NEUTRINOS FROM STELLAR COLLAPSE - EFFECTS OF FLAVOUR MIXING

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G. Dutta

- D. Indumathi

MVN. Murthy

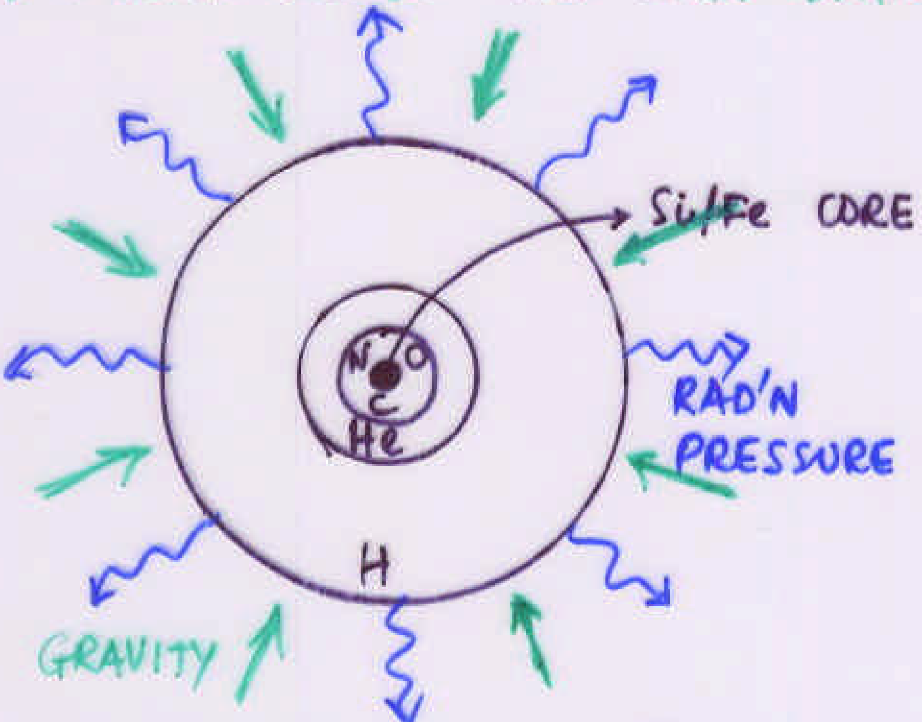
G. Rajasekaran

OUTLINE :

- NEUTRINOS FROM STELLAR COLLAPSE : BACKGROUND
- NEUTRINO MASSES & MIXING : BACKGROUND
- EFFECT OF MIXING ON ν's FROM STELLAR COLLAPSE
- CONCLUSIONS.

GRAVITATIONAL COLLAPSE & SUPERNOVAE (in brief):

- TYPE II SUPERNOVAE, FROM 8-20 $M_\odot$ STARS.
- MOST OF THE ENERGY FROM GRAV. COLLAPSE IS EMITTED IN NEUTRINOS (first few seconds)
- FIRST (AND ONLY) EXPT'AL OBS : SN1987A / LMC.
  (Kamioka, IMB, Mont Blanc)
- FUSION DRIVES THE STAR DYANAMICS (ONION-SKIN)

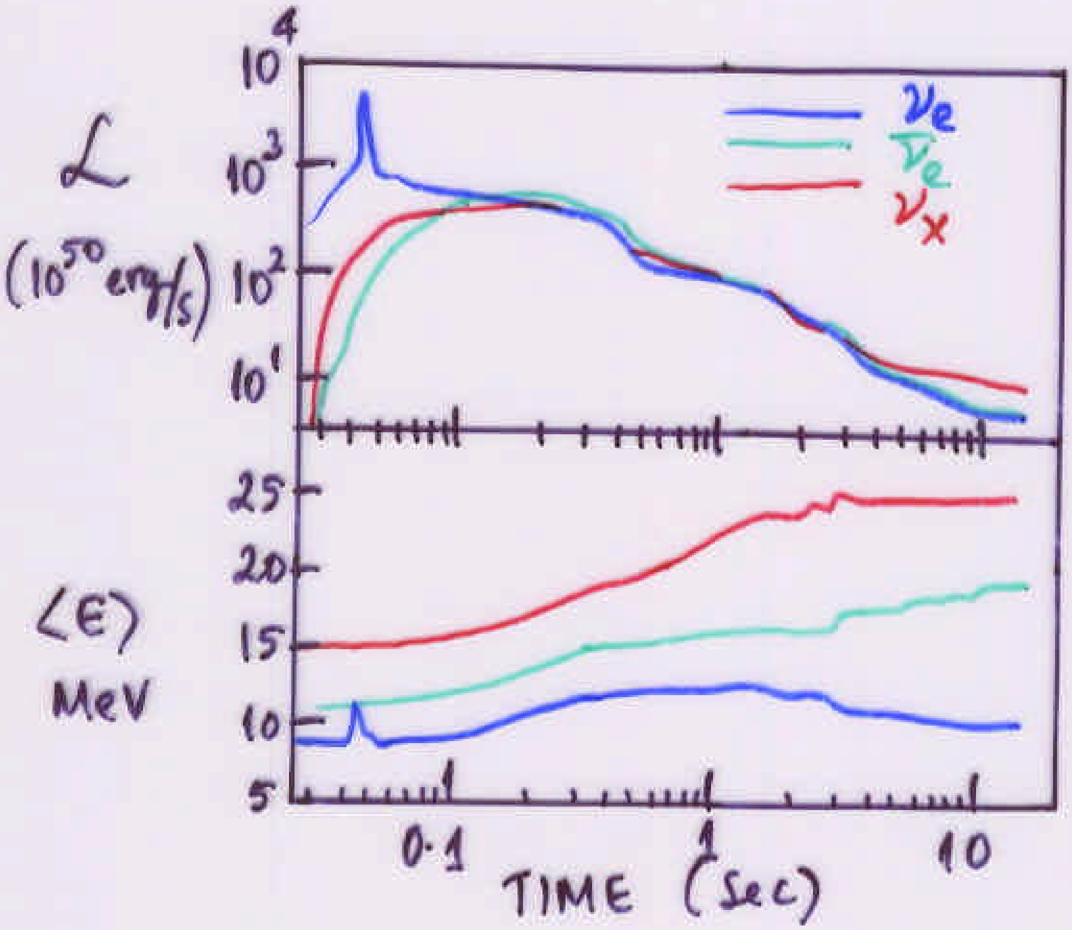


Landau '32
Baade Zwicky '34
Burbridge '57
Burrows, Lattimer '86
Mayle, Wilson, Schramm '87
Wilson '84
Trimble '82, '88
Bahcall, Bethe '90
Totani et al. '97

- CORE COLLAPSE $e^- + p \rightarrow n + \underline{\underline{\nu_e}}$ I
- CORE BOUNCE
- COOLING ; ENERGY ($\sim 3 \times 10^{53}$ ergs) EMITTED MOSTLY IN NEUTRINOS & ANTI NEUTRINOS OF ALL FLAVOURS:

$$\begin{aligned} p + e &\rightarrow n + \nu_e \\ n + e^+ &\rightarrow p + \bar{\nu}_e \\ n + n &\rightarrow n + n + \nu + \bar{\nu} \\ e^+ + e^- &\rightarrow \nu + \bar{\nu} \end{aligned} \qquad \text{II}$$

- APRROXIMATELY EQUAL ENERGY IN <u>ALL</u> FLAVOURS.



TOTANI, SATO, DALHED, WILSON, '97.

- $\langle E\rangle_{\nu_e} \sim 11$ MeV ; $\langle E\rangle_{\bar\nu_e} \sim 16$ MeV ; $\langle E\rangle_{\nu_{\mu,\tau}} \sim 25$ MeV .

- MORE THAN HALF THE ENERGY RADIATED WITHIN THE FIRST TWO SECONDS

- EMISSION CORRESPONDS TO A FERMI DIRAC THERMAL SPECTRAL DISTRIBUTION .

- DIFFERENT MODELS DIFFER IN THE DETAILS OF EXPLOSION OR DYNAMICS, BUT AGREE
  - ON THE TOTAL ENERGY
  - THE MEAN ENERGY HIERARCHY: $\nu_e \lesssim \bar\nu_e \lesssim \nu_\mu$.

THE NEUTRINO PUZZLE(S):

MANY EXPERIMENTS INDICATE THAT OBSERVED ν FLUXES ARE DEPLETED WITH RESPECT TO EXPECTATIONS

- SOLAR ν's
- ATMOSPHERIC ν's
- LAB EXPT'S.

Homestake,
KII, SuperK,
GALLEX, SAGE
CHOOZ, LSND, ...

POSSIBLE SOLUTIONS (from particle physics)

✓ - ν MASSES & MIXING WITH OSCILLATIONS
- ν MIXING & DECAY
- ν MAGNETIC MOMENT

- WE WILL APPLY THE KNOWN CONSTRAINTS ON THE OSCILLATION SOLUTION FROM THESE EXPERIMENTS IN OUR ANALYSIS.

  - MOSTLY 3 FLAVOUR ANALYSIS
  - LATER 4 FLAVOURS AS WELL

- 3 FLAVOURS:

$$\underset{\text{FLAVOUR}}{\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix}} = U^\nu \underset{\text{MASS BASIS}}{\begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}}$$

$$U^\nu = U_{23}(\underline{\Psi}) \times V_{phase} \times U_{13}(\underline{\phi}) \times U_{12}(\underline{\omega})$$

$$\Delta M_\nu^2 = U^\nu \Delta M_0^2 U^{\nu\dagger} = \delta_{31} M_{31} + \delta_{21} M_{21}$$

$\updownarrow$ VACUUM SOL'N.

Wolfenstein '78
Mikheyev, Smirnov '85, '86
Kuo & Pantaleone '88.

MATTER EFFECTS:

- $\Delta M_m^2 = \delta_{31} M_{31} + \delta_{21} M_{21} + A(r) M_A$; (flavour basis).

  $M_A = \mathrm{diag}\,(1, 0, 0)$.

  $A(r) = \sqrt{2}\, G_F\, N_e(r) \times 2E$

  $\propto N_e(r)$, election number density in SN.

- MASS^2 MATRIX NO LONGER DIAGONAL, IN THE PRESENCE OF MATTER: DIAGONALISE.

- ASSUMPTION : $A(\text{core}) \gg \delta_{31} \gg \delta_{21}$.
- RESULT : $\tan 2\phi_m = \dfrac{\delta_{31} \sin 2\phi}{\delta_{31} \cos 2\phi - A} \xrightarrow{A \to \infty} \dfrac{\pi}{2} \leftarrow \phi_m$

  $\Rightarrow$ $|\nu_e\rangle$ PRODUCED AS $|\nu_3\rangle$ IN THE CORE.

  ↳ (A PURE MASS E. STATE).

- CONSEQUENCE : THE SURVIVAL PROBABILITY OF $|\nu_e\rangle$ IS SIMPLY THE PROJECTION OF $|\nu_3\rangle$ ONTO THE $|\nu_e\rangle$ STATE IN THE DETECTOR

  (PROVIDED THERE ARE NO LANDAU ZENER JUMPS).

IN GENERAL, THE AVERAGE SURVIVAL PROB., INCLUDING NON-ADIABATICITY, IS,

$$P_{ee} = \sum_{i,j=1}^{3} |U_{ei}^v|^2 \, |U_{ej}^m|^2 \, |\langle \nu_i^v | \nu_j^m \rangle|^2$$

$$= \sin^2\phi\, \underline{P_3} + \cos^2\phi \sin^2\omega\, \underline{P_2} + \cos^2\phi \cos^2\omega\, \underline{P_1}.$$

RESULT FOR ANTI NEUTRINOS :

- MATTER TERM IS NEGATIVE :

$$A(r) = -\sqrt{2}\, G_F\, N_e(r) \times 2E.$$

- HENCE,

$$\tan 2\phi_m = \frac{\delta_{31} \sin 2\phi}{\delta_{31} \cos 2\phi + |A|},$$

or $\phi_m \xrightarrow{A \to \infty} 0$ IN THE CORE

- $|\bar{\nu}_e\rangle$ IS PRODUCED AS A PURE $|\bar{\nu}_1\rangle$ IN CORE.
- NO LANDAU - ZENER (NON-ADIABATIC) JUMPS SINCE THE RESONANCE CONDITIONS ARE NEVER SATISFIED.

  (POSSIBLE IN AN INVERTED MASS HIERARCHY, WHERE ν's WILL PROPAGATE PURELY ADIABATICALLY).

  Kuo, Pantaleone &
  Dighe, Smirnov '99

- THE ANTI - ELECTRON NEUTRINO SURVIVAL PROBABILITY IS THEN

$$\begin{aligned}\bar{P}_{ee} &= \cos^2\phi \, \cos^2\omega \\ &\sim \cos^2\omega \quad (\text{SINCE } \phi \text{ IS SMALL}).\end{aligned}$$

[RECALL $P_{ee} \sim \sin^2\phi$].

NEUTRINO FLUXES & CROSS SECTIONS :

$\nu_e, \bar{\nu}_e$: CC + NC PRODUCTION

$\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$: NC PRODUCTION.

- $F_X^0 = F_\mu^0 = F_{\bar{\mu}}^0 = F_\tau^0 = F_{\bar{\tau}}^0$.

- $$F_{\nu_e} = P_{ee} F_e^0 + P_{e\mu} F_\mu^0 + P_{e\tau} F_\tau^0$$
  $$= F_e^0 - (1 - \underline{P_{ee}})(F_e^0 - F_x^0),$$
  SINCE $\sum_j P_{ij} = 1$.

- $$2F_X = F_\mu + F_\tau$$
  $$= 2F_x^0 + (1 - P_{ee})(F_e^0 - F_x^0)$$

- $F_e + 2F_x = F_e^0 + 2F_x^0$: TOTAL FLUX IS CONSERVED.

- SIMILARLY FOR ANTI NEUTRINOS, WITH

$P_{ee} \longrightarrow \bar{P}_{ee}$
$F_e \longrightarrow F_{\bar{e}}$
$F_e^0 \longrightarrow F_{\bar{e}}^0$ $(F_X^0 = F_{\bar{X}}^0)$.
$(F_X \neq F_{\bar{X}})$.

ADIABATIC CASE :

$$F_e = \sin^2\phi \, F_e^0 + (1 - \sin^2\phi) \, F_x^0 .$$

$$2F_x = (1 + \sin^2\phi) \, F_x^0 + (1 - \sin^2\phi) \, F_e^0 .$$

$$F_{\bar{e}} = (1 - \sin^2\phi) \cos^2\omega \, F_{\bar{e}}^0 + (\sin^2\omega + \varepsilon^2 \cos^2\omega) \, F_{\bar{x}}^0 .$$

$$2F_{\bar{x}} = (1 + \cos^2\omega (1 - \sin^2\phi)) \, F_{\bar{x}}^0 + (\sin^2\omega + \varepsilon^2 \cos^2\omega) \, F_{\bar{e}}^0 .$$

$$(\varepsilon^2 = \sin^2\phi) .$$

CHOOZ : ϕ SMALL , $\phi \lesssim 6°$.

THEN

$F_e \simeq F_x^0$ $\Leftrightarrow$ HOTTER ν_e ON EARTH ,

$2F_x \simeq (F_x^0 + F_e^0)$ $\Leftrightarrow$ COLDER ADMIXTURE ,

$2F_{\bar{x}} \simeq \left(\frac{3}{2} F_{\bar{x}}^0 + \frac{1}{2} F_{\bar{e}}^0\right)$ $\Leftrightarrow$ SLIGHTLY COLDER .

$F_{\bar{e}} \simeq \left(\frac{1}{2} F_{\bar{e}}^0 + \frac{1}{2} F_{\bar{x}}^0\right)$ $\Leftrightarrow$ HOTTER $\bar{\nu}_e$.

- THE NET RESULT IS
  - ENHANCED $\bar{\nu}_e$ EVENT RATE
    - HOTTER ADMIXTURE
    - E_ν^2 DEP. OF CROSS SEC .
  - REDUCED $\bar{\nu}_x$ RATE
    - MAY NOT BE OBSERVABLE (SNO) .

INTERACTION AT THE DETECTOR : (WATER CERENKOV DETECTOR):

- INTERACTION WITH ELECTRONS :

$$\nu_\ell (\bar{\nu}_\ell) + e^- \longrightarrow \nu_\ell (\bar{\nu}_\ell) + e^- ;$$

$$\ell = e, \mu, \tau .$$

$d\sigma \propto E_\nu$

- FORWARD PEAKED

- INTERACTIONS WITH FREE PROTONS :

$$\bar{\nu}_e + p \longrightarrow e^+ + n ;$$

$d\sigma \propto E_\nu^2$ (~ 100 times $\sigma(\nu e)$ for $E_\nu \sim 10$ MeV).

- ISOTROPIC

- INTERACTION WITH OXYGEN NUCLEI :

$$\nu_e + {}^{16}O \rightarrow e^- + {}^{16}F ; \quad (15.4 \text{ MeV})$$

$$\bar{\nu}_e + {}^{16}O \rightarrow e^+ + {}^{16}N . \quad (11.4 \text{ MeV}).$$

$d\sigma$ increases rapidly with E_ν

SOMEWHAT BACKWARD PEAKED.

FOR A HOTTER SPECTRUM, ALMOST COMPLETELY BACKWARD PEAKED.

- HENCE ν OSCILLATION IMPLIES THE PRESENCE OF A STRONG BACKWARD PEAK IN EVENTS.

FORWARD

no mixing   mixing

ν_x ; $\bar{\nu}_x$

MAY NOT BE OBSERVABLE

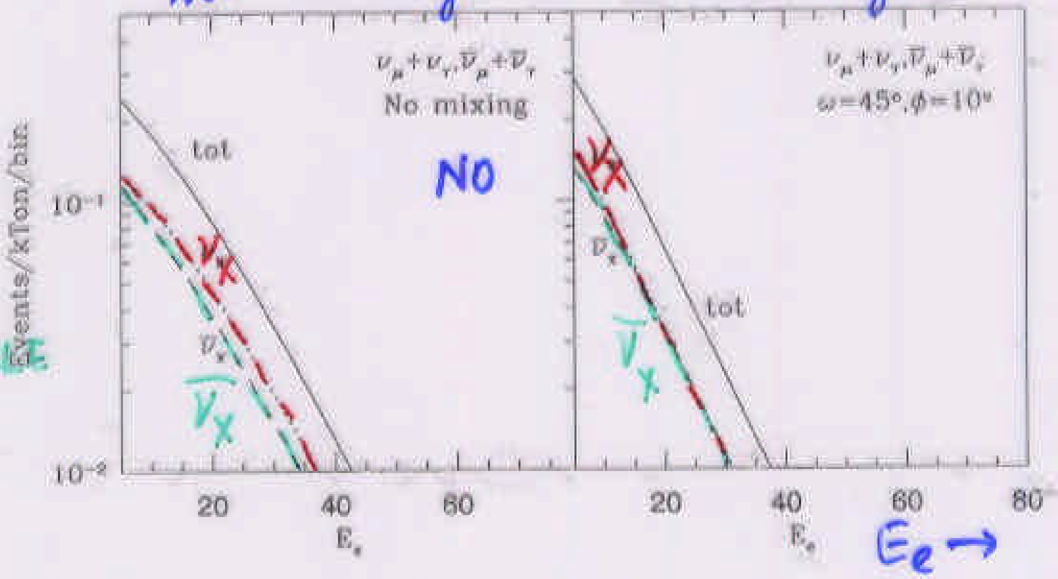


FIG. 3. The number of events in bins of 1 MeV each, with and without mixing, due to $\nu_{\mu,\tau} e$ and $\bar{\nu}_{\mu,\tau} e$ elastic scattering in the detector, are shown as a function of the electron energy, as dotted and dashed lines respectively. The solid line denotes the total contribution to the event rate from all these channels, that is from ν_μ, ν_τ, $\bar{\nu}_\mu$, and $\bar{\nu}_\tau$.

no mixing   mixing

TOTAL x

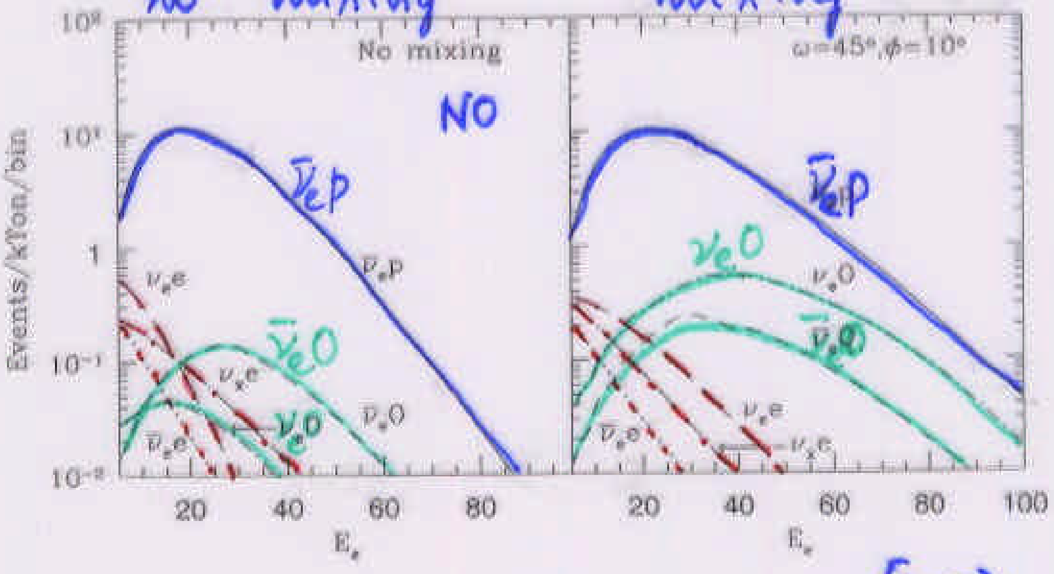


FIG. 4. A comparison of the number of events in bins of 1 MeV each, due to various processes, is shown as a function of the electron energy, with and without mixing. The line types indicate events from the processes $\bar{\nu}_e p$ (solid), $\bar{\nu}_e e$ (dotted), $\bar{\nu}_e O$ (dashed), $\nu_e e$ (long-dashed), $\nu_e O$ (dot-dashed), and $\nu_x e$ (dot-long dashed) processes respectively. The subscript x denotes the NC contribution from ν_μ, ν_τ and their antiparticles.

4.1

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MOSTLY ISOTROPIC

FIGURES

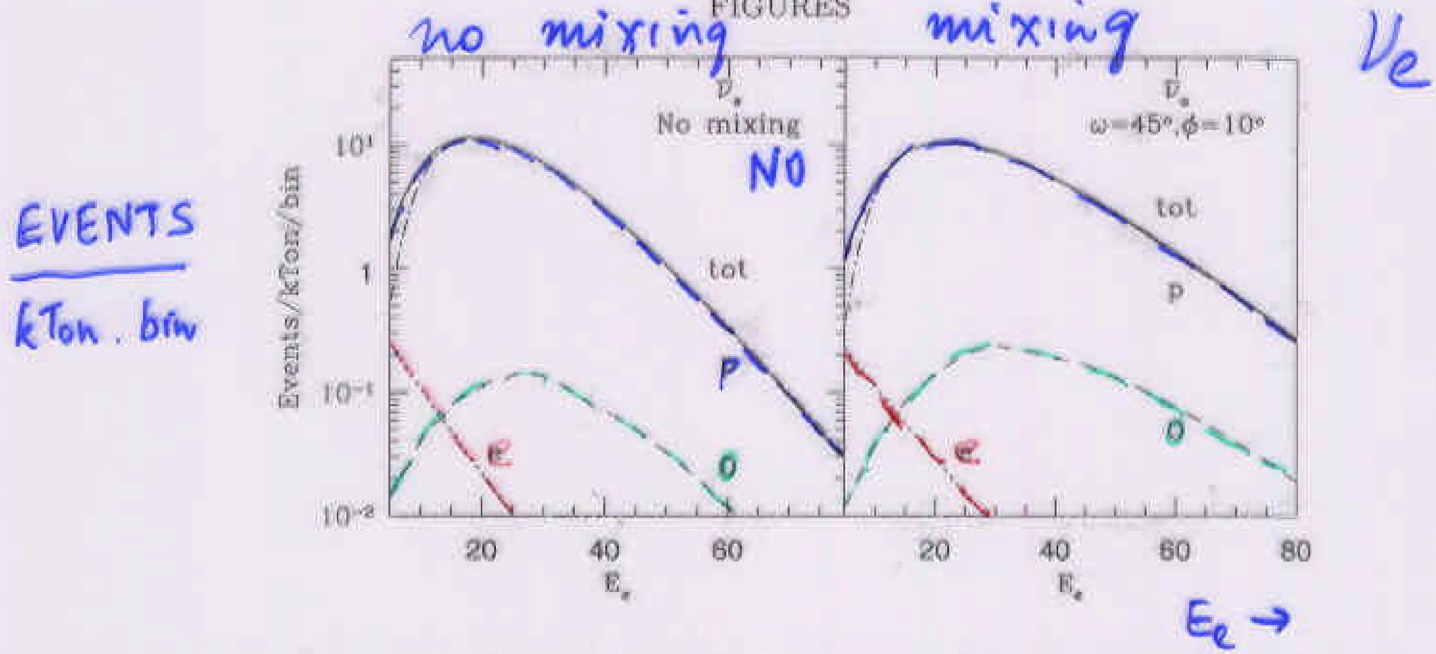


FIG. 1. The number of events in bins of electron energy of 1 MeV each, due to $\bar{\nu}_e$ interactions, are shown as a function of the electron energy, with and without mixing. The long-dashed, dashed, and dotted lines correspond to interactions with p, O and e respectively, in the detector. The dot-dashed line indicates the effect of inclusion of detector efficiency and resolution on the interaction with p. See text for more details. The solid line denotes the total contribution to the event rate from $\bar{\nu}_e$.

MOSTLY BACKWARD

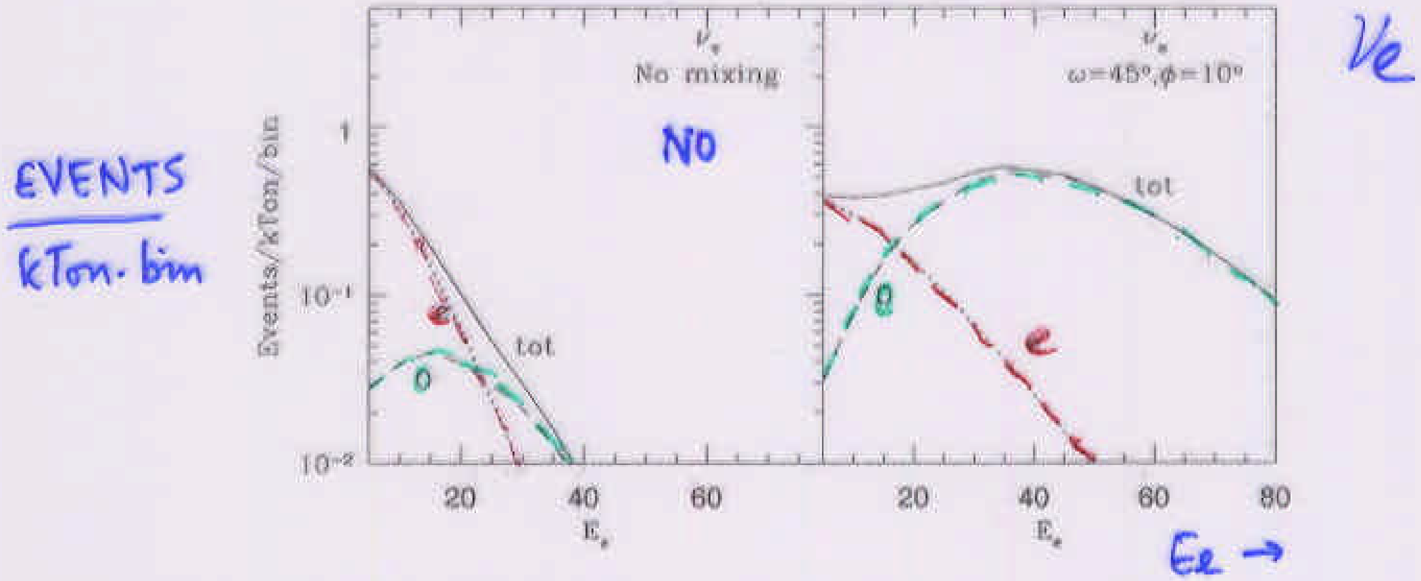


FIG. 2. The number of events in bins of 1 MeV each, due to ν_e interactions, are shown as a function of the electron energy, with and without mixing. The dashed and dotted lines correspond to interactions with O and e respectively, in the detector. The solid line denotes the total contribution to the event rate from ν_e.

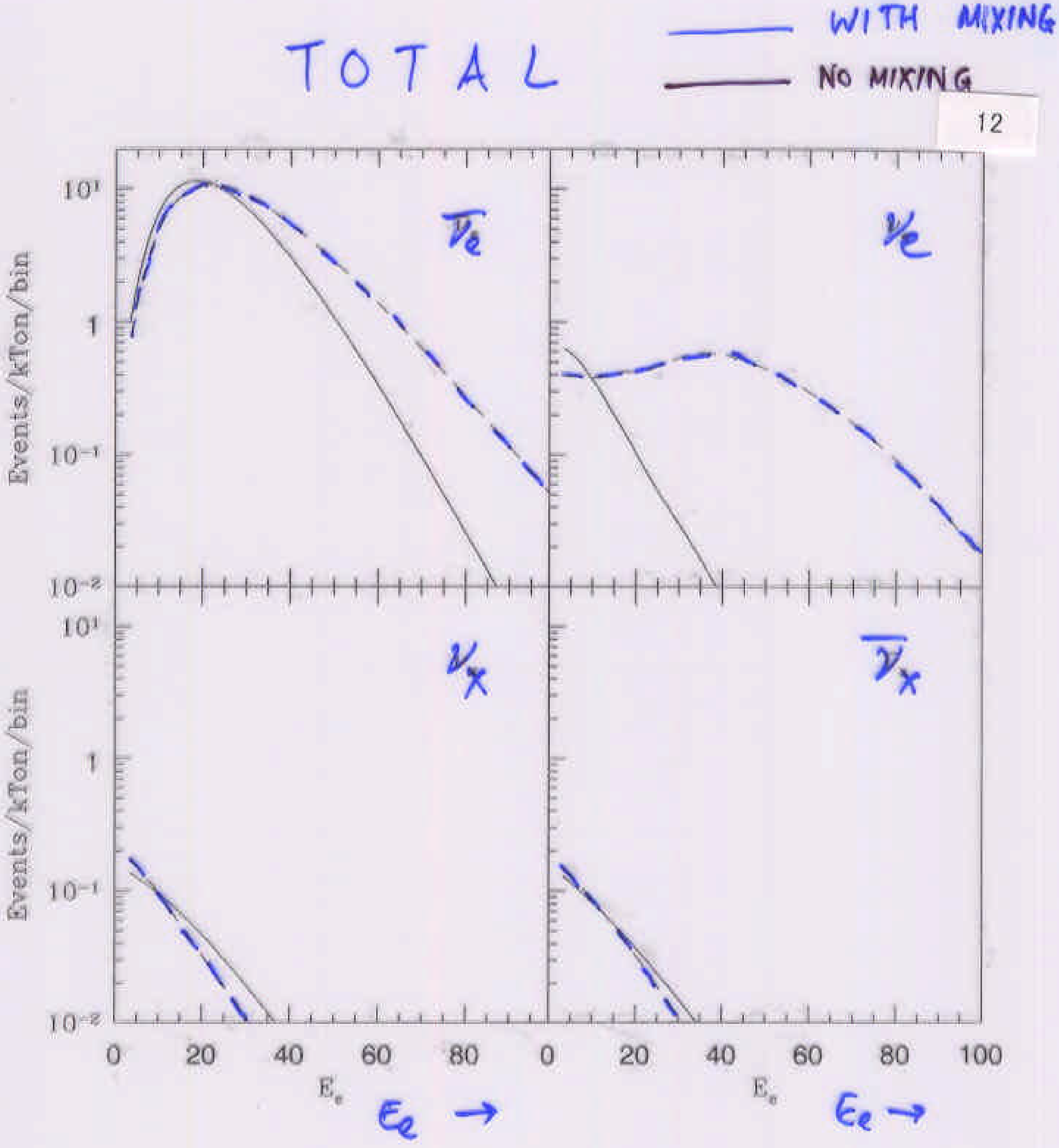


FIG. 5. The total number of events (summed over all processes) in bins of 1 MeV each, due to $\bar{\nu}_e$, ν_e, $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ interactions, are shown as a function of the electron energy. The solid and dashed lines denote the event rates without and with (maximal effect due to) mixing.

CHANNEL	NO OSC.	OSC.	
ν e	5	7	FORWARD
ν_e O	1	24	BACKWARD
$\bar{\nu}_e$ p	272	323	ISOTROPIC
$\bar{\nu}_e$ O	4	8	BACKWARD.

EVENTS ($E_e > 8$ MeV) FOR 1 kTon & 10 kPc.

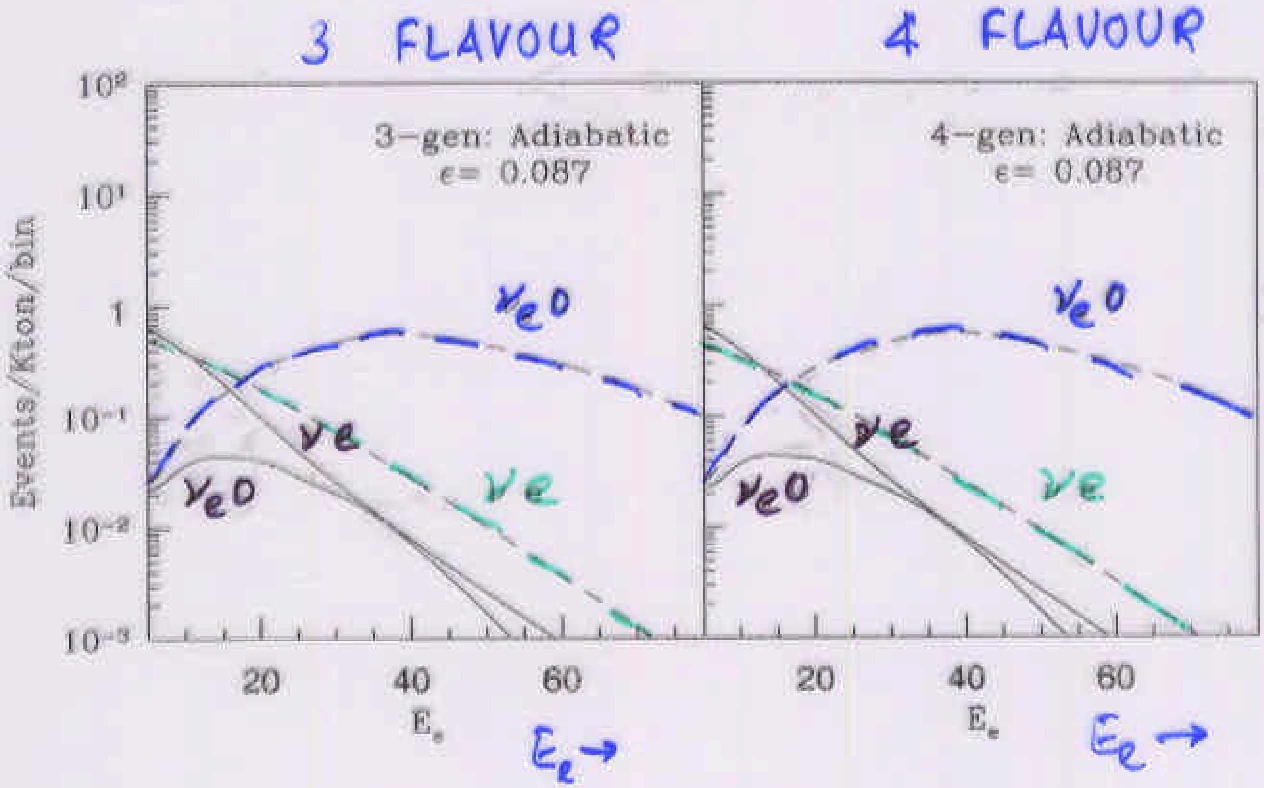
4·4

- INCLUSION OF A 4th FLAVOUR :
  - STABILITY OF RESULTS TO MORE FLAVOURS
  - DISTINCTION BETWN/ DETERMINATION OF NO. OF FLAVOURS.
  - TWO DOUBLET SPECTRUM.

ADIABATIC (NEUTRINOS)

— $\nu_e O$ — NO MIXING

— νe


3 FLAVOUR

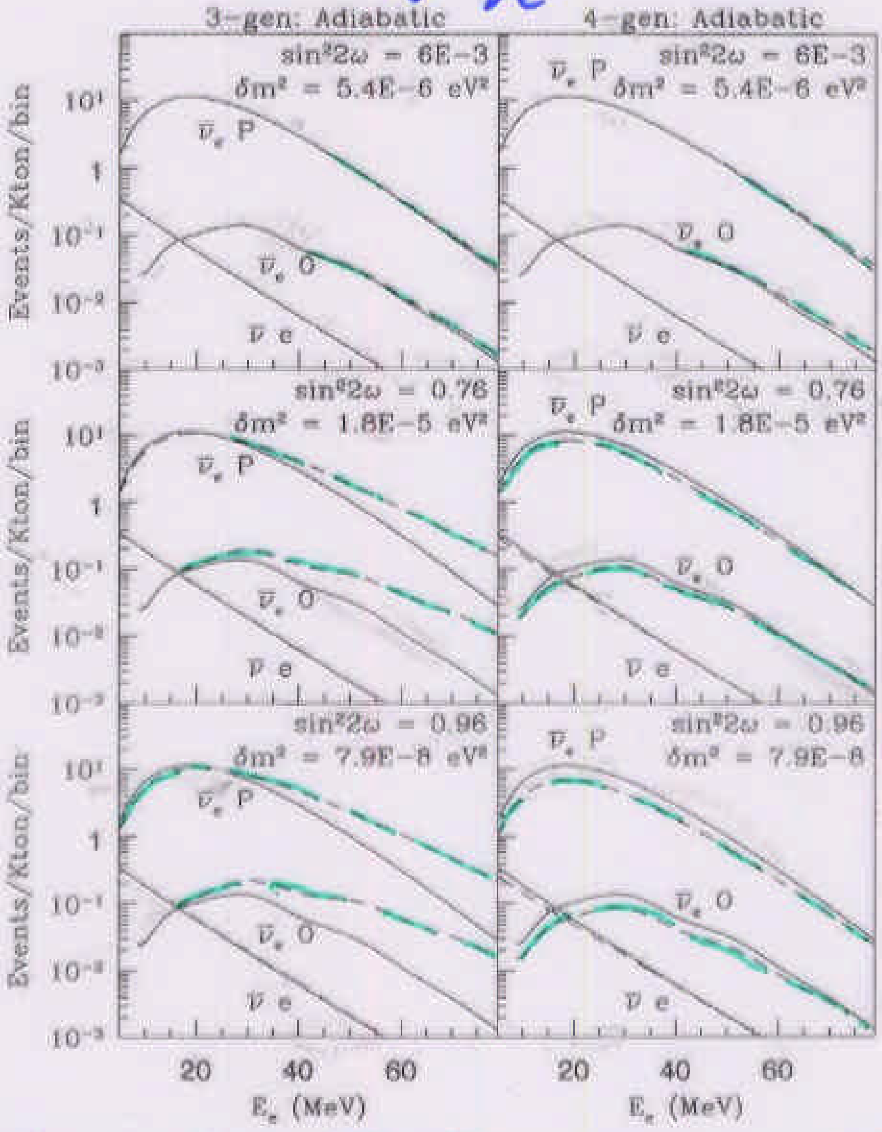
4 FLAVOUR

FIG. 3. $\nu_e O$ and νe (for all flavours of ν) event rates when the upper resonance is completely batic. The solid lines represent the no mixing case and is plotted in all the graphs for compar- . The dashed lines are due to the effects of mixing. The oxygen events show dramatic increase to mixing. Note that 3 and 4 flavour cases cannot be distinguished.

ADIABATIC (ANTINEUTRINOS)

- $\bar{\nu}_e P$
- $\bar{\nu}_e O$
- $\bar{\nu} e$

3 FLAV. 4 FLAV.



I SMA

II LMA

III LMA - V.

ω

- HIGH E_e ENHANCEMENT

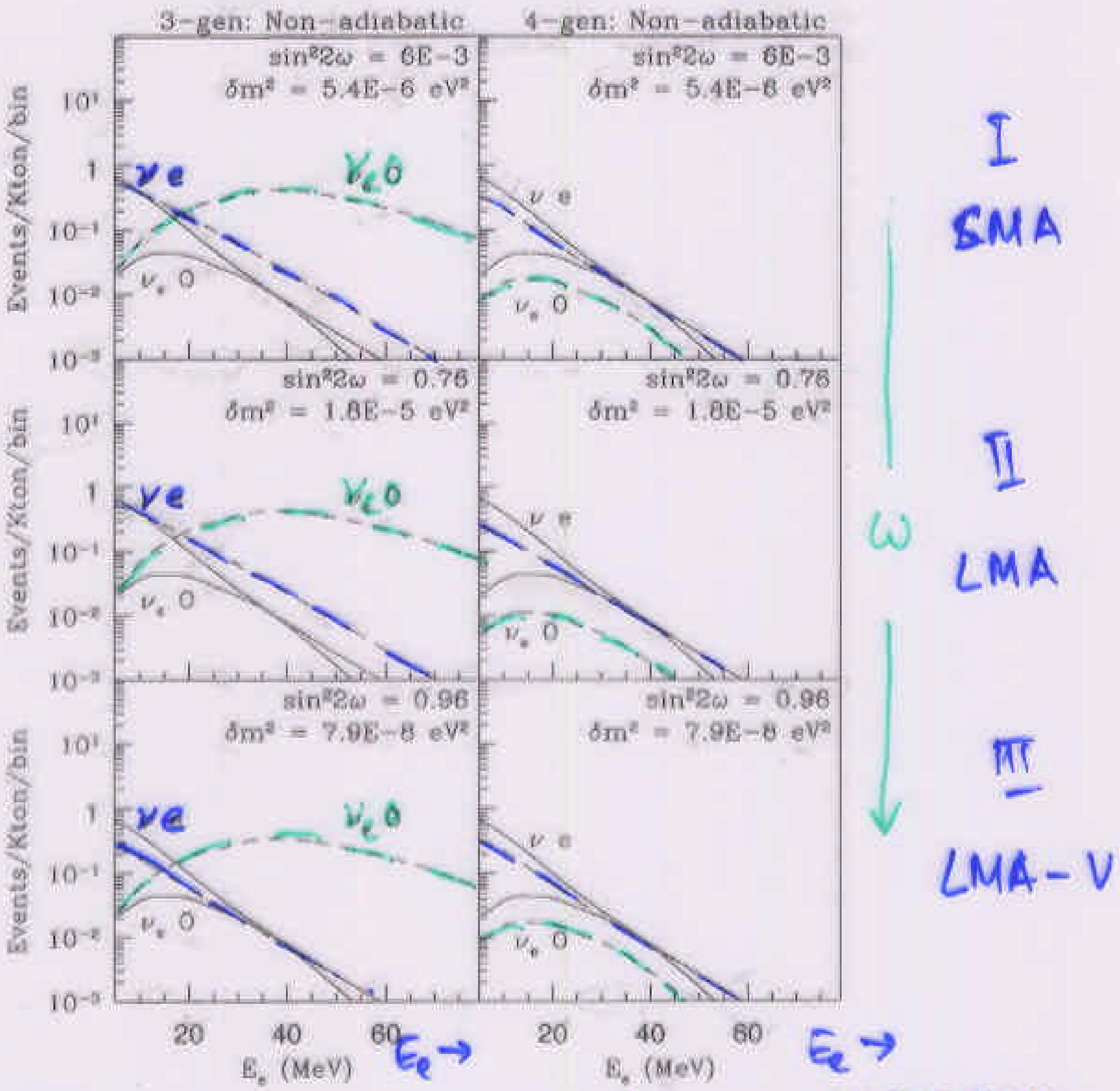
- ACTUAL DEPLETION (LOSS TO STERILE FL.)

FIG. 5. $\bar{\nu}_e$ event rates for $\epsilon = 0.087$. The solid (dashed) lines are due to (no) mixing. While the 3 flavour scheme shows enhancement of event rates at high energies due to mixing, the 4 flavour scheme shows suppression at lower energies.

NON ADIABATIC

— ν_e O

3 FLAV. — νe 4 FLAV.



• AS IN ADIABATIC

• STRONGER DEPLETION THAN IN ADIABATIC / 3 FL.

FIG. 4. $\nu_e O$ and νe (for all flavours of ν) event rates when the upper resonance is completely non-adiabatic. The results depend upon the three possible solutions to the solar neutrino puzzle and are shown in the three panels, top, middle and bottom. The three flavour results are similar to the adiabatic case shown in Fig. 3 but the 4 flavour case shows suppression of the event rates in all cases. Here the different cases are distinguished by the extent of suppression.

CONCLUSIONS:

- NEUTRINO MIXING & OSCILLATIONS GIVE RISE TO CHARACTERISTIC SIGNATURES OF NEUTRINO EMISSIONS FROM SUPERNOVAE.

- NEUTRINOS & ANTI NEUTRINOS OF ALL FLAVOURS ARE EMITTED ; HENCE DIFFERENT MIXING ANGLES CAN BE PROBED.

- LARGE $\nu_e - \nu_x$ OR $\bar{\nu}_e - \bar{\nu}_x$ MIXING IS SIGNALED BY BACKWARD PEAKED HIGH ENERGY EVENTS

- IN SOME PARTS OF THE PARAMETER SPACE, IT IS POSSIBLE TO DISTINGUISH 3- AND 4-FLAVOUR MIXING.

- HENCE A LOT OF ν-PHYSICS ISSUES CAN BE STUDIED THROUGH SUPERNOVAE.

- QUESTION : HOW FREQUENT ARE SUPERNOVAE ?!

  OUR GALAXY : 1 EVERY 10 YEARS.

  AVG : 30 YEARS.