Smirnov - 01

Neutrino Mass Spectrum and Lepton Mixing

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Status and perspectives of reconstruction of the neutrino mass and flavor spectrum

Major steps
Recent results
New ideas

Neutrino 2000
Sudbury
June 18

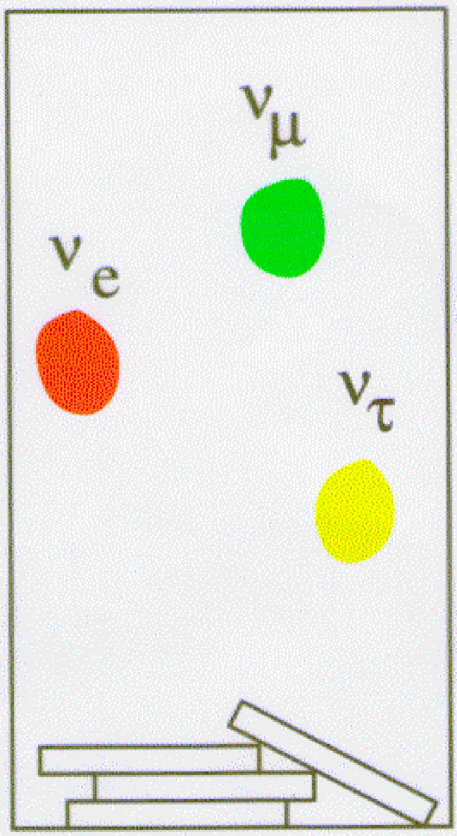
Two remarks:

- *There is a hope that detailed information on neutrino mass spectrum and mixing (just knowledge of the fact that the masses are small is not enough) may eventually shed some light on*
  - *the origin of neutrino mass*
  - *quark-lepton symmetry / unification / GUT*
  - *fermion mass problem in general*
  - *physics beyond the standard model*

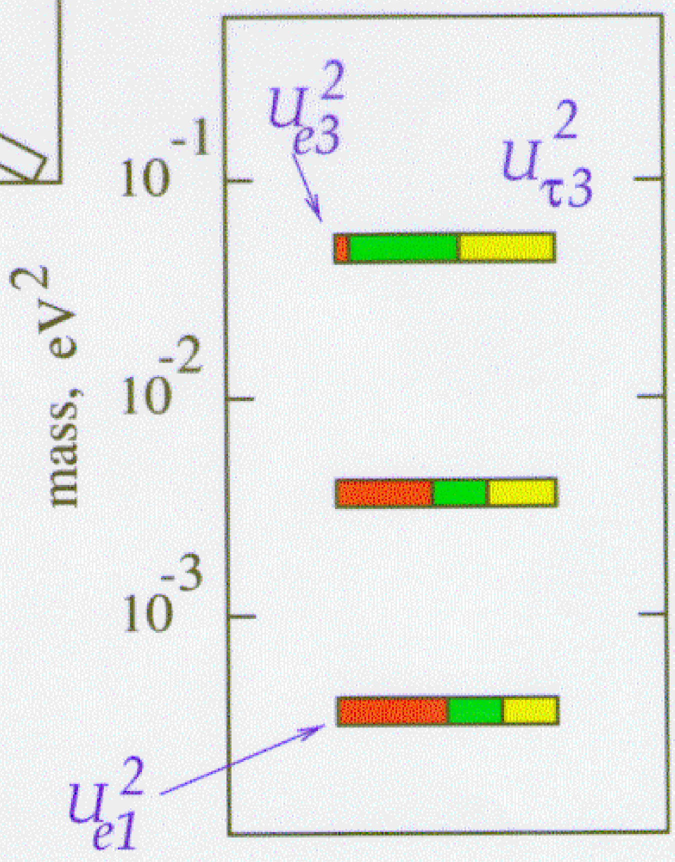
- *Results on atmospheric neutrinos show that the simplest possibility:*
  hierarhical mass spectrum
  with small flavor mixing
  has not realized

  We should consider without prejudice <u>all possible</u> mass and mixing spectra which do not contradict experiment.

Neutrino Mass Spectrum



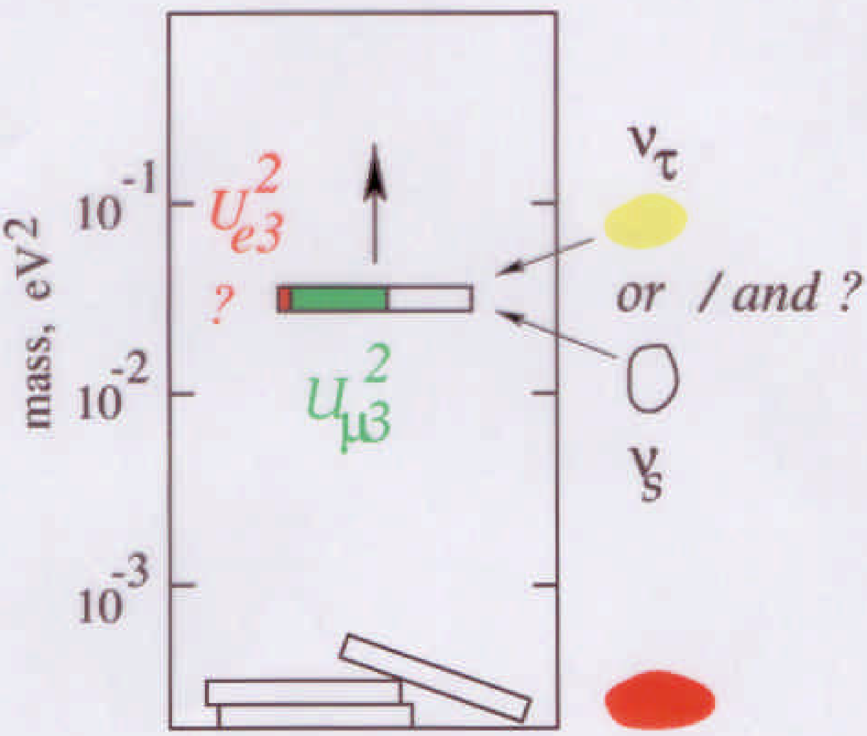
mixing flavors in the mass eigenstates



Where we are now?

ν_{atm} : *provide us with the most reliable and unambiguous information*

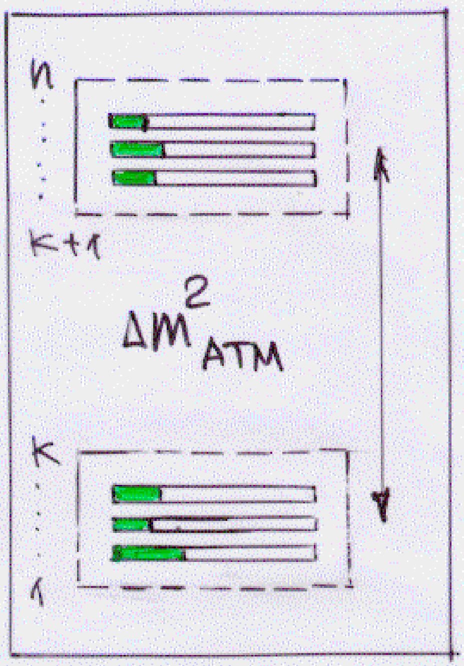
the highest confidence level



- $m_3 \gtrsim \sqrt{|\Delta m^2_{atm}|} \gtrsim 3 \cdot 10^{-2}$ eV
- $U_{\mu 3}^2 = 0.3 - 0.7$
- $U_{e3}^2 \lesssim 0.015 - 0.05$

CONTINUED ...

IN GENERAL:



IF ONLY ONE Δm^2 RELEVANT FOR ν_{ATM}

TWO BLOCKS OF STATES WITH $\Delta m^2_{ij} \ll \Delta m^2_{ATM}$

- DEPTH OF OSCILLATIONS:

$$4\, \tilde{U}_{\mu 3}^2 \cdot (1 - \tilde{U}_{\mu 3}^2)$$

$$\tilde{U}_{\mu 3}^2 \equiv \sum_{i=k+1}^{n} U_{\mu i}^2$$

- ATMOSPHERIC ν WITHOUT LARGE MIXING

IF THERE ARE MANY STATES:

$U_{\mu i}^2 \ll 1$ BUT $\tilde{U}_{\mu 3}^2 = O(1)$

$\nu_\mu \to \nu_\tau / \nu_s$ ν_s-CHANNEL DOMINATE.

QUESTIONS:

ν_{ATM}: $\nu_\mu \to \nu_\tau$, ν_S

U_{s3}

$U_{e3} = ?$

U_{ei}

DISTRIBUTION OF ν_e-FLAVOR

SIGN OF Δm^2_{32}: TYPE OF MASS HIERARCHY

$\Delta m^2_{\odot} = ?$

ν_S IN SOLAR ν OSCILL.

HOW MANY MASS EIGENSTATES (Δm^2) PARTICIPATE IN ν_{ATM} OSC.?

HOW MANY Δm^2?

ABSOLUTE MASS SCALE m_1

LEVEL OF DEGENERACY

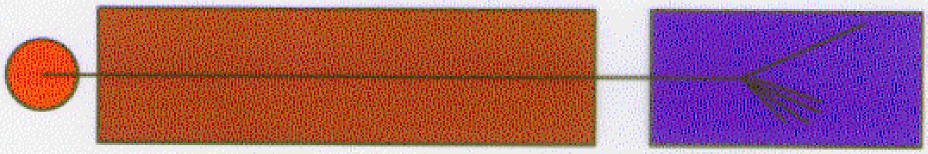
CP-VIOLATION PHASE δ_{cp}

PHASES OF MASS EIGENSTATES φ_2, φ_3

↑ NON-OSCILLATION PARAMETERS

↑ OSCILLATION PARAMETERS

ν_τ versus ν_s



Propagation

Interaction in detector

$\nu_\mu - \nu_\tau$

Vacuum Oscillations
No matter effects

CC:
- *τ-appearance*

NC: unchanged
- *π^o -events*
- *NC enriched sample*

$\nu_\mu - \nu_s$

Matter effects on oscillations

Modifications of
- *zenith angle distribution*
- *energy dependence*

CC: suppressed
- *no τ*

NC: suppressed
suppression of
- *π^o -events*
- *NC enriched sample*

ν_τ and ν_s

- *In schemes with sterile neutrinos (e.g. when ν_s is mainly responsible for the solar neutrino conversion) one expects, in general, some mixing of ν_s in the third mass eigenstate:*

$$U_{s3} \neq 0$$

- *Atmospheric neutrinos: effects intermediate between pure ν_s and ν_τ cases*

- *Long Base Line experiments:*

$$\tau\text{-appearance} \neq 1 - \mu\text{-disappearance}$$

$$1 - P_{\mu\mu} - P_{\mu\tau} = 4\, U_{\mu 3}^2 U_{s2}^2 \sin^2\frac{\phi}{2}$$

Where are other mass eigenstates?

Assume that ν_1 , ν_2 *are responsible for solution of the solar neutrino problem:*

$$\Delta m^2_{12} = \Delta m^2_{\odot}$$

Hierarchy of Δm^2 *?*

$$\Delta m^2_{\odot} << \Delta m^2_{atm}$$

Best fit points of the solar neutrino data (LMA, LOW, SMA, VO solution regions) satisfy this inequality

Measuring $\Delta m^2_{\odot}$

- *Reactor experiments, KAMLAND*
- *Day-Night asymmetry of the solar neutrino rate*
- *Atmospheric neutrino data: excess of the e-like events in sub-GeV sample. Screening ot the effect?*

Distribution of the electron flavor

$U_{ei} = ?$

mainly in ν_1 and ν_2 mass eigenstates

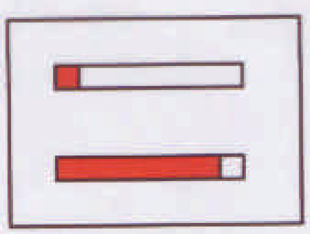
will be determined by solving the solar neutrino problem

Key step:

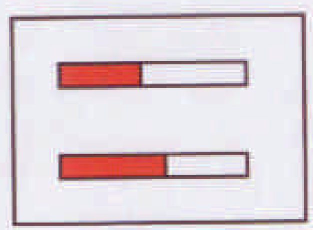
Identification of the solution of the solar neutrino problem

Set of solutions:

SMA

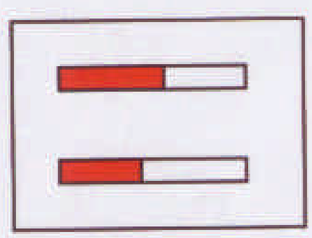


LMA, LOW, VO

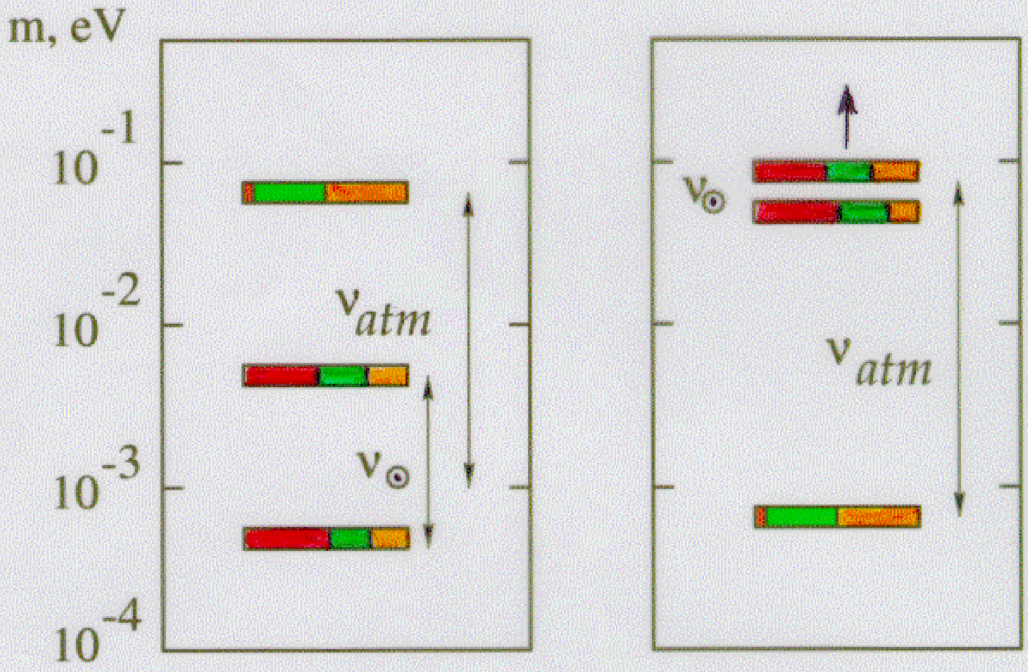


inverted hierarchy

(dark side)



Type of the mass hierarchy



Normal mass hierarchy

$\Delta m^2_{atm} > 0$

Inverted mass hierarchy

$\Delta m^2_{atm} < 0$

(partial degeneracy)

$\rho_\nu \gtrsim 2 \cdot \sqrt{\Delta m^2_{ATM}}$

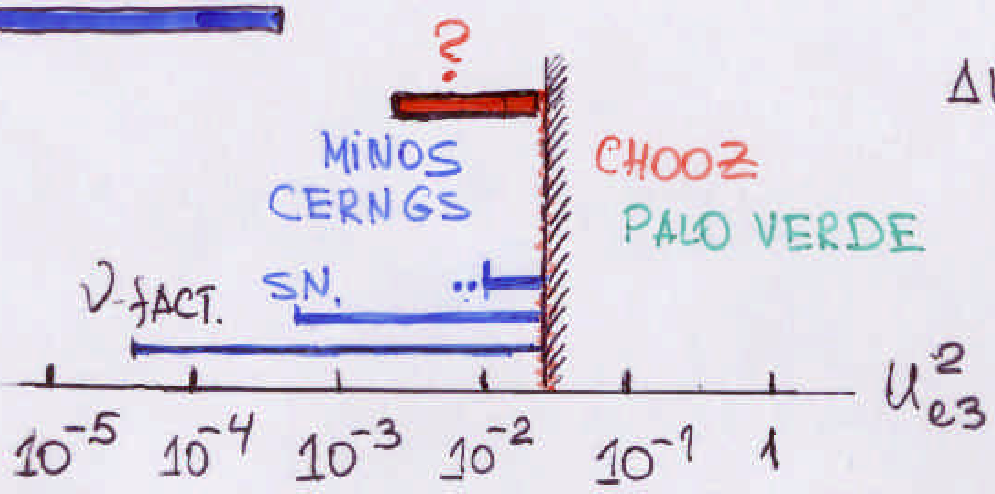
Phenomenology is different:

- *Supernova neutrinos*
- *Neutrinoless double beta decay*
- *Earth matter effects,* $U_{e3}^2 \neq 0$

CONTINUED... →

U_{e3} :

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



ARE WE CLOSE TO DISCOVERY ?

SMALL   NO TUNING

$$M = m_0 \begin{vmatrix} K & \epsilon & \epsilon' \\ \epsilon & 1+\delta-\delta' & 1-\delta \\ \epsilon' & 1-\delta & 1+\delta+\delta' \end{vmatrix}$$

$$U_{e3}^2 = \frac{1}{4} \cdot \frac{\tan^2 2\theta_{12}}{(1+\tan^2 2\theta_{12})^{1/2}} \cdot \frac{\Delta m_\odot^2}{\Delta m_{ATM}^2}$$

Akhmedov
Branco
Rebelo

LMA

TWO PARAMETERS $\tilde{\epsilon}, \tilde{\delta}$

⇒ RELATION BETWEEN 3 observables

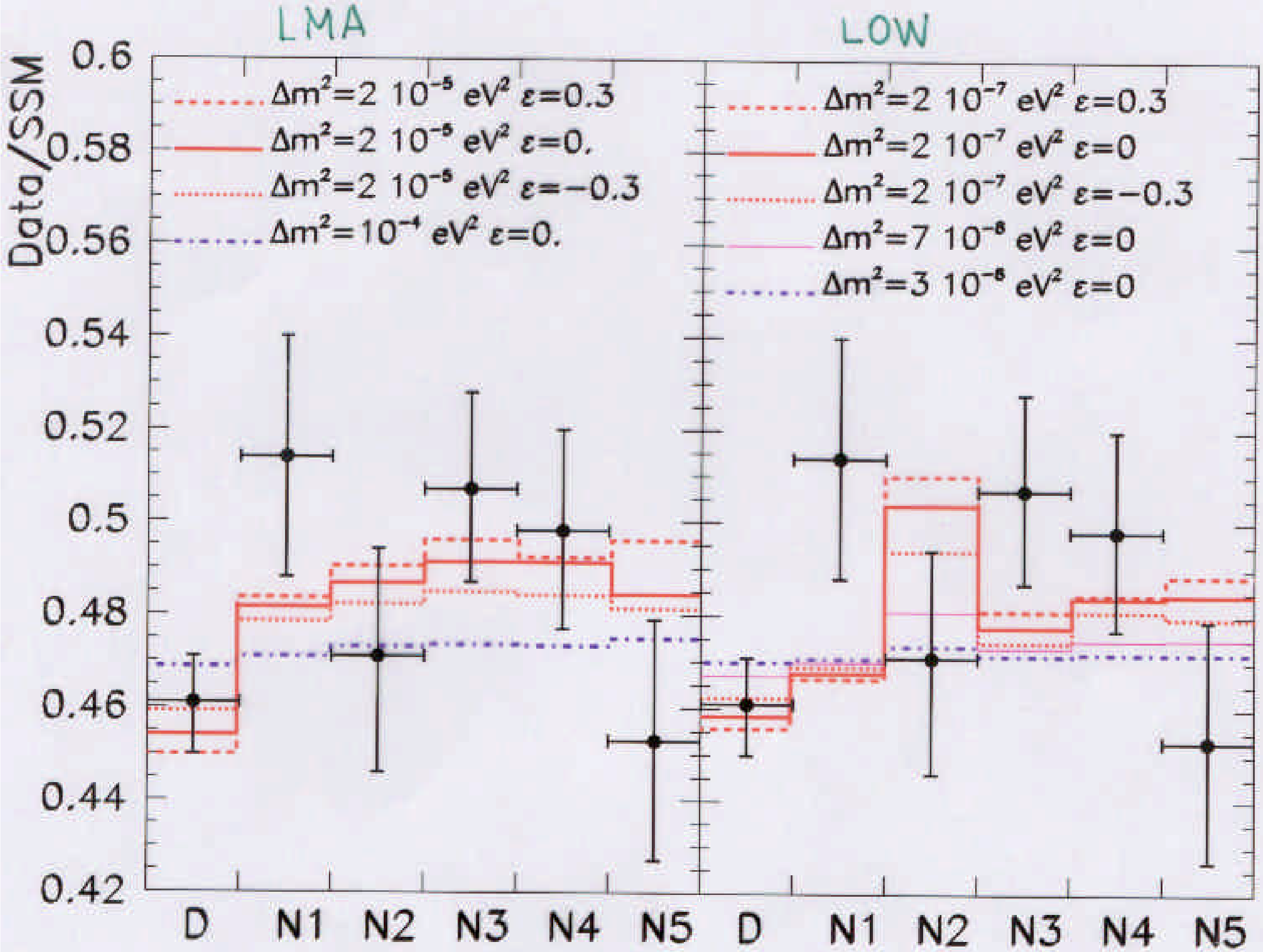
LMA: $U_{e3}^2 = 2.5 \cdot 10^{-3} \div 0.02$

IDENTIFYING SOLUTION OF THE $\nu_{\odot}$-PROBLEM

- FLUX DURING THE NIGHT
- CORRELATIONS OF OBSERVABLES
- CAN ATMOSPHERIC NEUTRINOS HELP ?
- LARGE OR MAXIMAL ?

. Guth, Randall, Serna
. De Gouvea Friedland
. Murayama
. Gonzalez-Garcia
Peña - Garay.
Y. Nir, A.S

ZENITH ANGLE DISTRIBUTION



GONZALEZ GARCIA
PEÑYA-GARAY
NIR
S.

Correlations of Observables

BAHCALL
KRASTEV
S.
hep-ph/
0006078

Observables: X Y Z

- *rates, (total fluxes)*
- *characteristics of spectrum distortion (shift of the first moment, slope ...)*
- *characteristics of time variations of signals (A_{N-D} θ_Z distribution winter-summer asymmetry*

Correlations

- signatures of solutions

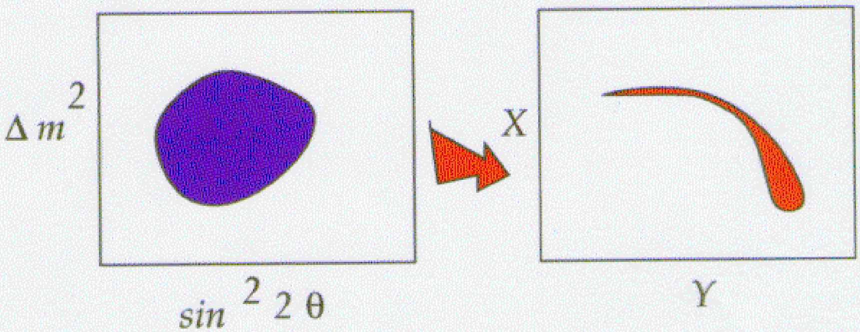
enhancement of the identification power of analysis

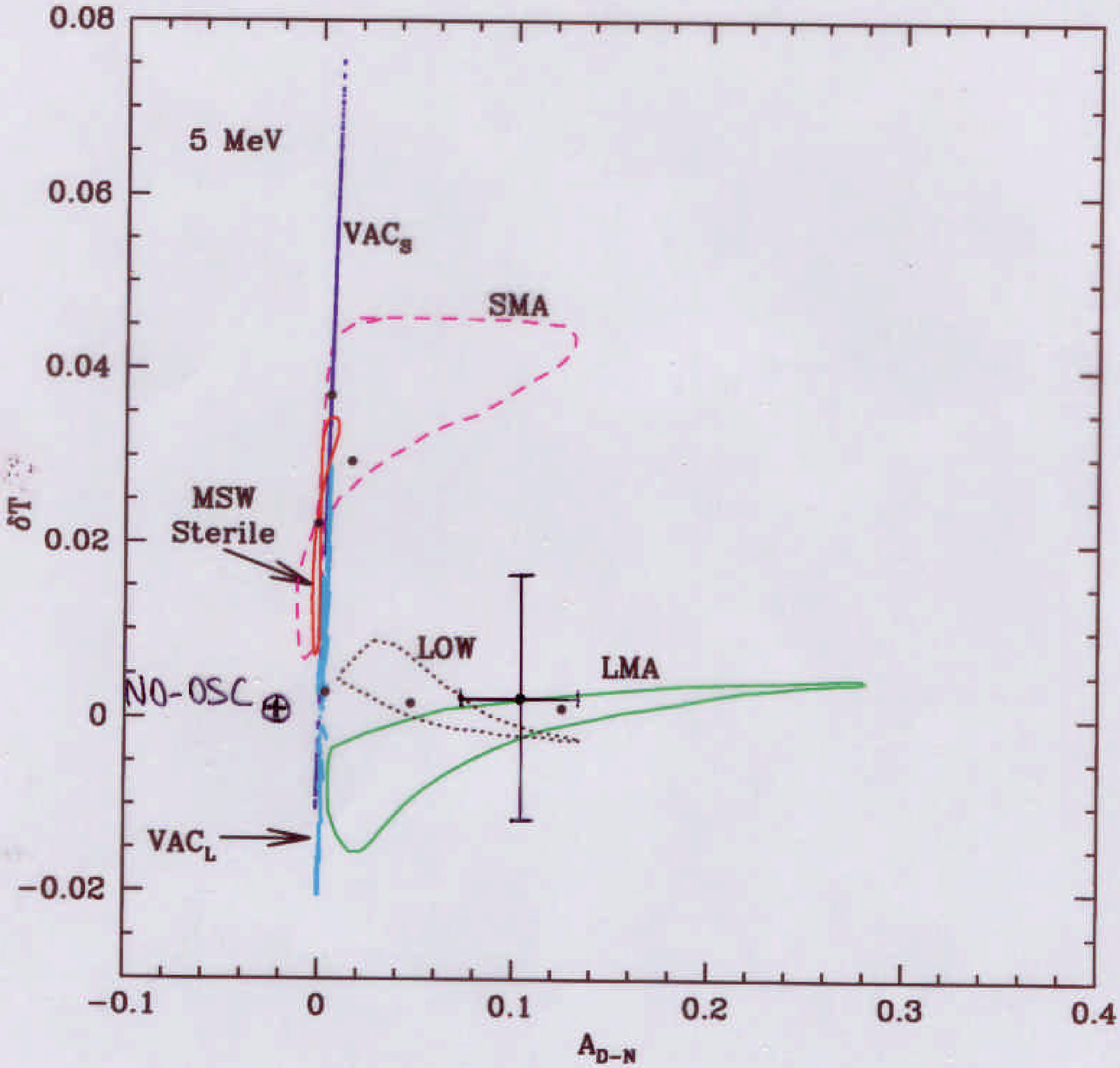
SNO observables

f_B *from the SK rate*

$X = X(\Delta m^2 \quad \theta)$ $\qquad$ $Y = Y(\Delta m^2 \quad \theta)$

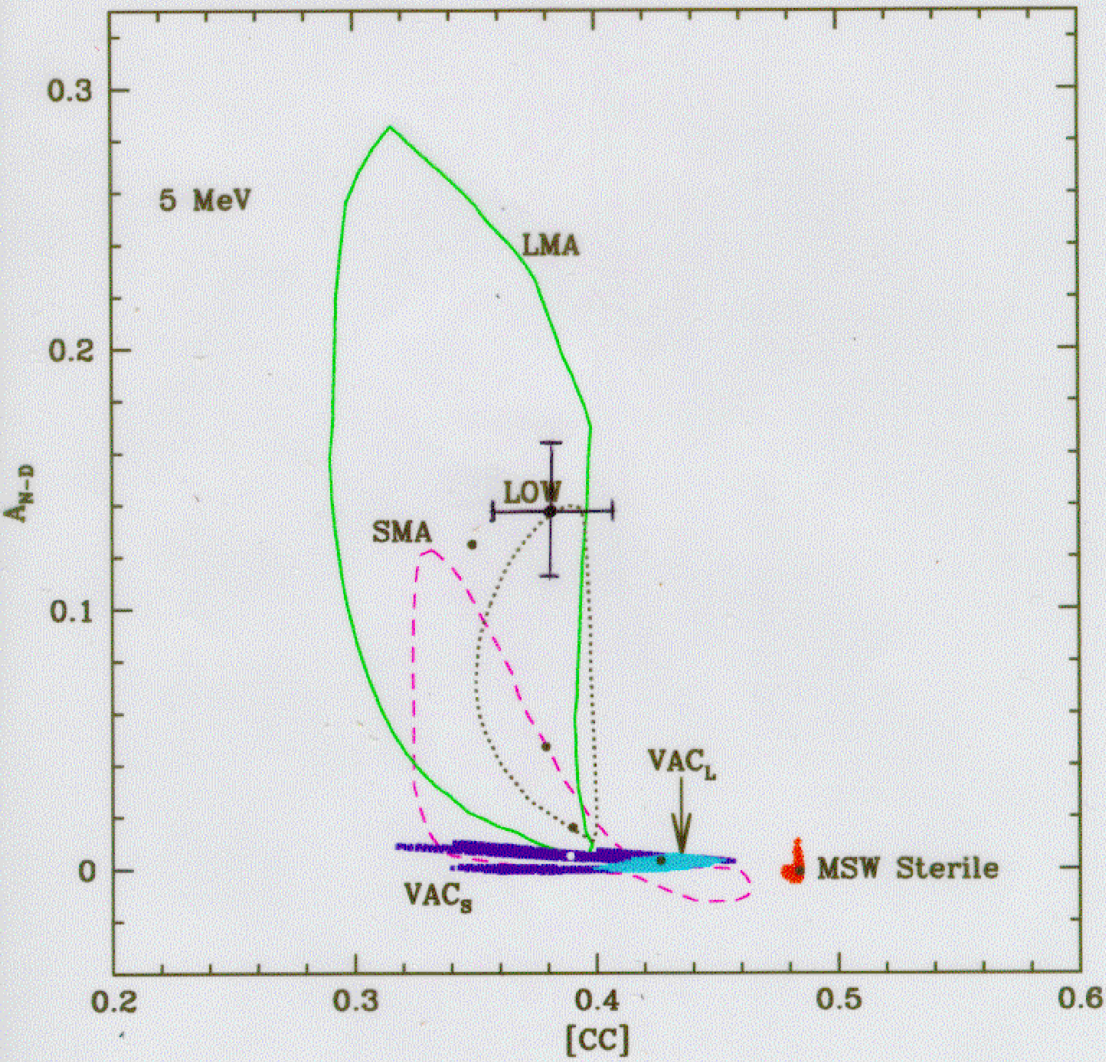
Mapping



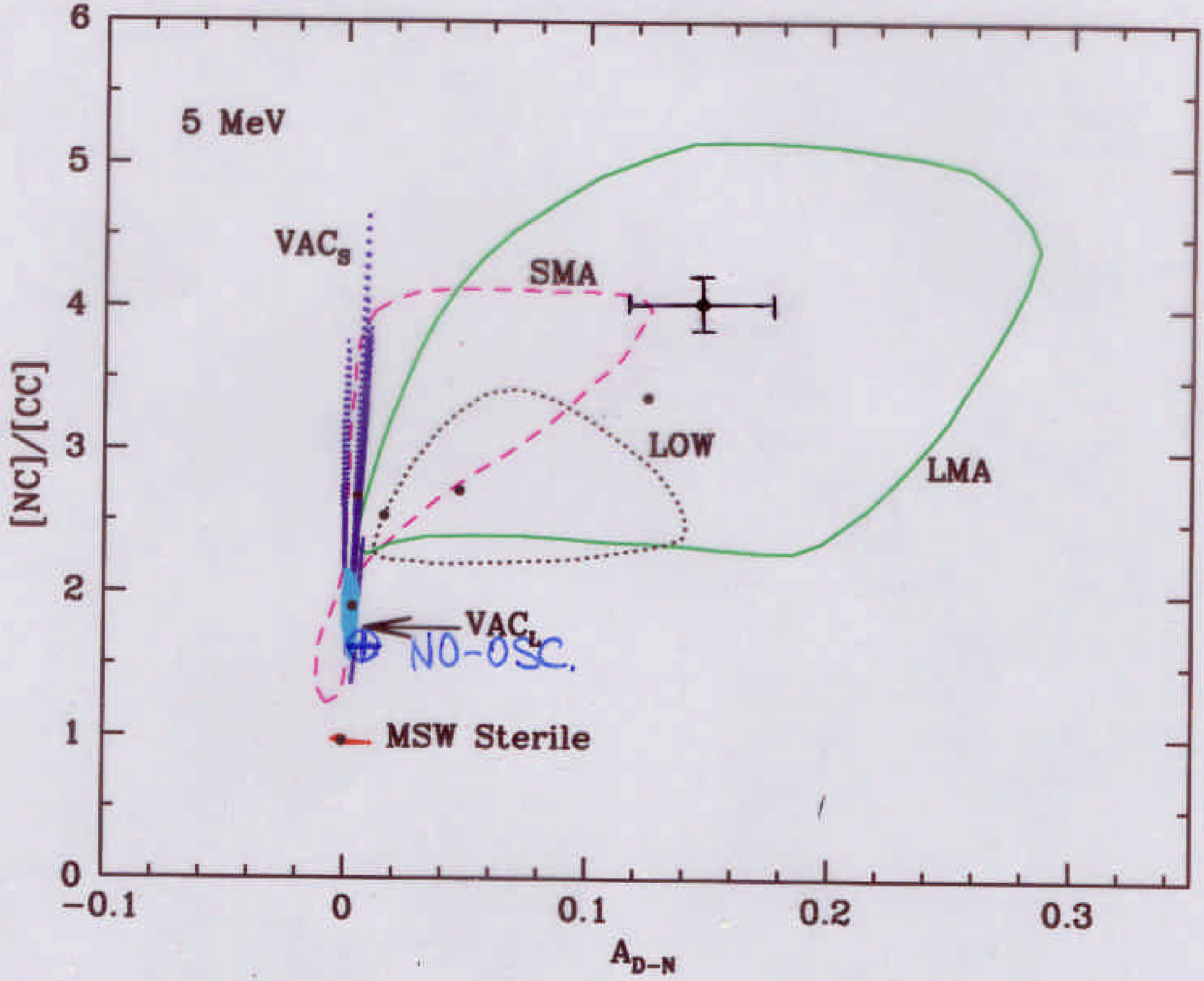

5 MeV
VAC$_S$
SMA
MSW
Sterile
LOW
LMA
NO-OSC ⊕
VAC$_L$
δT
A_{D-N}
0.08
0.06
0.04
0.02
0
−0.02
−0.1
0
0.1
0.2
0.3
0.4

1σ

δT – A_{D-N}

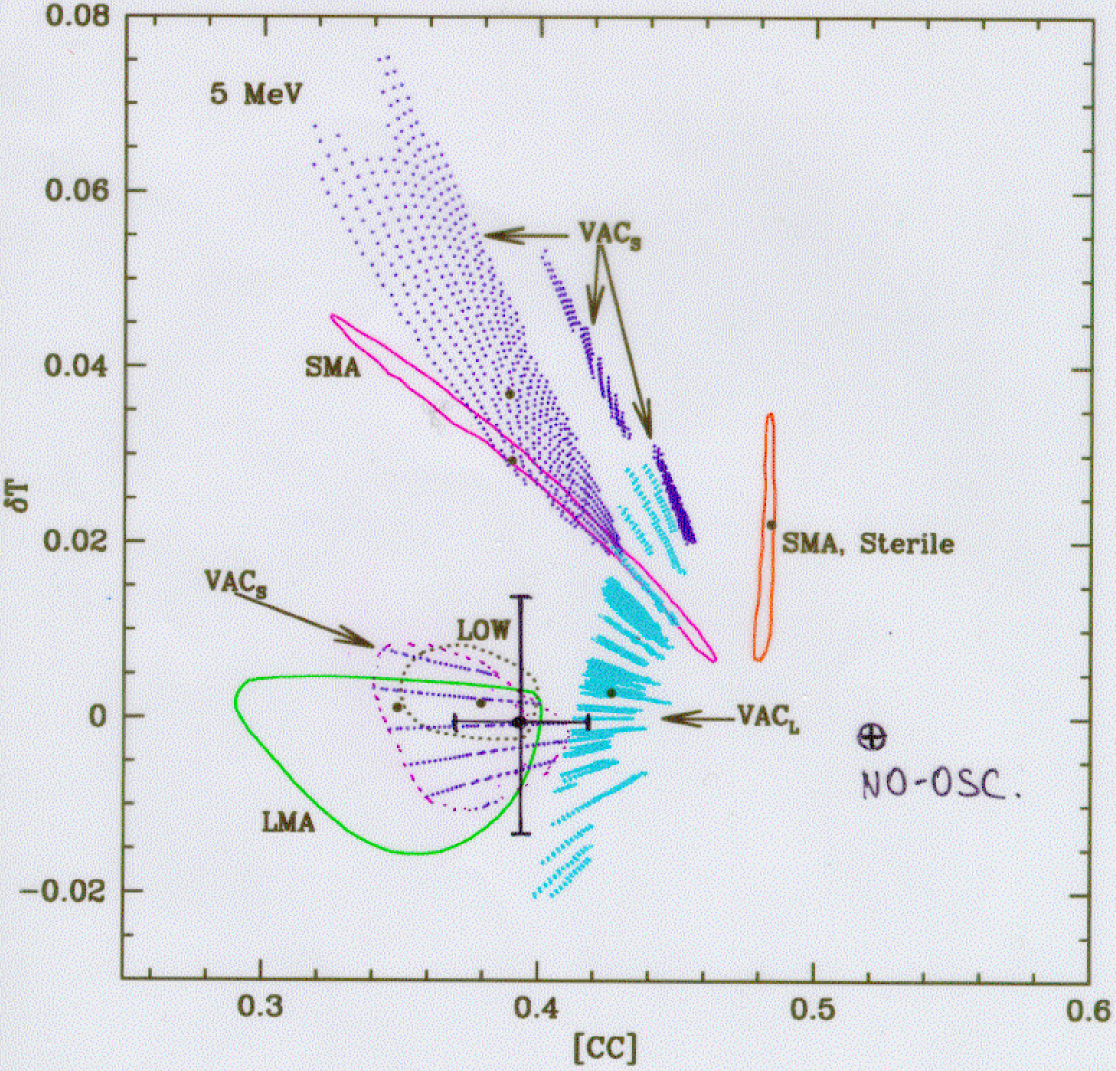

5 MeV
LMA
LOW
SMA
VAC_L
VAC_S
MSW Sterile
A_{N-D}
[CC]
0.3
0.2
0.1
0
0.2
0.3
0.4
0.5
0.6

CC - A_{DN}



5 MeV
VAC$_S$
SMA
LOW
LMA
VAC$_L$
NO-OSC.
MSW Sterile
[NC]/[CC]
A_{D-N}
0
1
2
3
4
5
6
−0.1
0
0.1
0.2
0.3

NC/CC – A_{D-N}


5 MeV
VAC$_S$
SMA
SMA, Sterile
VAC$_S$
LOW
VAC$_L$
LMA
NO-OSC.
δT
[CC]
0.08
0.06
0.04
0.02
0
−0.02
0.3
0.4
0.5
0.6

ST-CC

$\nu_\odot$ PROBLEM & ATMOSPHERIC NEUTRINOS

- IF LMA IS THE SOLUTION, CORRESPONDING PARAMETERS CAN BE PROBED IN ν_{ATM}

EXCESS OF e-LIKE EVENTS IN SUB-GEV RANGE

$$F_e = F_e^0 \cdot \left[1 + P_{e\mu} \cdot (r \cdot \cos\theta_{23}^2 - 1) \right]$$

. PERES
.S

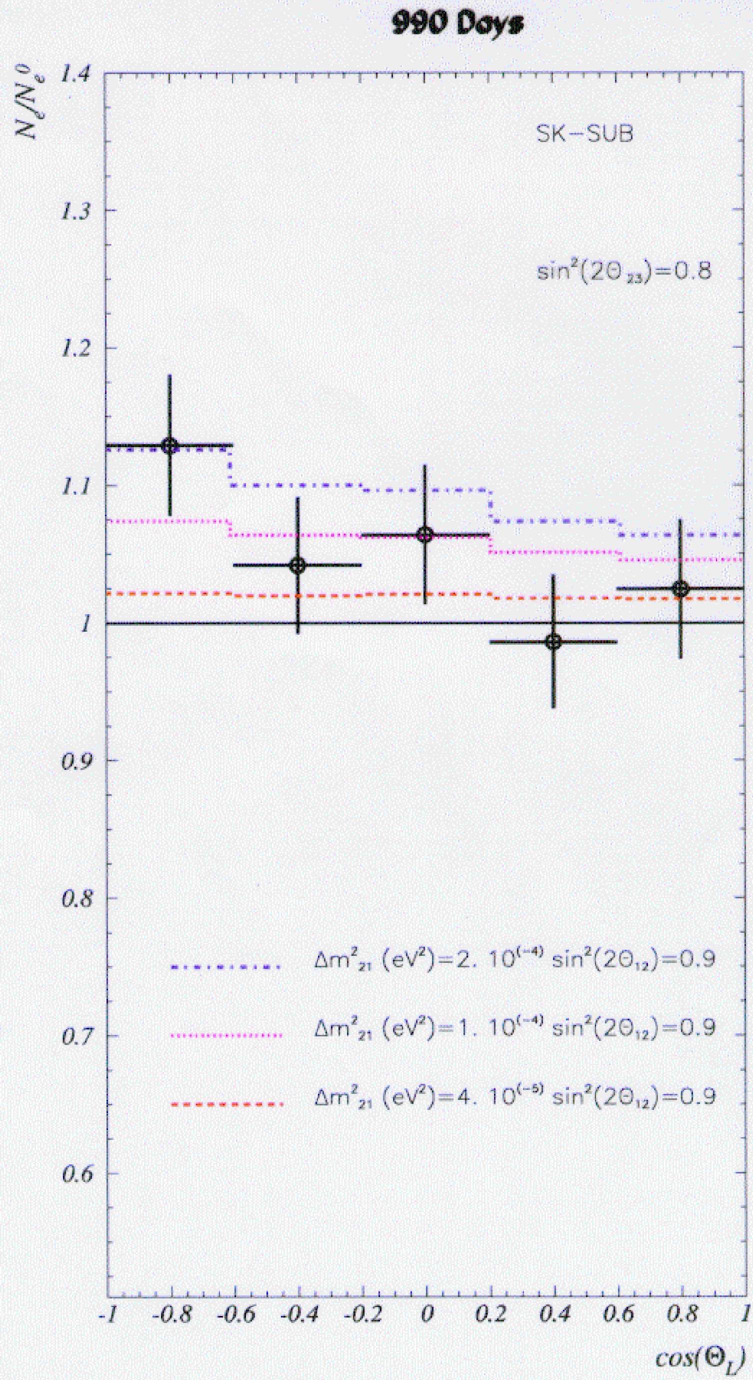
$$r \equiv \frac{F_\mu^0}{F_e^0}$$

"SCREENING FACTOR" CLOSE TO 0

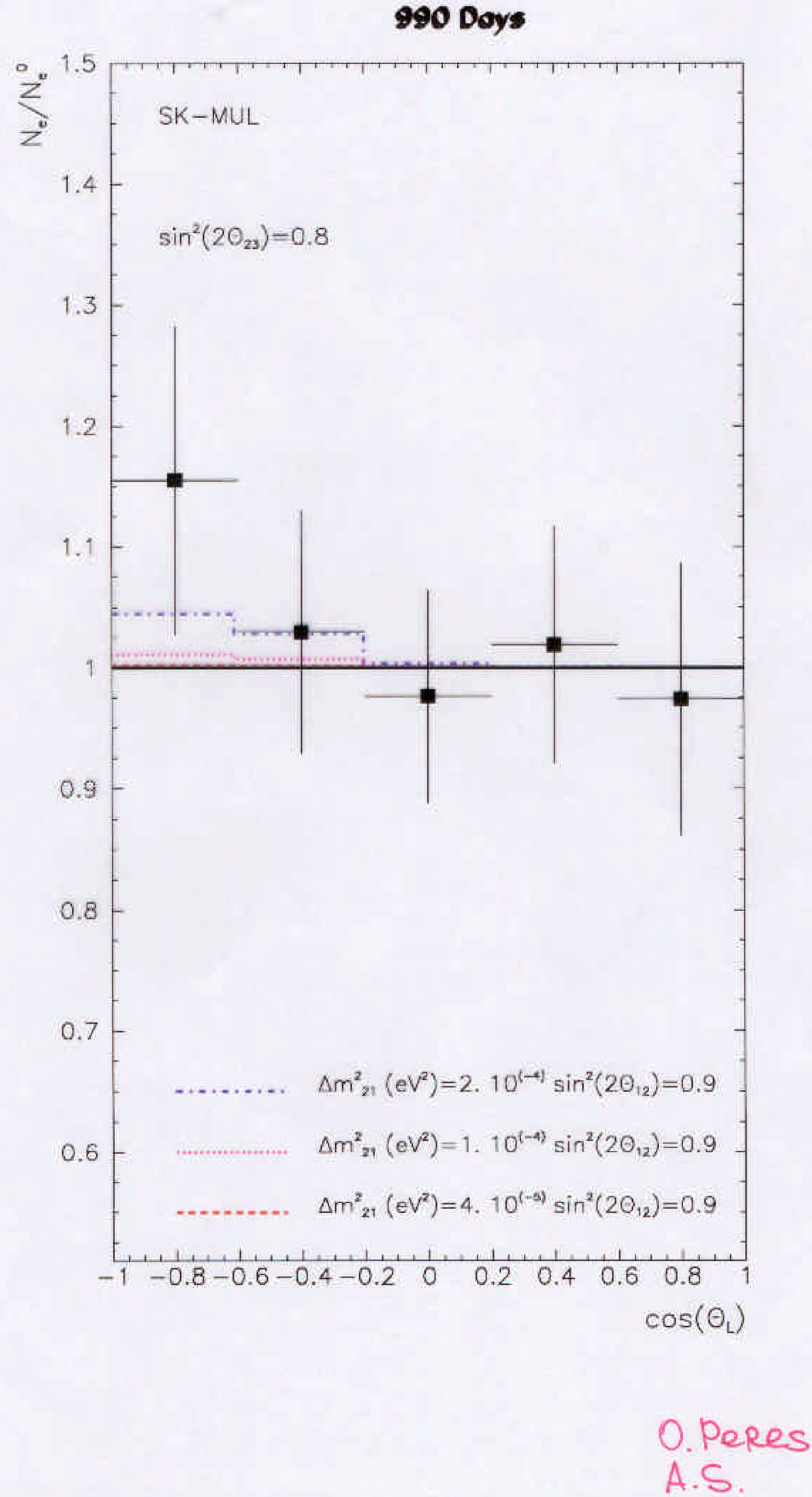
$$\text{EXCESS} \propto \cos 2\theta_{23}$$

FOR MAXIMAL MIXING IN ν_{ATM}: $\theta_{23} = \frac{\pi}{4}$
$\Rightarrow$ EXCESS = 0
EXCESS FOR $\theta_{23} < \frac{\pi}{4}$

HIGH SENSITIVITY TO DEVIATION FROM MAXIMAL MIXING


990 Days
N_e/N_e^0
SK-SUB
$\sin^2(2\Theta_{23})=0.8$
Δm^2_{21} (eV^2)=2. $10^{(-4)}$ $\sin^2(2\Theta_{12})=0.9$
Δm^2_{21} (eV^2)=1. $10^{(-4)}$ $\sin^2(2\Theta_{12})=0.9$
Δm^2_{21} (eV^2)=4. $10^{(-5)}$ $\sin^2(2\Theta_{12})=0.9$
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
$\cos(\Theta_L)$

O. PERES
A.S.


990 Days
N_e/N_e^0
SK-MUL
$\sin^2(2\Theta_{23})=0.8$
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
Δm^2_{21} (eV^2)=2. 10$^{(-4)}$ $\sin^2(2\Theta_{12})=0.9$
Δm^2_{21} (eV^2)=1. 10$^{(-4)}$ $\sin^2(2\Theta_{12})=0.9$
Δm^2_{21} (eV^2)=4. 10$^{(-5)}$ $\sin^2(2\Theta_{12})=0.9$
−1 −0.8 −0.6 −0.4 −0.2 0 0.2 0.4 0.6 0.8 1
$\cos(\Theta_L)$
O. Peres
A.S.

Phenomenology of Maximal Mixing

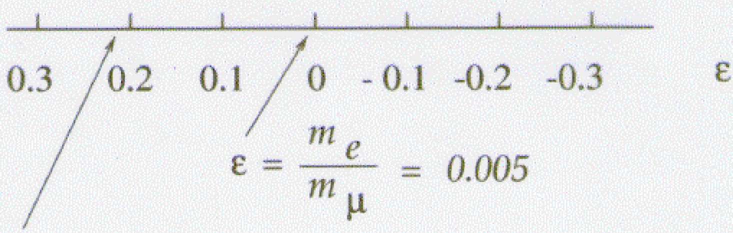
Solar neutrinos: $\theta \sim \frac{\pi}{4}$ *is accepted by global fit*

Atmospheric neutrinos: $\theta \sim \frac{\pi}{4}$ *gives the best fit*

> *Is maximal or close to maximal mixing a generic property of leptons?*

Deviation from maximal mixing: ε

$$\sin^2\theta = \frac{1}{2}(1 - \varepsilon) \qquad (\cos 2\theta = \varepsilon)$$



$$\varepsilon = \frac{m_e}{m_\mu} = 0.005$$

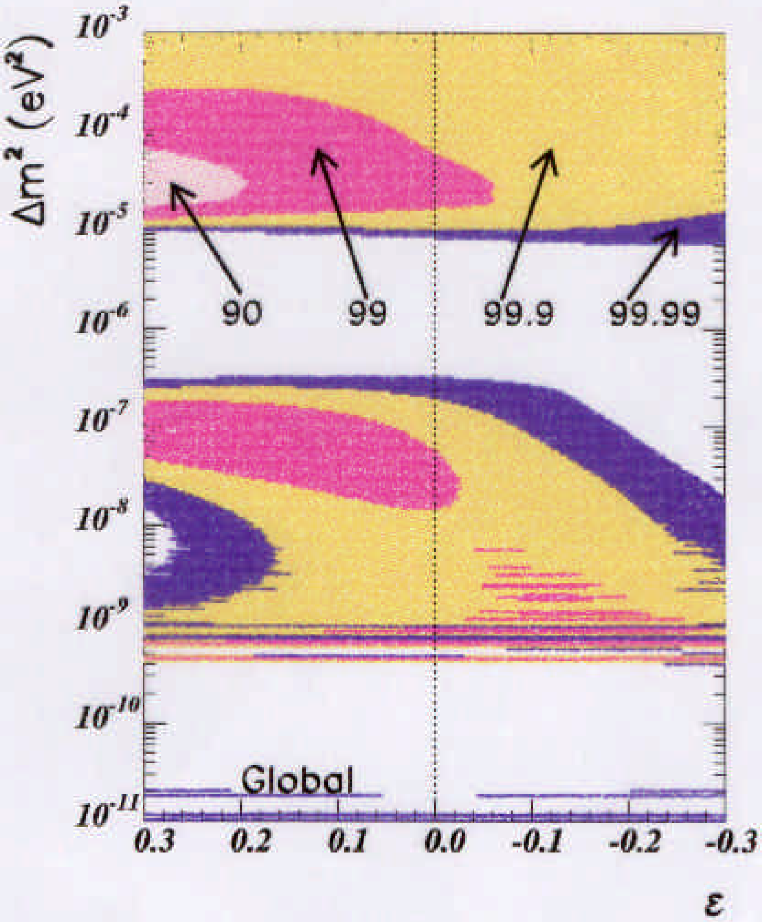
$$\varepsilon \sim \lambda = 0.22$$

Phenomenology: Nothing dramatic!

all observables change smoothely when ε changes the sign.

no divergencies, discontinuities

some observables depend on ε very weakly



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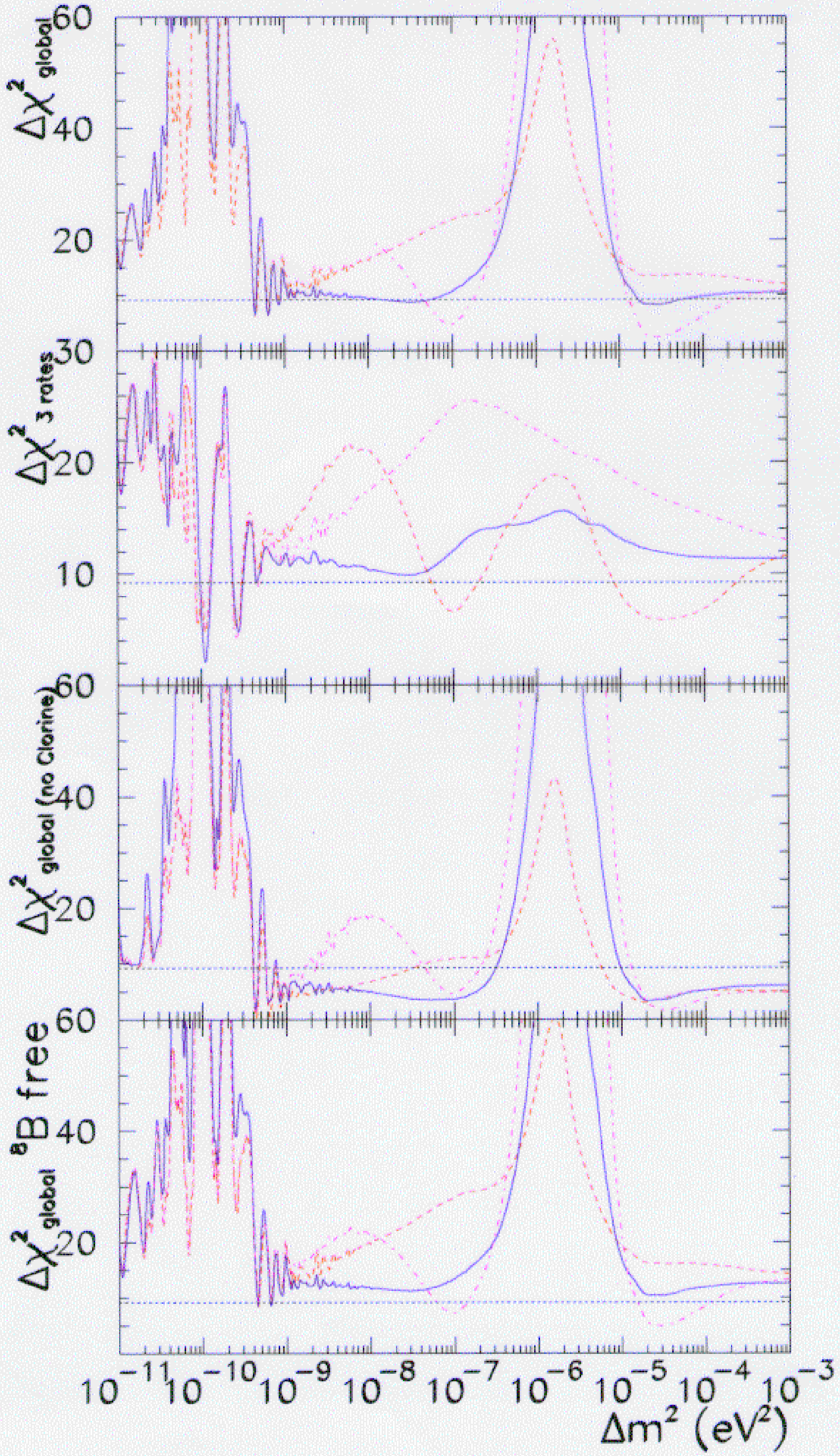
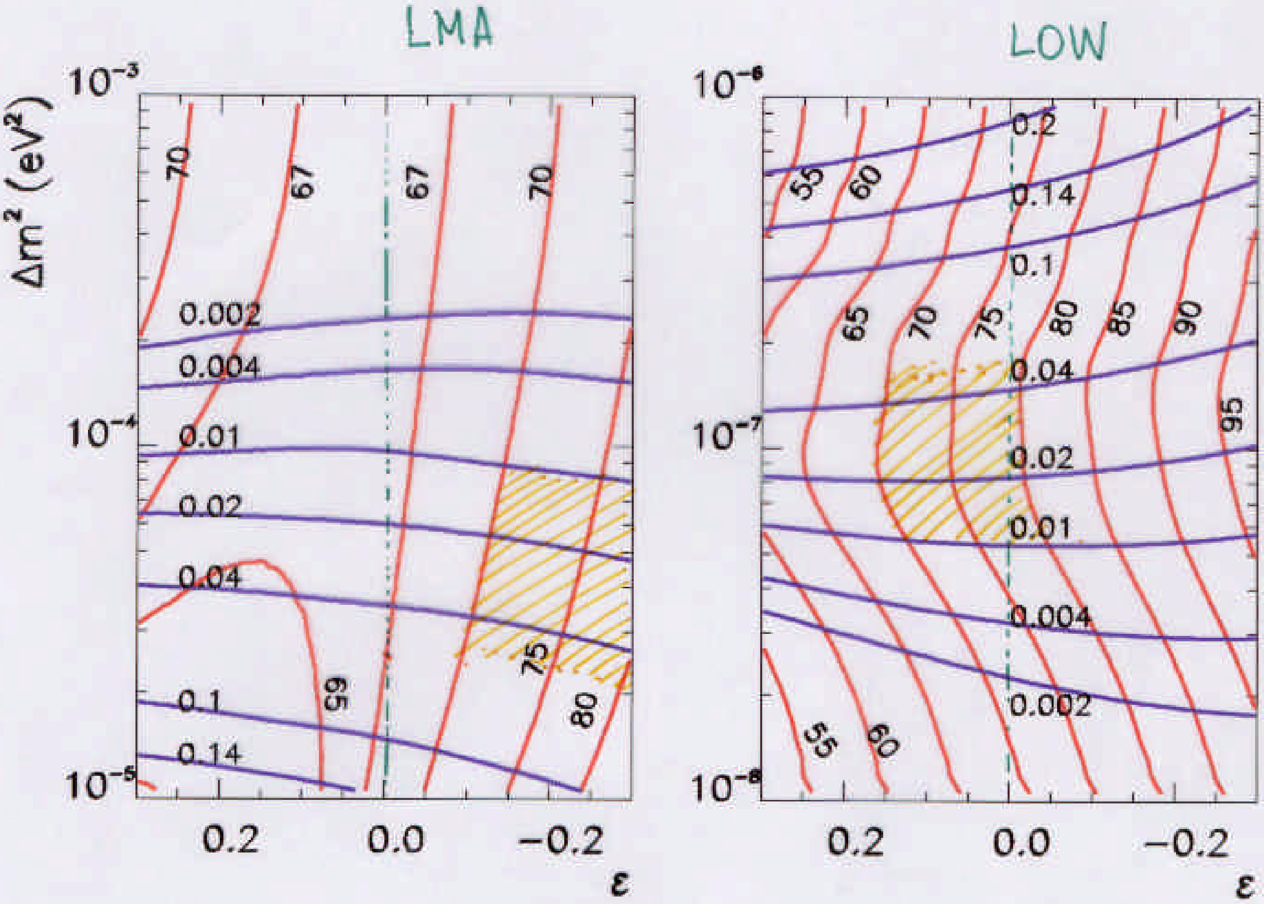
NIR
S.

THE DEPENDENCE OF χ^2 SHIFT ON Δm^2.

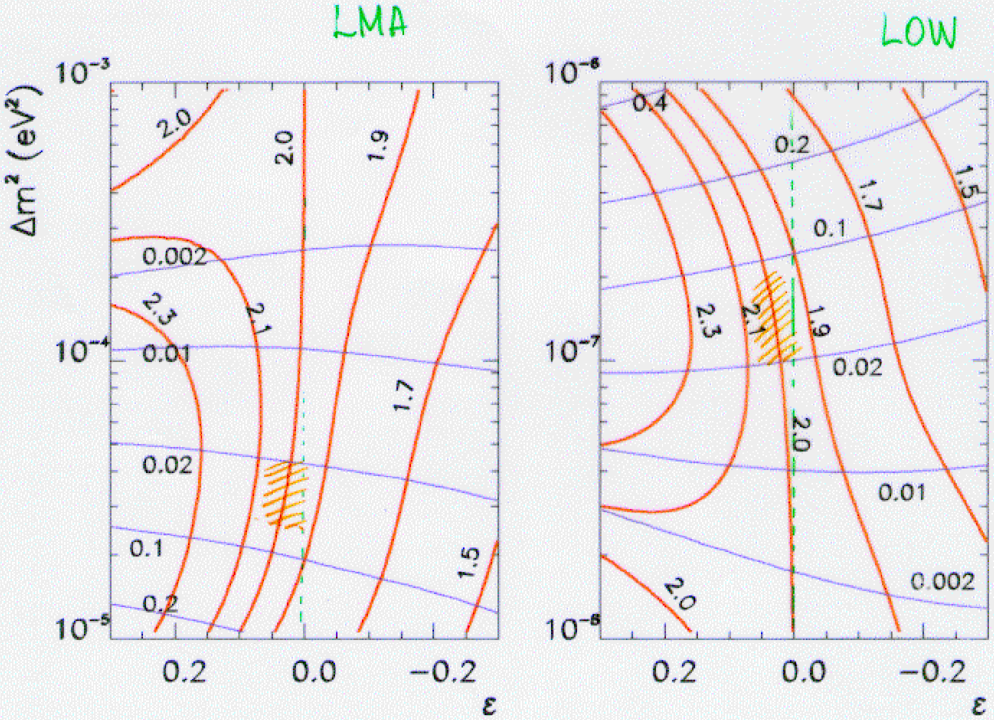


CONTOURS OF CONSTANT A_{N-D} AND Q_{GE} IN $\Delta m^2 - \epsilon$ PLANE



CONTOURS OF CONSTANT [NC]/[CC] AND A^{CC}_{N-D} IN THE $\Delta m^2 - \epsilon$ PLANE

SNO



- $\beta\beta_{0\nu}$ decay,
- SN-Neutrinos,
- and type of mass hierarchy

KLAPDOR-KLEINGROTHAUS, PÄS, S.
hep-ph/0003219

$\beta\beta_{0\nu}$ & NEUTRINO MASS SPECTRUM

- FOR ANY OSCILLATION PATTERN m_{ee} (EFFECTIVE MAJORANA MASS) CAN TAKE ANY VALUE:

$$m_{ee} = 0 \div m \text{ (upper bound)}$$

FOR NORMAL MASS HIERARCHY

- m_{ee} HAS MINIMUM $|m_{ee}| > 0$ FOR INVERTED MASS HIERARCHY IF $|U_{e1}|^2 > \frac{1}{2}$

COMPLEMENTARY INFORMATION

- IN GENERAL: NO PREDICTIONS FOR m_{ee}

$m_{ee}(\Delta m^2, \theta, \delta_{CP}, m_1; \rho_i)$

- IF m_{ee} WILL BE MEASURED, AT LEAST ONE MASS SHOULD BE

$$\boxed{m_j > \frac{m_{ee}}{n}}$$

(n IS THE NUMBER OF MASS EIGENSTATES) UNLESS OTHER MECHANISMS CONTRIBUTE TO $\beta\beta_{0\nu}$-DECAY

m_{ee} & OSCILLATION PARAMETERS

- Coincidence OF VALUE OF m_{ee} AND CERTAIN COMBINATION OF OSCILLATION PARAMETERS CAN TESTIFY FOR CERTAIN NEUTRINO MASS SPECTRUM

- $$m_{ee} = \sqrt{\Delta m^2_{ATM}} \cdot U^2_{e3}$$

NORMAL MASS HIERARCHY
SMA, LOW, VAC,

- $$m_{ee} \simeq \frac{1}{2} \cdot \left(1 - \sqrt{1 - \sin^2 2\theta_\odot}\right) \sqrt{\Delta m^2_\odot}$$

LMA, MASS HIERARCHY, SMALL U_{e3}

- $$m_{ee} = \sqrt{\Delta m^2_{ATM}}$$

INVERTED MASS HIERARCHY, SMA, LMA ($\varphi = 0$)

- $$m_{ee} = \cos 2\theta_\odot \sqrt{\Delta m^2_{ATM}}$$

INVERTED MASS HIERARCHY, LMA ($\varphi = \pi$).

$\beta\beta_{0\nu}$ AND IDENTIFICATION OF SPECTRUM

NORMAL MASS HIERARCHY

$$m_{ee} \cong \sqrt{\Delta m^2_{ATM}}\, U_{e3}^2$$

$$\lesssim 2 \cdot 10^{-3}\,\mathrm{eV}$$

INVERTED MASS HIERARCHY

$$m_{ee} = \sqrt{\Delta m^2_{ATM}} \cdot \epsilon$$

if $\sin^2 2\theta_\odot < 0.91$

$\epsilon > 0.3$

$m_{ee} \gtrsim 10^{-2}\,\mathrm{eV}$

HOWEVER PREDICTIONS OF THESE TWO SPECTRA OVERLAP IN THE CASE OF PARTIAL OR COMPLETE DEGENERACY

SUPERNOVA ν AND ν-MASS SPECTRUM

- PROBE WHOLE MASS (Δm^2) SPECTRUM
  $\rho(\text{production}) \gg \rho_R(\Delta m^2_{ATM})$
- MIXING ASSOCIATED WITH BOTH Δm^2 CAN BE MATTER-ENHANCED
- UNCERTAINTIES:
  - DENSITY PROFILE
  - ORIGINAL SPECTRA $F_\alpha(E)$ $\alpha = e, \mu ..$

CAN WE GET SN MODEL INDEPENDENT RESULTS ?

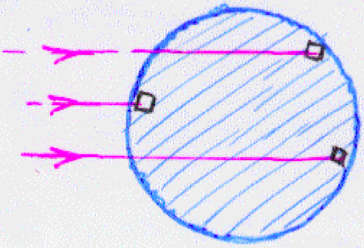
GENERIC:

(1). $E(\nu_e) < E(\bar{\nu}_e) < E(\nu_\mu)$

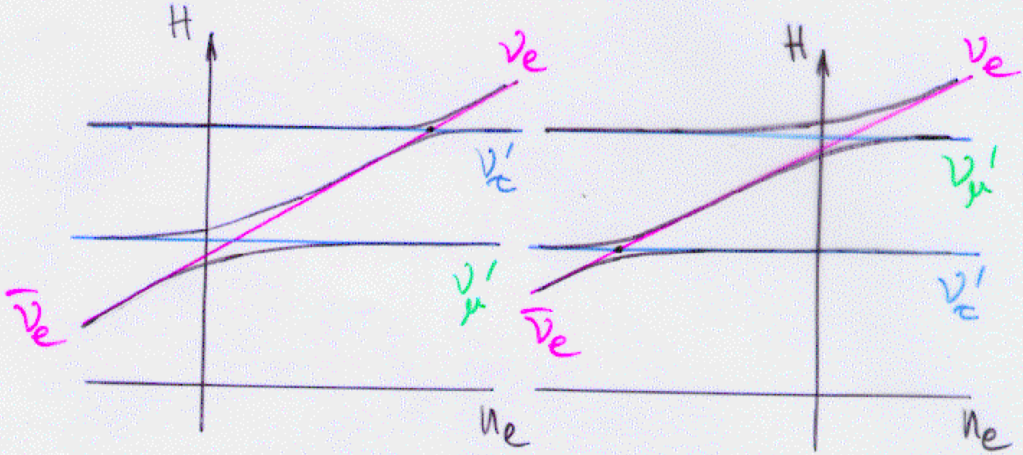
(2). "pinched" ENERGY SPECTRA ($\eta > 0$)

SIGNATURES:

- VIOLATION OF INEQUALITY (*)
- WIDE COMPOSITE SPECTRA
- → EARTH MATTER EFFECTS



DUE TO EARTH MATTER EFFECTS SIGNALS IN DETECTORS WILL BE DIFFERENT



NORMAL HIERARCHY

INVERTED HIERARCHY

IF $|U_{e3}|^2 > 10^{-3}$
PROPAGATION IN HIGH DENSITY RESONANCE – ADIABATIC

$F(\nu_\mu') = F(\nu_\tau')$

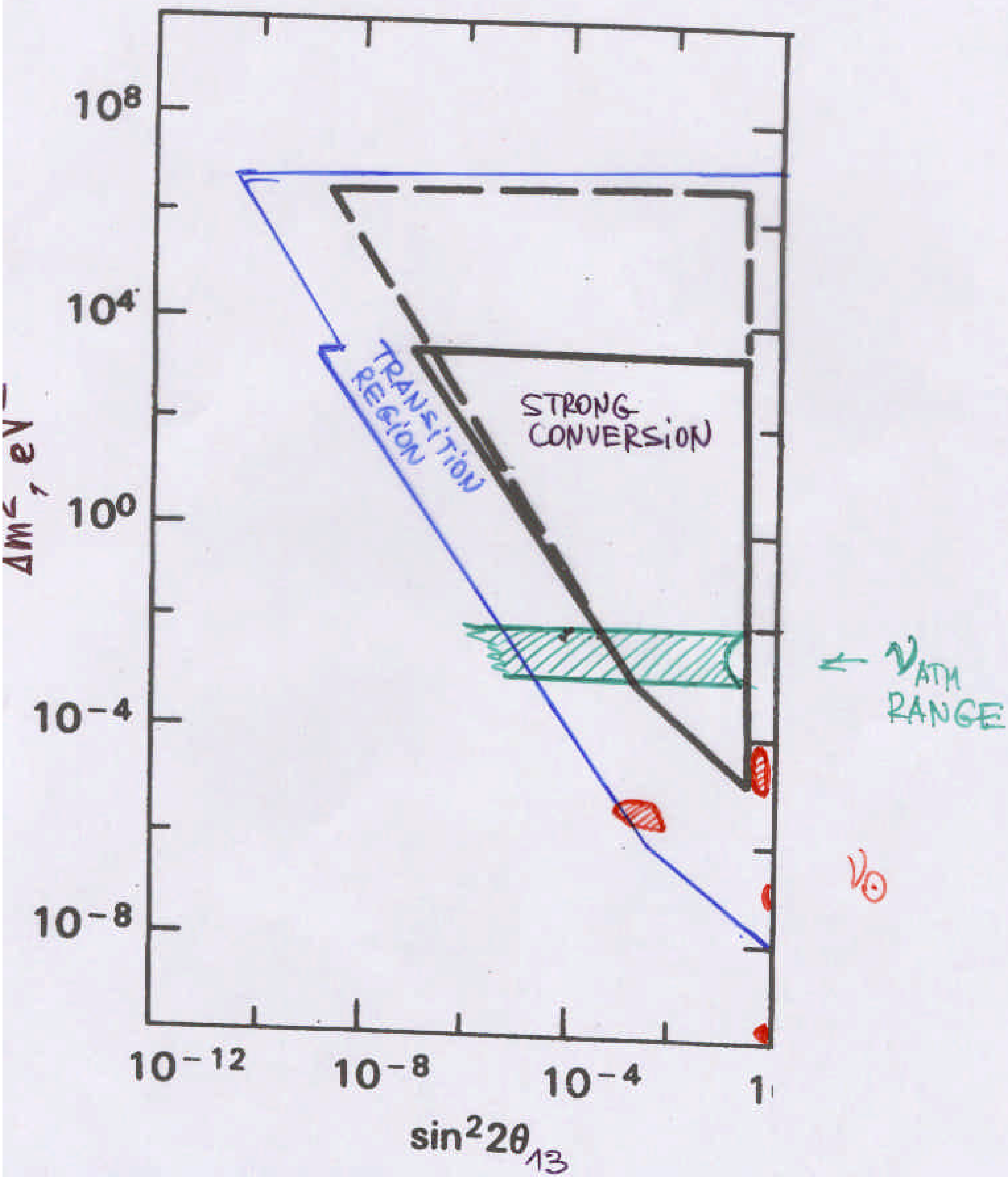
EARTH MATTER EFFECT IN $\bar{\nu}_e$-SIGNAL

NO EFFECT IN ν_e SIGNAL

EARTH MATTER EFFECT IN ν_e-SIGNAL

NO EFFECT IN $\bar{\nu}_e$-SIGNAL

SUPERNOVA ν



CAN PROBE $|U_{e3}|^2 \gtrsim 10^{-4} - 10^{-3}$

$\nu_\odot$ ν_{ATM} AND LSND

LSND

→ THREE VERY DIFFERENT $\Delta m^2 \Rightarrow \nu_s$

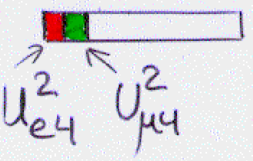
→ EITHER $\nu_\odot$ OR ν_{ATM} SHOULD CONVERT TO ν_s ?

Bilenki
Giunti
Grimus

Peres
A.S.

- $\nu_{ATM} \to \nu_s$ - DISFAVORED
- $\nu_\odot \to \nu_s$?

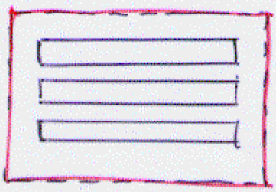
- IF BOTH $\nu_{ATM} \to \nu_{ACTIVE}$ AND $\nu_\odot \to \nu_{ACTIVE}$



$$\sin^2 2\theta_{LSND} = 4 U_{e4}^2 \cdot U_{\mu4}^2$$

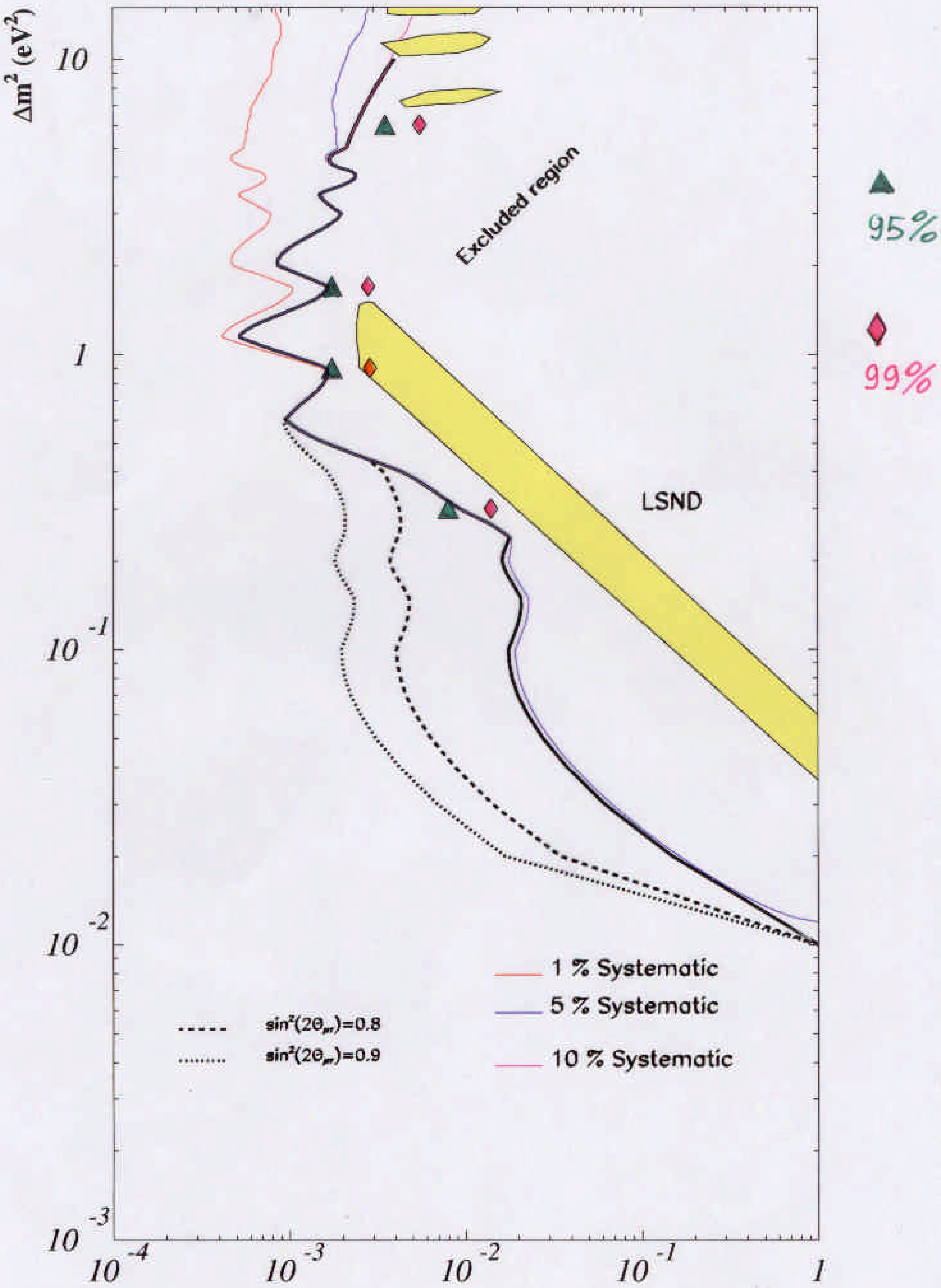
BUGEY (U_{e4}^2)

CDHS; SK ($U_{\mu4}^2$)



ACTIVE NEUTRINOS

INTRODUCTION OF ADDITIONAL STERILE NEUTRINOS DOES NOT CHANGE SITUATION SUBSTANTIALLY



Δm² (eV²)
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
Excluded region
LSND
1 % Systematic
5 % Systematic
10 % Systematic
95%
99%

O.Peres, A.S.

ν_s IN SOLAR NEUTRINOS

SMA $\nu_e \to \nu_s$ CONVERSION :

- SMALL ($< 2\%$) D-N ASYMMETRY
- $[CC]_{SNO} \gtrsim R_{SK}$
- $\frac{[NC]}{[CC]} \approx 1$
- TURN DOWN OF SPECTRUM DISTORTION CURVE AT SMALL ENERGIES