# SUPERNOVA NEUTRINOS: EARTH MATTER EFFECTS AND THE $\nu$ MASS SPECTRUM.

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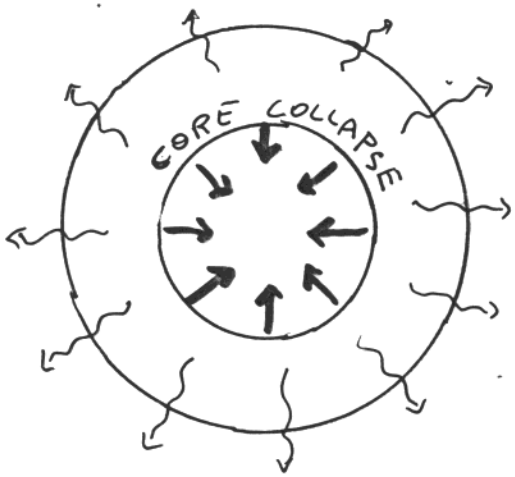
hep-ph/0106149

- SN $\nu$ FROM PRODUCTION TO DETECTION
- REGENERATION IN THE EARTH: POSSIBLE? LIKELY? OBSERVABLE?
- WHAT CAN WE LEARN?

# SOME BASICS ...




TREMENDOUS ENERGY OUTPUT:

$E_B \simeq 3 \cdot 10^{53}$ ergs !

99% $\nu$ , 1% $\gamma$ (DELAYED)

- THERMAL (F-D) SPECTRUM:

$$F_\alpha^\circ = \frac{L_\alpha}{4\pi D^2 T_\alpha^4 F_3} \frac{E^2}{e^{E/T_\alpha} + 1}$$

$L_\alpha$ = ENERGY IN $\nu_\alpha$

D = DISTANCE TO EARTH

$F_3 \simeq 5.68$

(NO MIXING, $\vartheta = 0$)

- HIERARCHY OF TEMPERATURES:

$$T_e < T_{\bar{e}} < T_x \qquad x = \mu, \tau \ (\bar{\mu}, \bar{\tau})$$

$T_e = 2\text{-}4$ MeV, $T_{\bar{e}} = 4\text{-}6$ MeV, $T_x = 7\text{-}9$ MeV

- EQUIPARTITION OF ENERGY:

$$L_\alpha = E_B/6 \qquad \forall \alpha$$

- RATE: ~ 3/CENTURY GALACTIC SNOVAE

(PATIENCE AND LUCK REQUIRED...)

# LIFE OF SN $\nu$:

CONVERSION IN THE STAR:

$\rho_s \propto r^{-3}$

$\nu_3$

$\nu_2$

$\nu_1$

OSCILLATION STOP:
(ADIABATIC CONVERSION, DECOHERENCE)
PROPAGATION AS MASS EIGENSTATES

MATTER FILTER:

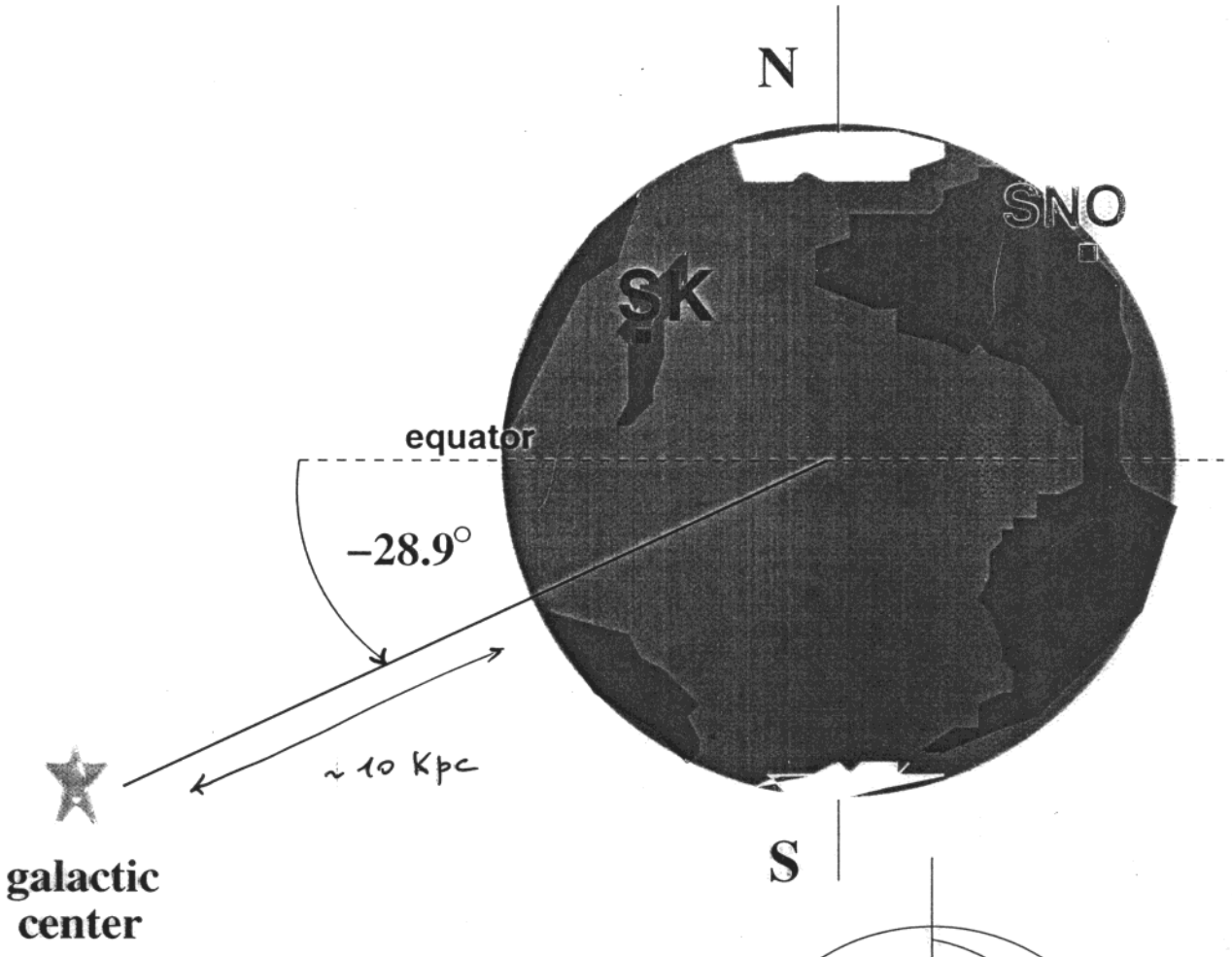
EARTH?

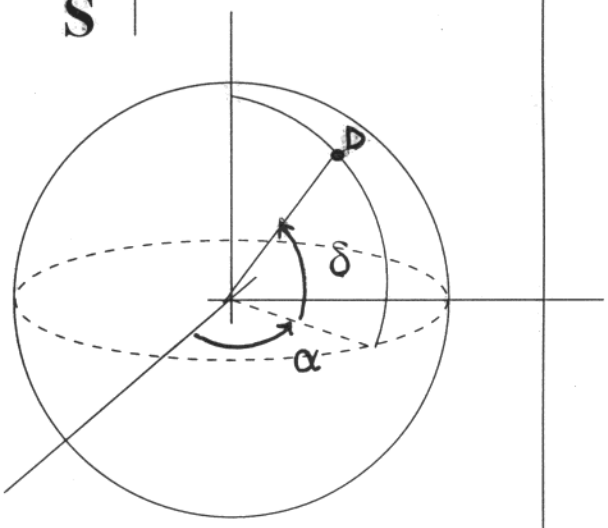
(SUN, MOON...

**OSCILLATIONS RESTARTED!**

($\nu_i \neq \nu_{i_m}$)

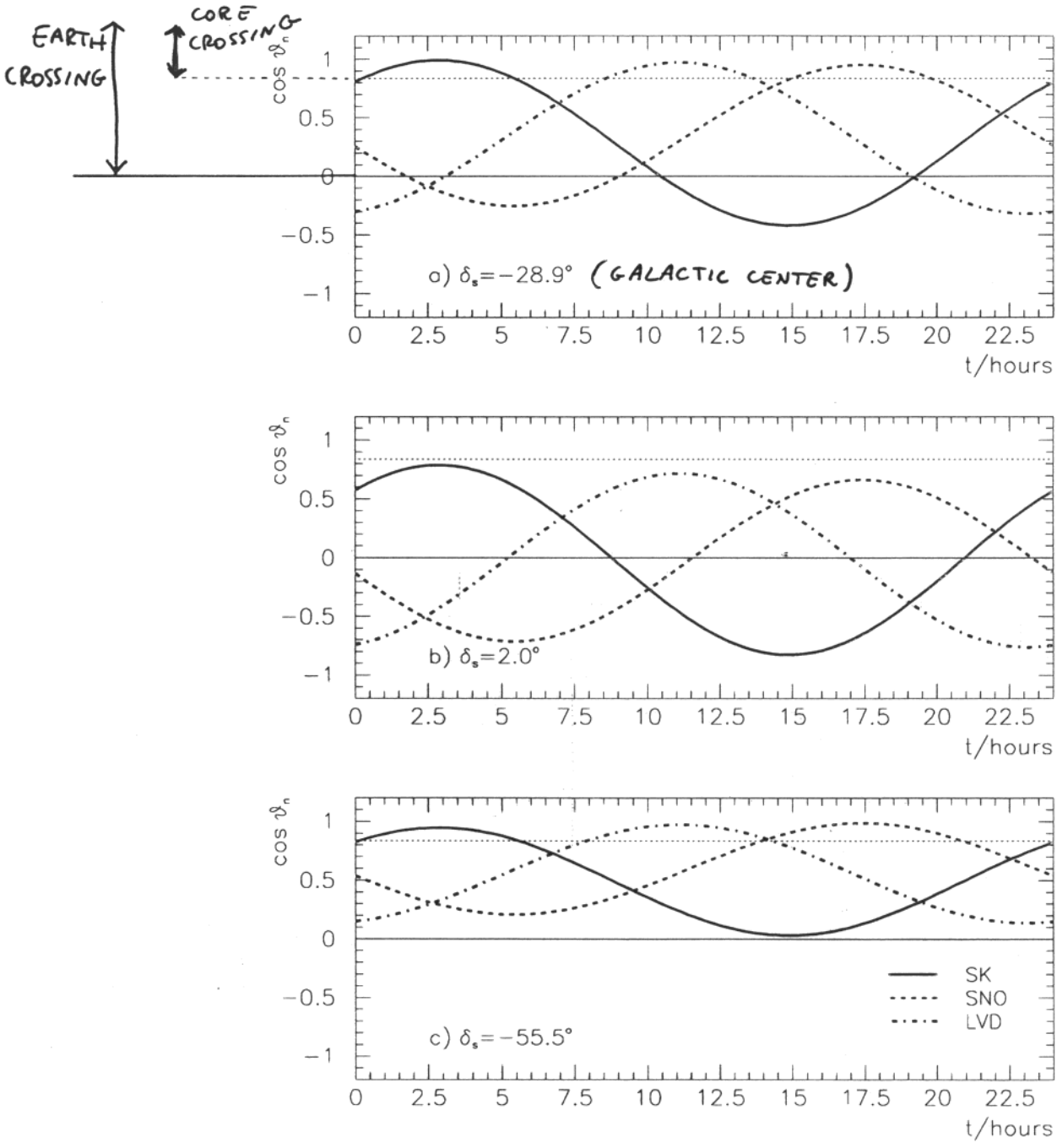
# Earth crossing: possible? likely?



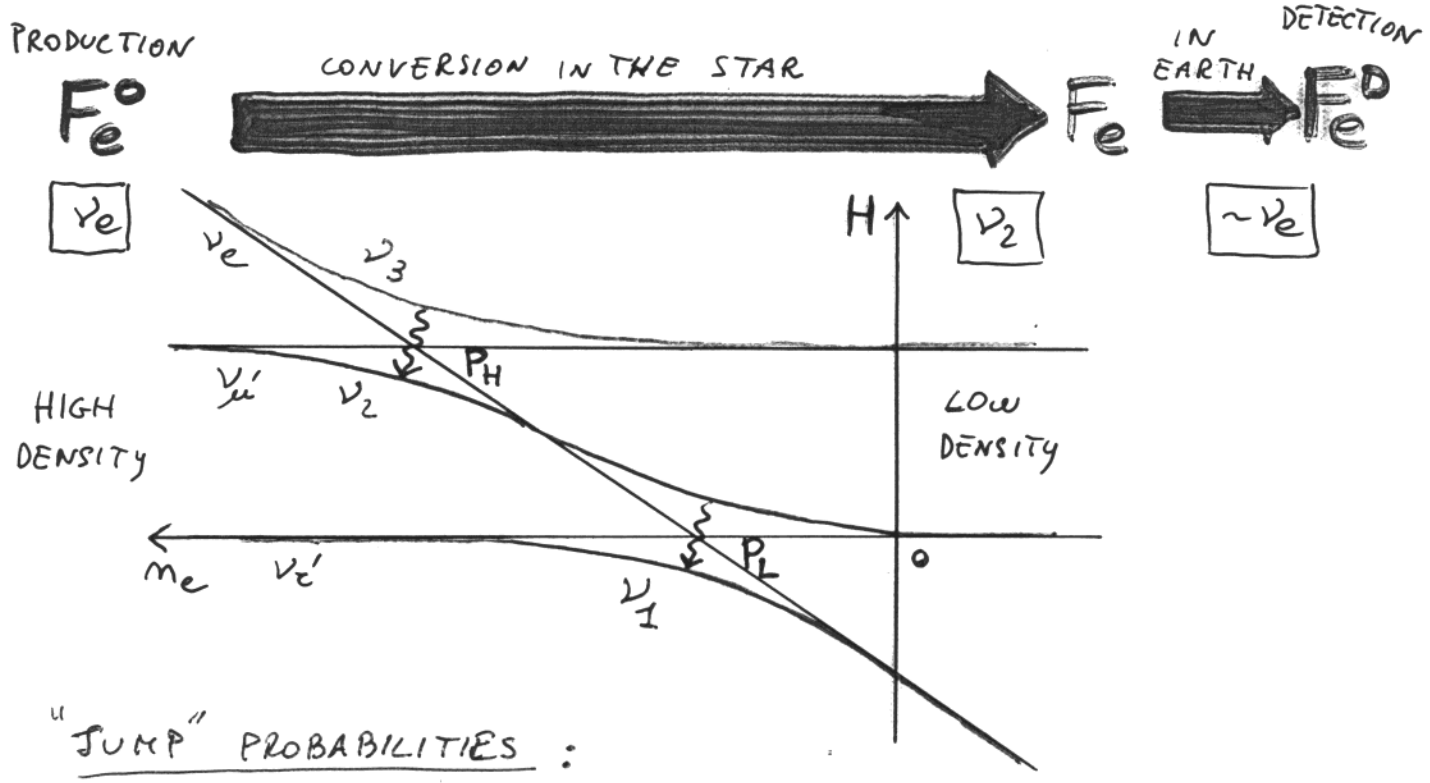

| detector | δ (deg) | α (deg) |
|---|---|---|
| SK | 36 21 | 137 18 |
| SNO | 46 30 | −81 01 |
| LVD | 42 25 | 13 31 |

# DAILY NADIR ANGLES:



# FLUXES IN THE DETECTOR:

e.g. 3 $\nu$, NORMAL HIERARCHY ($m_3 > m_2 > m_1$)




"JUMP" PROBABILITIES :

$$P_H(\Delta m^2_{atm}, U_{e3}, \rho_s, E)$$

$\Delta m^2_{atm} \approx 10^{-3} \div 10^{-2}\ eV^2$

$|U_{e3}|^2 \leq 0.02$ (CHOOZ, PALOVERDE)

$$P_L(\underbrace{\Delta m^2_\odot, \theta_\odot}, \rho_s, E)$$

↖ LMA, SMA, LOW, V.O.

$0 \leq P_{H,L} \leq 1$

↑ ADIABATICITY ↖ ADIABATICITY BREAKING

RESULT: COMPOSITE FLUX

$$\boxed{F_e^D = p F_e^0 + (1-p) F_x^0}$$

↑ HARD COMPONENT

$p$ PERMUTATION PARAMETER

# IN GENERAL:

$$F_e^D - F_e = P_H(1-2P_L)\left[P_{2,e} - \sin^2\theta_\odot\right](F_e^\circ - F_x^\circ)$$

CONVERSION IN THE STAR:

$\rho_{STAR}$, $\Delta m^2_\odot, \theta_\odot$

MASS HIERARCHY

$|U_{e3}|^2$

OSCILLATIONS IN THE EARTH:

$\rho_{EARTH}$, $\theta_\odot$, $\Delta m^2_\odot$

$P_{2e} \equiv P(\nu_2 \to \nu_e)$

$> 0 \quad E < E_c$

$< 0 \quad E > E_c$

STAR PARAMETERS

$(L_\nu, T_\nu, \dots)$

| | $\nu_e$ | $\bar{\nu}_e$ |
|---|---|---|
| $m_1 < m_2 < m_3$ NORMAL HIERARCHY | $\underline{P_H}(1-2P_L)$ $[P_{2e} - \sin^2\theta_\odot]$ $(F_e^\circ - F_x^\circ)$ ADIABATICTY BREAKING REQUIRED! ($P_H \sim 1$) | $(1-2\bar{P}_L)$ $[P_{1e} - \cos^2\theta_\odot]$ $(F_{\bar{e}}^\circ - F_x^\circ)$ |
| $m_3 < m_1 < m_2$ INVERTED HIERARCHY | $(1-2P_L)$ $[P_{2e} - \sin^2\theta_\odot]$ $(F_e^\circ - F_x^\circ)$ | $\underline{\bar{P}_H}(1-2\bar{P}_L)$ $[P_{1e} - \cos^2\theta_\odot]$ $(F_{\bar{e}}^\circ - F_x^\circ)$ ADIABATICITY BREAKING REQUIRED! ($\bar{P}_H \sim 1$) |

MORE ON $P_H$ :

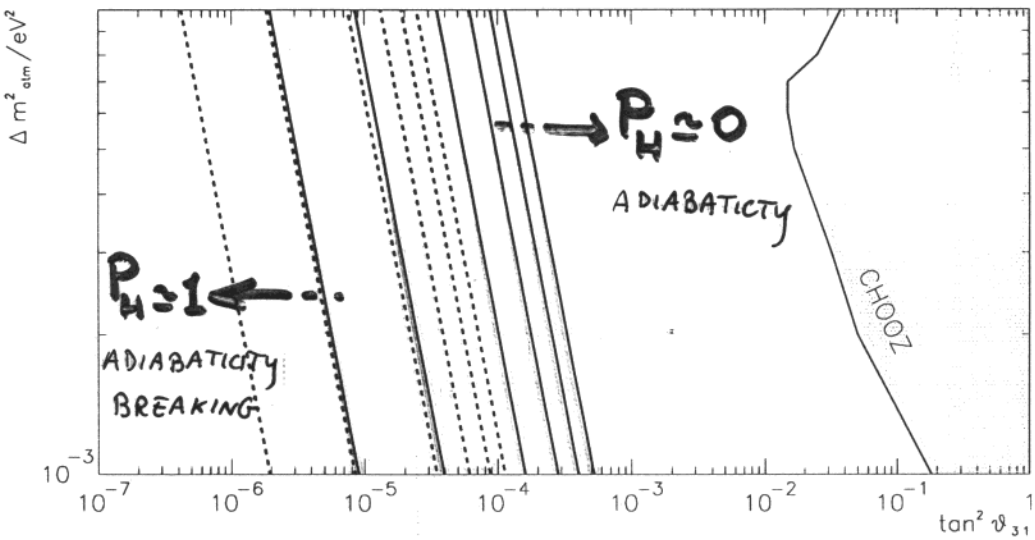


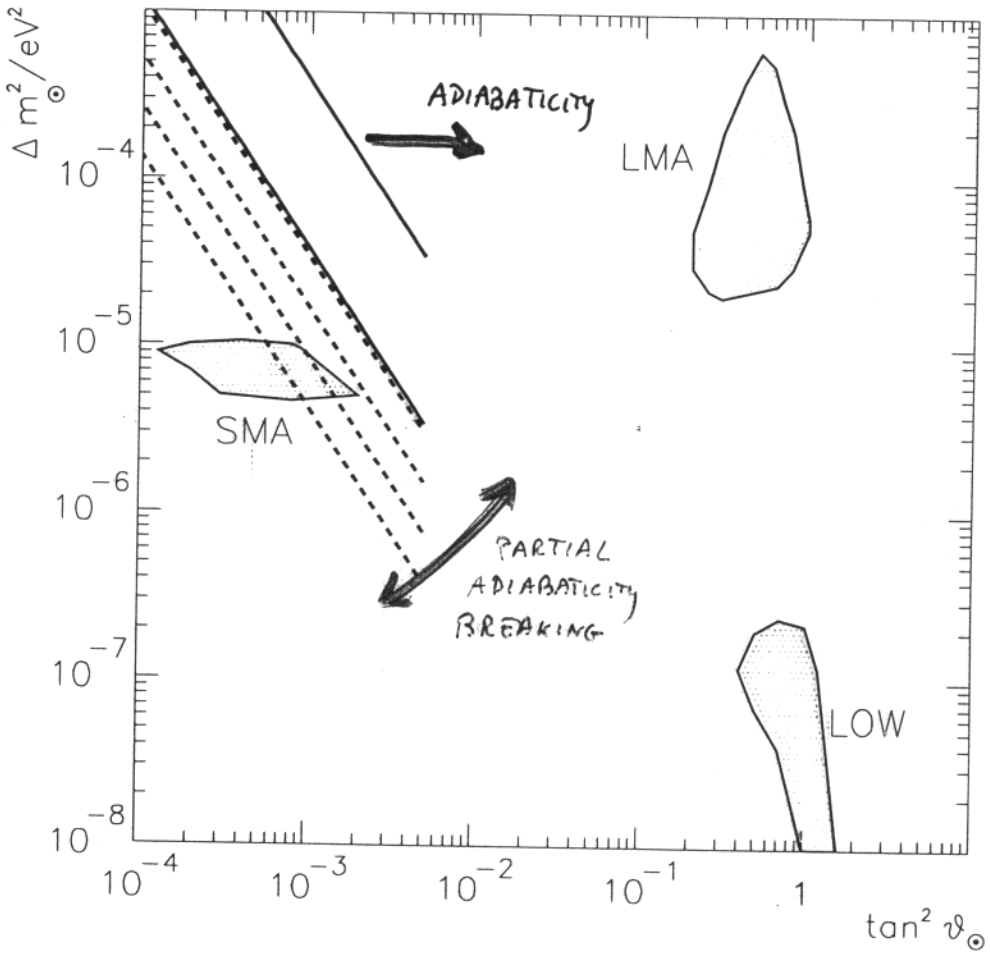

Figure 1: Lines of constant flip probability $P_H$ in the $\Delta m^2_{atm}$-$\tan^2\theta_{31}$ plane. The solid lines refer to $E = 50$ MeV and correspond, from right to left, to $P_H = 0.05, 0.1, 0.2, 0.4, 0.8, 0.95$. The dashed lines correspond to the same values of $P_H$ with $E = 5$ MeV. The exclusion region from the CHOOZ experiment is shown.

# MORE ON $P_L$ :

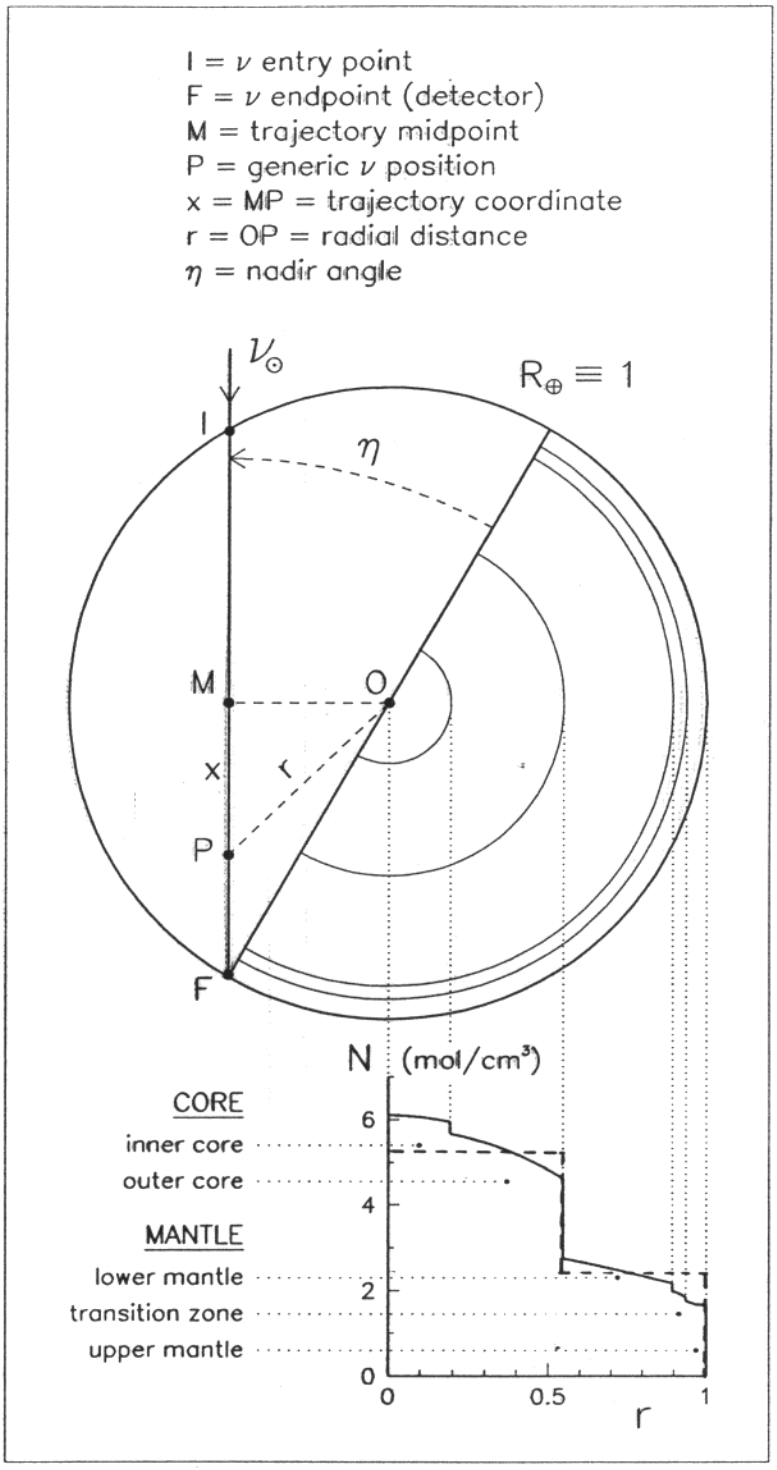
(LINES ONLY FOR $\rho_{Res} \gtrsim 1\ g \cdot cm^{-3}$)

—— $P_L = 0.05$ $E = 50$ MeV
$E = 5$ MeV

----- $P_L = 0.5$ $E = 40, 20, 10, 5$ MeV
FROM UPPER TO LOWER



# THE EARTH: DENSITY PROFILE




--- 3 LAYERS APPROXIMATION

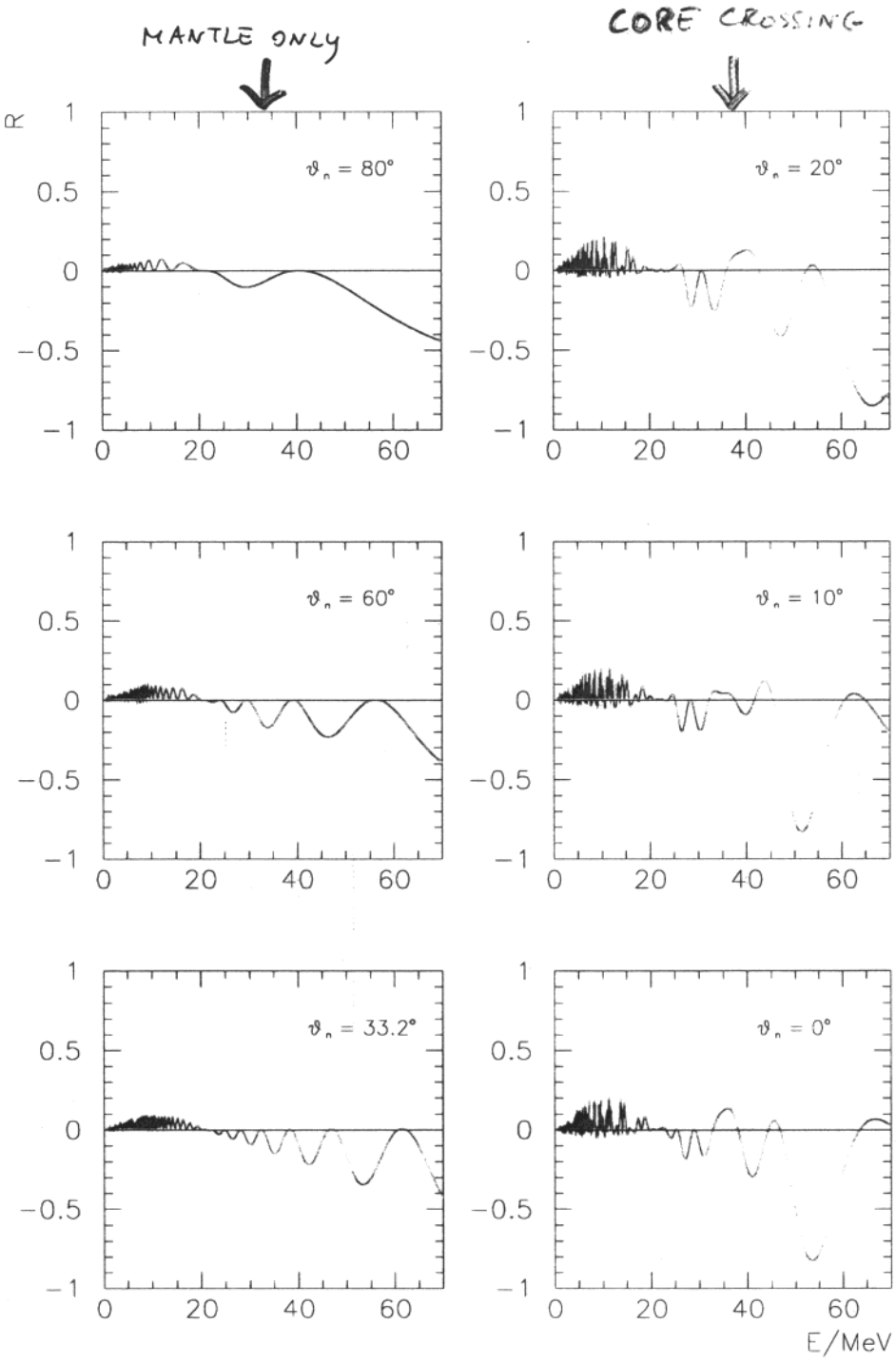
FIG. 1. Section of the Earth showing the relevant shells (in scale) and the electron density profile $N(r)$. The geometric definitions used in the text are also displayed.

from: E. Lisi and D. Montanino, Phys. Rev. D 56 1792-1803, 1997 hep-ph/9702343.

# OSCILLATIONS: RELATIVE EFFECT

$$R \equiv \left(F_e^D - F_e\right)/F_e$$

$\nu_e$, LMA, $P_H = 1$ (OR INVERTED HIERARCHY)




LMA $\begin{cases} \Delta m^2_{\odot} = 5 \cdot 10^{-5}\ eV^2 \\ \sin^2 2\vartheta_{\odot} = 0.75 \end{cases}$

$T_e = 3.5$ MeV

$T_x = 8$ MeV

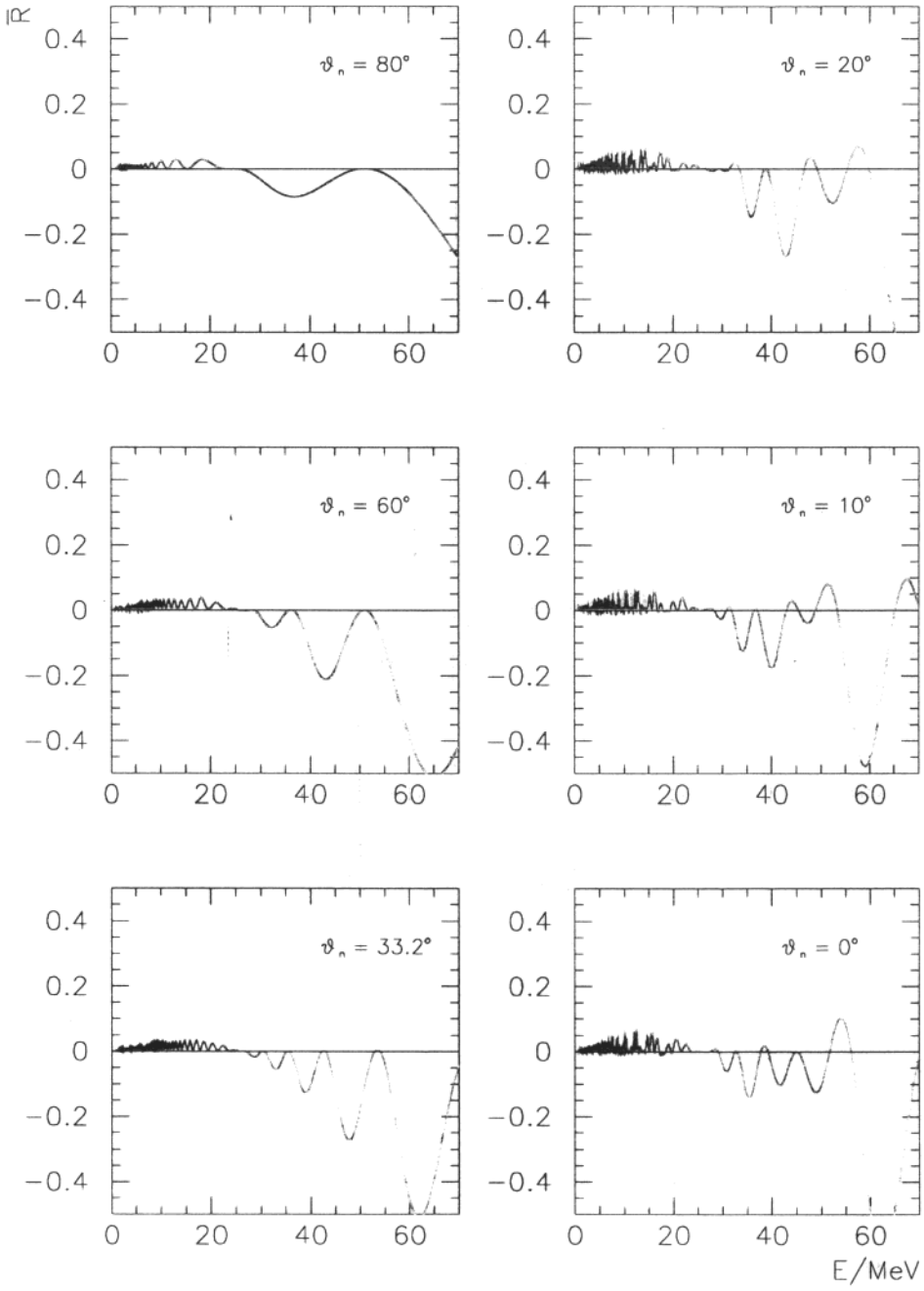


[REALISTIC (PREM) EARTH PROFILE USED]

$$\bar{R} \equiv \left(F_{\bar{e}}^{D} - F_{\bar{e}}\right) / F_{\bar{e}}$$

$\bar{\nu}_e$ , LMA

( $P_H = 1$ IF HIERARCHY INVERTED )




LMA $\begin{cases} \Delta m^2_{\odot} = 5 \cdot 10^{-5}\ eV^2 \\ \sin^2 2\vartheta_{\odot} = 0.75 \end{cases}$

$T_{\bar{e}} = 5$ MeV

$T_x = 8$ MeV

# EXPECTED SPECTRA: "PESSIMISM"

$\Delta m^2_{\odot} = 5 \cdot 10^{-5}\ eV^2$

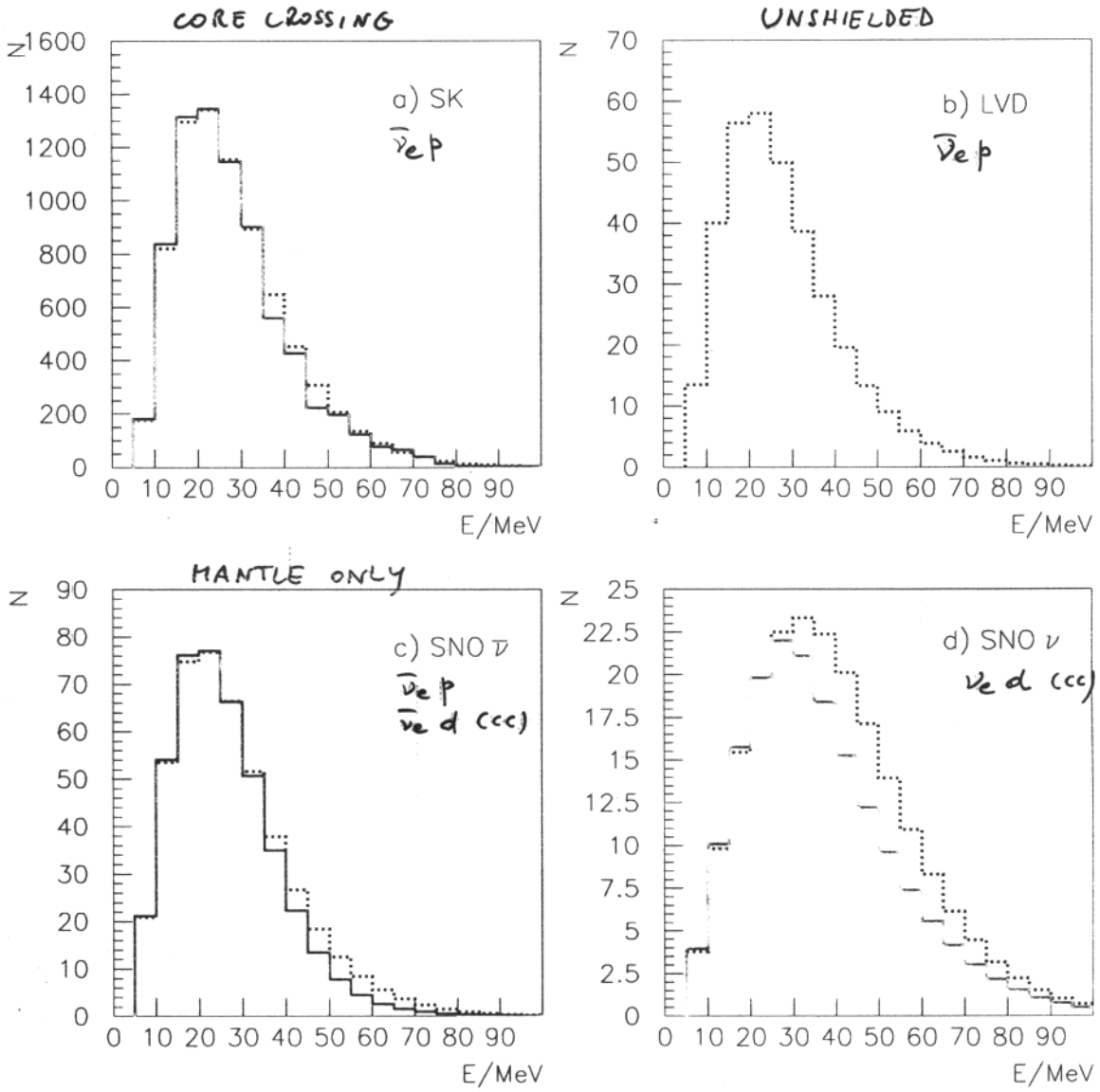
$\sin^2 2\vartheta_{\odot} = 0.75$

$T_e = 3.5$ MeV, $T_{\bar{e}} = 5$ MeV, $T_{\nu} = 8$M

$E_B = 3 \cdot 10^{53}$ ergs, $D = 10$ kpc

- - - - - WITHOUT EARTH EFFECT

t=1 hour



"OPTIMISM"

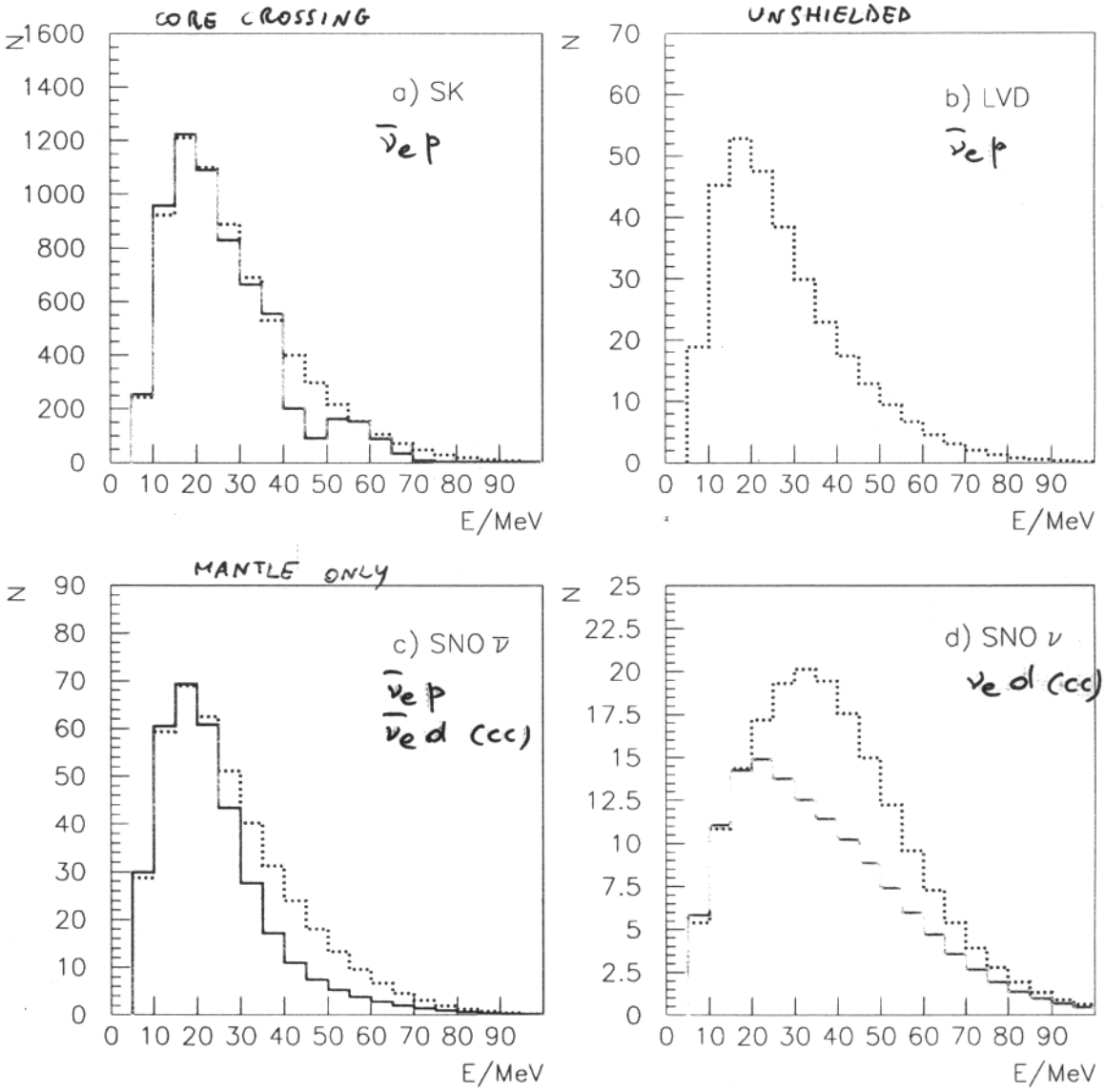
$\Delta m^2_{\odot} = 3 \cdot 10^{-5}\ eV^2$

$\sin^2 2\vartheta_{\odot} = 0.9$

$T_e = 3$ MeV, $T_{\bar{e}} = 4$ MeV, $T_{\nu_x} = 8$ MeV

$E_B = 3 \cdot 10^{53}$ ergs, $D = 10$ kpc

t=1 hour

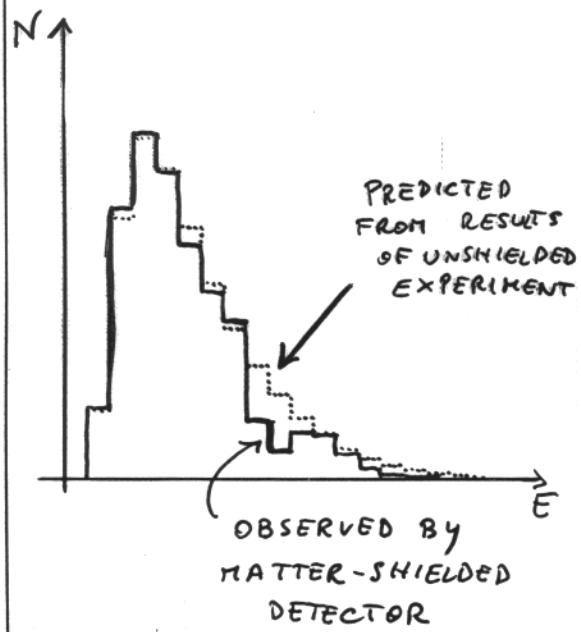


# HOW TO OBSERVE EARTH EFFECTS:

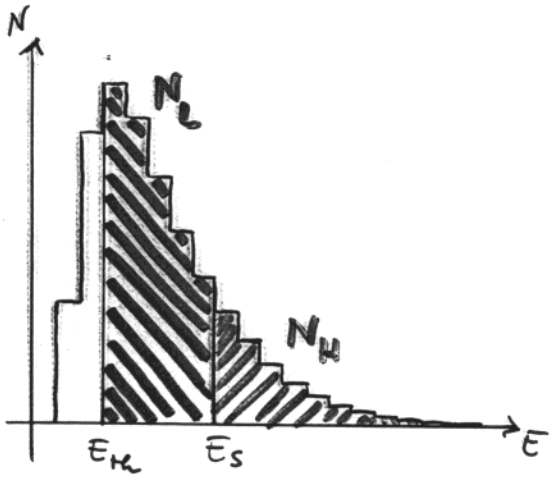
## 1. LOOK FOR DISTORTIONS OF THE ENERGY SPECTRUM (OSCILLATIONS)

## 2. COMPARISON WITH UNSHIELDED DETECTOR:

ENERGY SPECTRA:




INTEGRATED QUANTITIES:



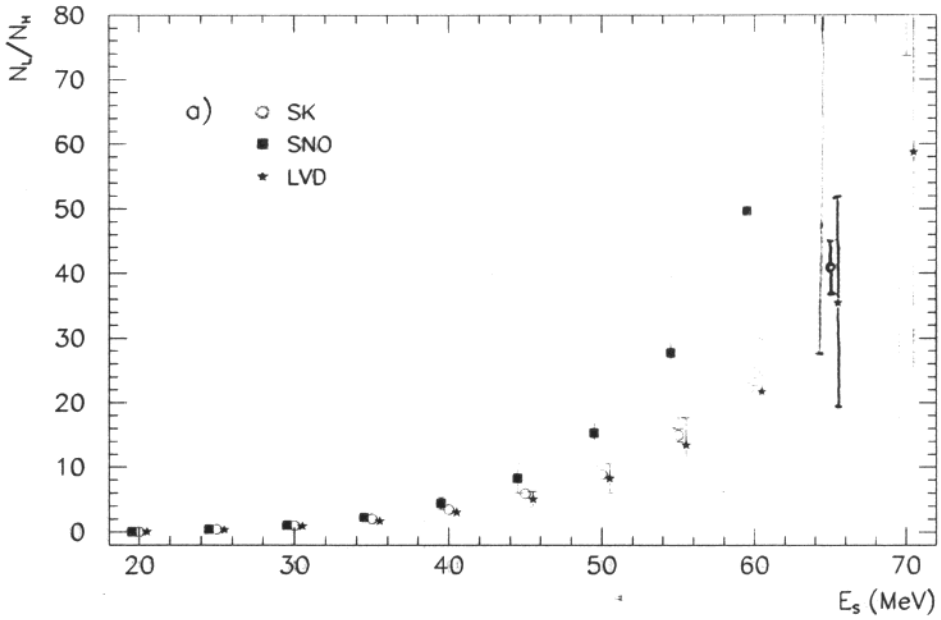

$$R \equiv \frac{N_L(\bar{\nu}_e p)}{N_H(\bar{\nu}_e p)}$$

RATIO LOW/HIGH ENERGY NUMBERS OF EVENTS

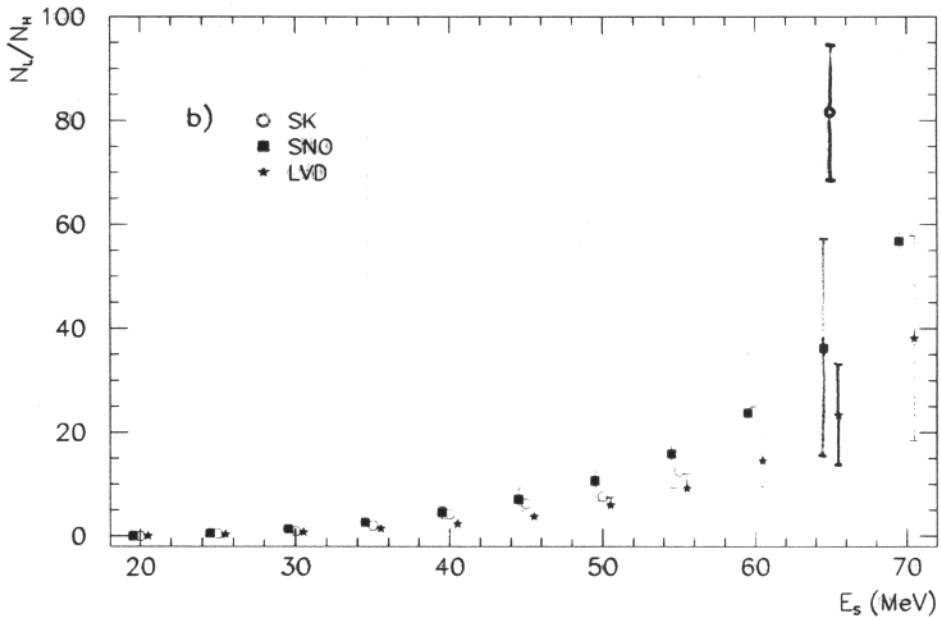
**RESULT:** 2-3 $\sigma$ EFFECT FOR LARGE - SMALL (SK) (LVD)

4-5 $\sigma$ EFFECT FOR LARGE - LARGE (SK, HYPERK.) (UNO, NUSL, ...)

"PESSIMISM":




"OPTIMISM":



# WHAT CAN BE LEARNT?

EARTH EFFECTS CAN:

- SELECT THE SOLUTION OF $\nu_\odot$ PROBLEM:

  OSCILLATIONS $\Longrightarrow$ LMA

  LOCALIZED DISTORTION $\rightsquigarrow$ SMA ($\nu_e$ ONLY)

- "STAR-INDEPENDENT" INFO ON MASS HIERARCHY

  BOUNDS ON $|U_{e3}|^2$ ($\leftarrow P_H$)

| $P_H$ | $\lvert U_{e3}\rvert^2$ | HIERARCHY | EARTH EFFECT (LMA) | |
|---|---|---|---|---|
| | | | $\nu_e$ | $\bar{\nu}_e$ |
| $\sim 0$ | $\gtrsim 10^{-4}$ | NORMAL | NO | YES |
| | | INVERTED | YES | NO |
| $\sim 1$ | $\lesssim 10^{-5}$ | NORMAL | YES | YES |
| | | INVERTED | YES | YES |

- RESTRICTION OF THE $\Delta m^2_\odot - \sin^2 2\theta_\odot$ REGION (BY OBSERVING DIFFERENCES)

# CONCLUSIONS

- NEUTRINOS FROM A GALACTIC SUPERNOVA ARE LIKELY TO CROSS THE EARTH BEFORE DETECTION

- $\nu$ CONVERSION EFFECTS IN THE EARTH ARE IMPORTANT AND CAN BE OBSERVED
  (OBSERVATION IN 187 IS NOT EXCLUDED*...)

- ONE CAN LEARN ON:
  - $\nu_\odot$ SOLUTION
  - $\nu$ MASS HIERARCHY
  - $|U_{e3}|^2$

* C.L. and A.Yu. Smirnov, Phys. Rev D63 (2001) 073009 (hep-ph/0009356)