M. CHIZHOV, S.T.P. '99)

$\nu_e \rightarrow \nu_\mu : h = 0°$



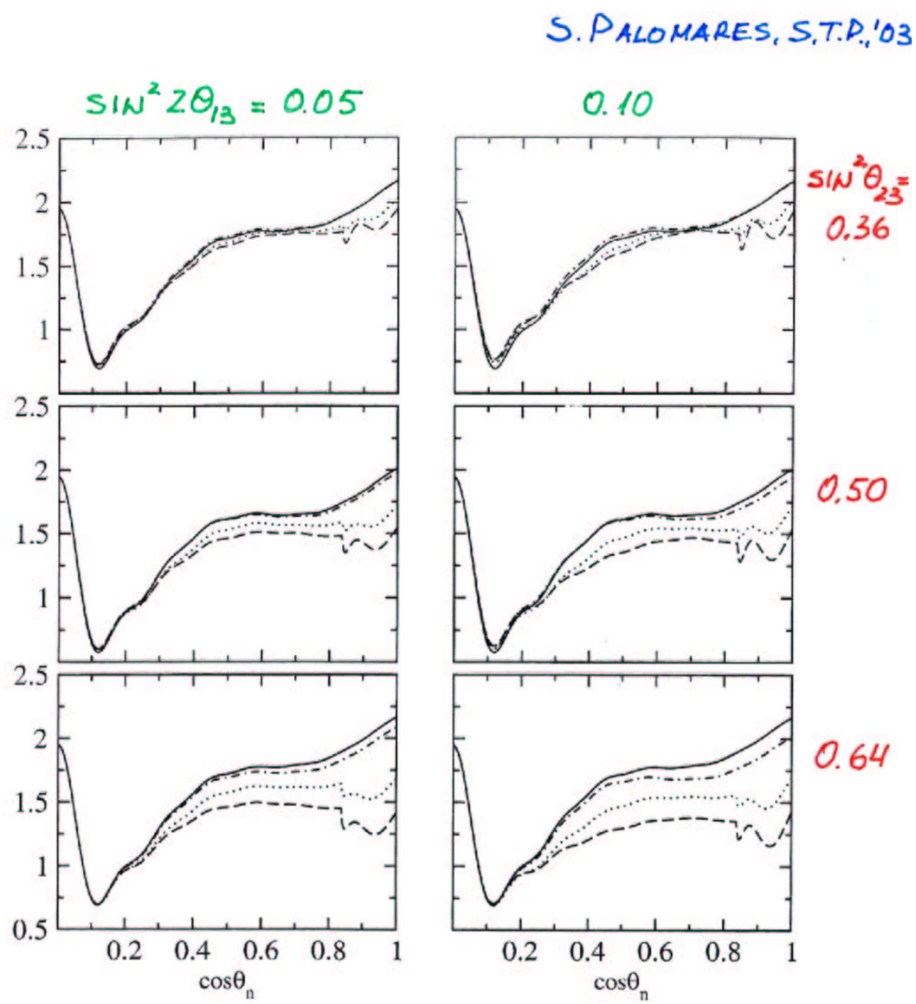



Figure 1: Muon- to electron-like events ratio, $N_\mu/N_e$, in different scenarios: two neutrino oscillation case (solid lines), $N_\mu^{2\nu}/N_e^o$, three neutrino oscillation case for normal hierarchy (dashed lines), $(N_\mu^{3\nu}/N_e^{3\nu})_{NH}$, three neutrino oscillation case for inverted hierarchy (dotted lines), $(N_\mu^{3\nu}/N_e^{3\nu})_{IH}$, and three neutrino oscillation case for vacuum (dot-dashed lines), $(N_\mu^{3\nu}/N_e^{3\nu})_{vac}$. They are depicted as a function of the cosine of the nadir angle, $\cos\theta_n$, for different values of $\theta_{13}$ and $\theta_{23}$ : $\sin^2 2\theta_{13} = 0.05$ (left panels), 0.10 (right panels); $\sin^2\theta_{23} = 0.36, 0.50, 0.64$ (from top to bottom).

13

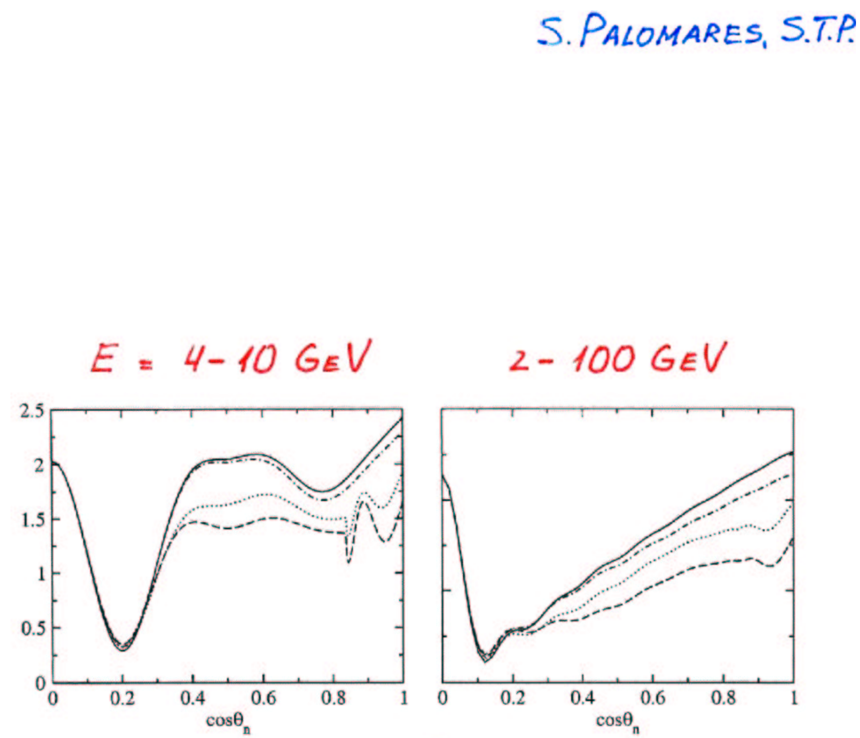



Figure 2: Muon- to electron-like events ratio, $N_\mu/N_e$, in different scenarios: two neutrino oscillation case (solid lines), $N_\mu^{2\nu}/N_e^o$, three neutrino oscillation case for normal hierarchy (dashed lines), $(N_\mu^{3\nu}/N_e^{3\nu})_{NH}$, three neutrino oscillation case for inverted hierarchy (dotted lines), $(N_\mu^{3\nu}/N_e^{3\nu})_{IH}$, and three neutrino oscillation case for vacuum (dot-dashed lines), $(N_\mu^{3\nu}/N_e^{3\nu})_{vac}$. They are depicted as a function of the cosine of the nadir angle, $\cos\theta_n$, for $|\Delta m^2_{31}| 3 \times 10^{-3}\,\mathrm{eV}^2$, $\sin^2 2\theta_{13} = 0.10$ and $\sin^2\theta_{23} = 0.50$ for neutrino energies within the intervals: [4, 10] GeV (left panel) and [2, 100] GeV for also PC events (right panel).

14

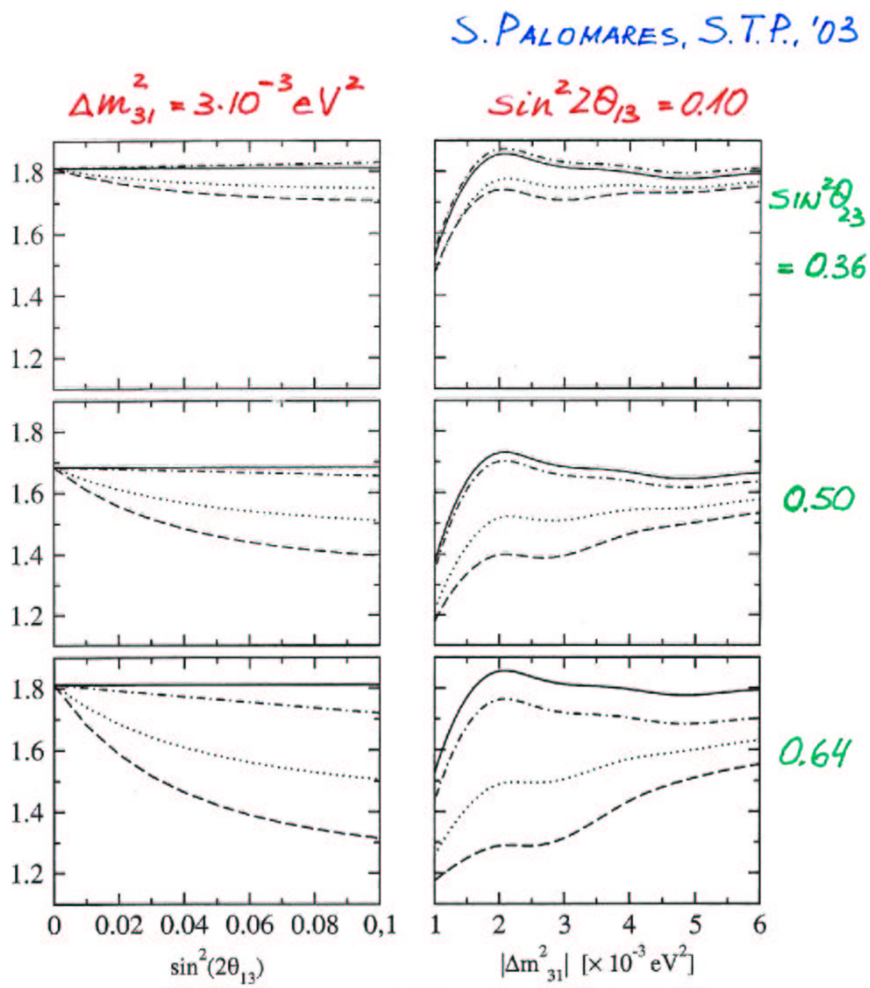



Figure 3: Muon- to electron-like events ratio, $N_\mu/N_e$, integrated for $\cos\theta_n \geq 0.4$, in different scenarios: two neutrino oscillation case (solid lines), $N_\mu^{2\nu}/N_e^o$, three neutrino oscillation case for normal hierarchy (dashed lines), $(N_\mu^{3\nu}/N_e^{3\nu})_{NH}$, three neutrino oscillation case for inverted hierarchy (dotted lines),$(N_\mu^{3\nu}/N_e^{3\nu})_{IH}$, and three neutrino oscillation case for vacuum (dot-dashed lines), $(N_\mu^{3\nu}/N_e^{3\nu})_{vac}$. Left panel: as a function of $\sin^2 2\theta_{13}$ for $|\Delta m^2_{31}| = 3\times 10^{-3}\text{eV}^2$. Right panel: as a function of $|\Delta m^2_{31}|$ for $\sin^2 2\theta_{13} = 0.10$. From top to bottom: $\sin^2 2\theta_{23} = 0.36, 0.50, 0.64$.



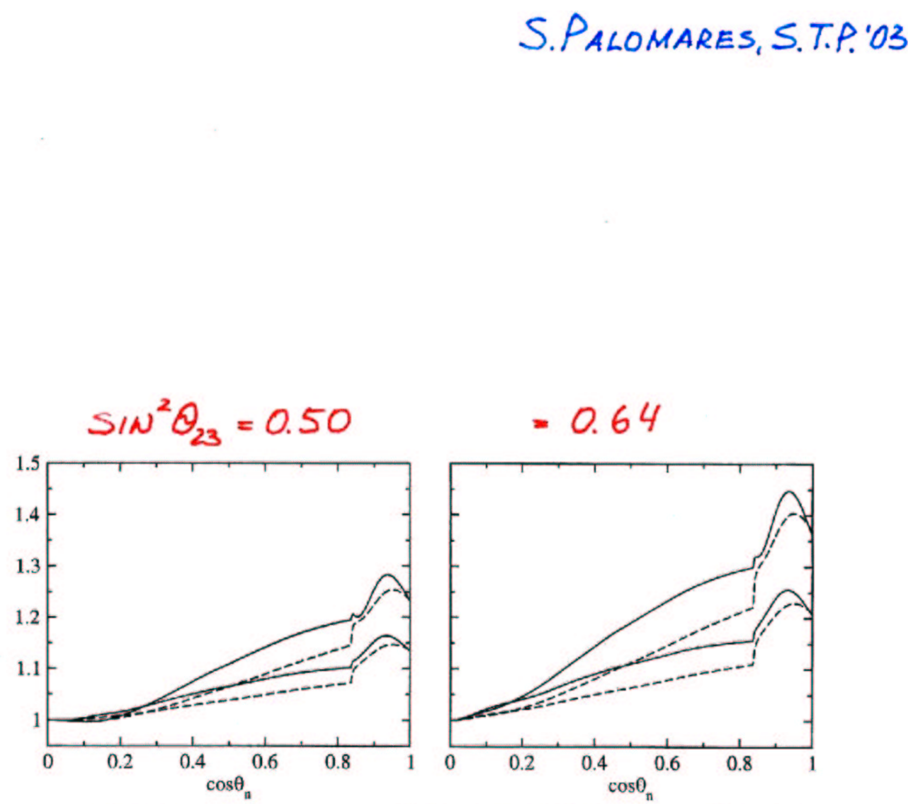



Figure 4: $N_e^{3\nu}/N_e^o$ as a function of $\cos\theta_n$ for $\sin^2 2\theta_{13} = 0.10$ (solid lines) and $\sin^2 2\theta_{13} = 0.05$ (dashed lines), for normal (upper lines) and inverted (lower lines) hierarchy, for $\sin^2\theta_{23} = 0.5$ (left panel) and $\sin^2\theta_{23} = 0.64$ (right panel). $N_e^{3\nu}$ and $N_e^o$, are the e-like events in the case of three neutrino oscillation and in the case of no oscillations, respectively

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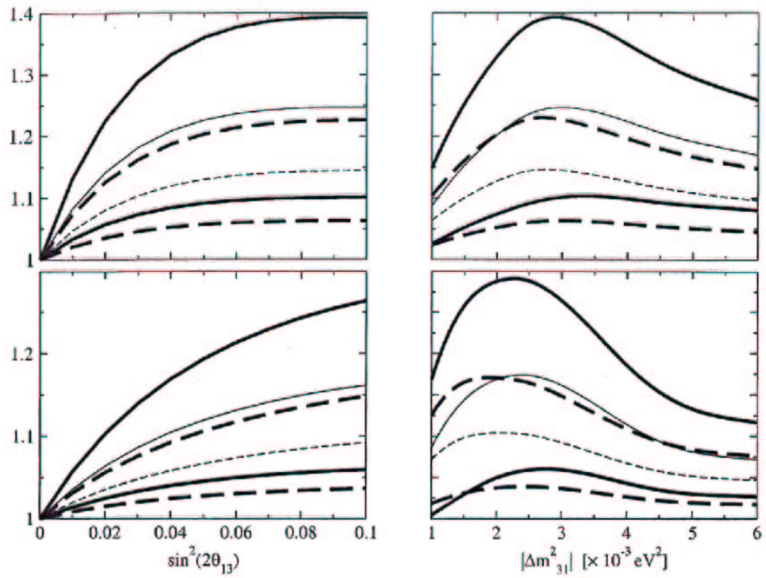
$\Delta m^2_{31} = 3 \cdot 10^{-3} eV^2$ $\sin^2 2\theta_{13} = 0.10$




CORE

CORE + MANTLE

Figure 5: $N_e^{3\nu}/N_e^o$ as a function of $\sin^2\theta_{13}$ for $|\Delta m^2_{31}| = 3 \times 10^{-3}\mathrm{eV}^2$ (left panels) and as a function of $|\Delta m^2_{31}|$ for $\sin^2\theta_{13} = 0.10$ (right panels), where $N_e^{3\nu}$ and $N_e^o$, are the e-like events in the core (upper panels) and from $\cos\theta_n = 1$ to $\cos\theta_n = 0.4$ (lower panels) in the case of three neutrino oscillation and in the case of no oscillations, respectively. Normal hierarchy (solid lines) and inverted hierarchy (dashed lines) are depicted for $\sin^2 2\theta_{23} = 1$ (thin lines) and $\sin^2 2\theta_{23} = 0.92$ (thick lines).

17



# CPT Violation and the Nature of Neutrinos

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**Abstract**

In order to accommodate the neutrino oscillation signals from the solar, atmospheric, and LSND data, a sterile fourth neutrino is generally invoked, though the fits to the data are becoming more and more constrained. However, it has recently been shown that the data can be explained with only three neutrinos, if one invokes CPT violation to allow different masses and mixing angles for neutrinos and antineutrinos. We explore the nature of neutrinos in such CPT-violating scenarios. Majorana neutrino masses are allowed, but in general, there are no longer Majorana neutrinos in the conventional sense. However, CPT-violating models still have interesting consequences for neutrinoless double beta decay. Compared to the usual case, while the larger mass scale (from LSND) may appear, a greater degree of suppression can also occur.

*Key words:* Neutrino mass and mixing, double beta decay
*PACS:* 14.60.Pq, 23.40.-s

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## 1 Introduction

In recent years, stronger and stronger experimental evidence for neutrino oscillations has been accumulating. As is well-known, this evidence would extend the Standard Model by requiring neutrino masses and mixings. While knowing the values of the mass and mixing parameters may be an important clue to physics beyond the Standard Model, more information is needed. For example,

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HAPPY BIRTHDAY, BORIS!

THANK YOU
FOR BEING
AROUND!