STERILE NEUTRINOS: THEORY

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WIN2002

1. PHENOMENOLOGICAL STATUS
2. m_ν AND NEW SYMMETRIES
   $\Rightarrow$ LEFT-RIGHT SYM.
3. ULTRA LIGHT ν_s AND MORE NEW SYMMETRIES:

   $\Rightarrow$ MIRROR WORLD

1. WHY INTRODUCE A STERILE NEUTRINO ?

$$\Delta m^2_{\odot} + \Delta m^2_{ATM.} + \Delta m^2_{LSND} \neq 0$$

AS WOULD BE FOR 3 ν'S.

$\Rightarrow$ $\nu_e, \nu_\mu, \nu_\tau \oplus \nu_s$

ACTIVE STERILE

$\Rightarrow$ ALL SUPER-LIGHT ($m \lesssim$ eV).

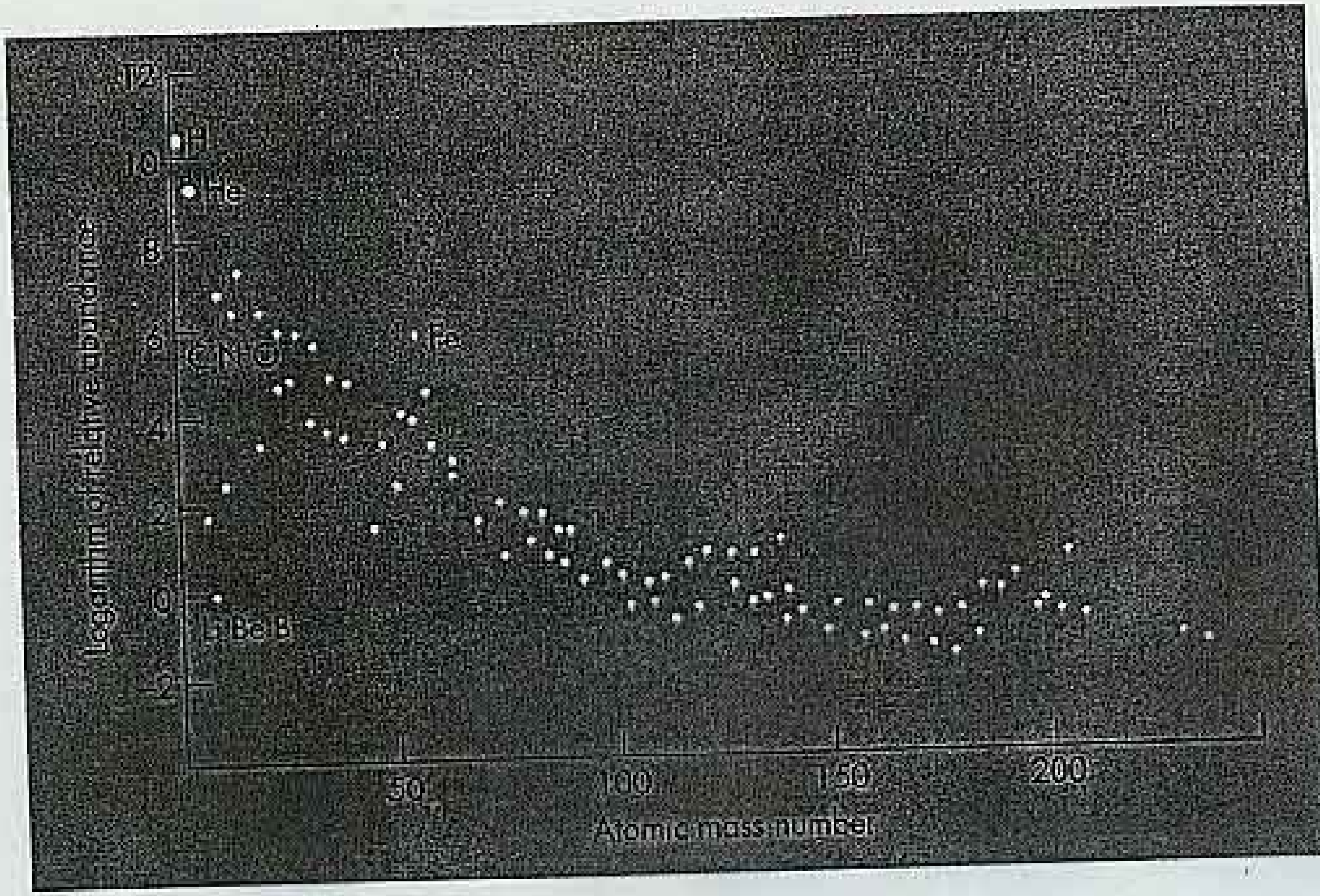
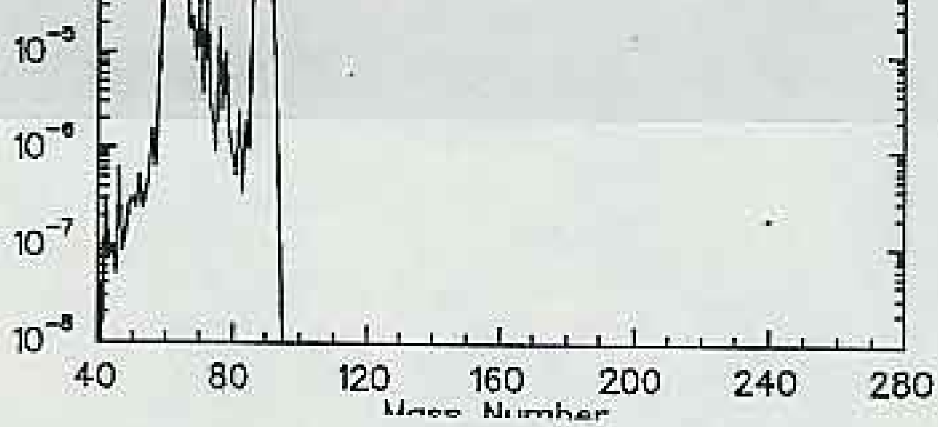


Figure 16.5 Relative Abundances of Atomic Nuclei

The abundances of naturally occurring atomic nuclei are highest for hydrogen and helium. Lithium, beryllium, and boron evidently form an anomalous grouping. Like deuterium, these three elements are very fragile, being destroyed rather than created in stars, and lithium may have been produced in the big bang. Note the relative prominence of iron among the heavier elements.

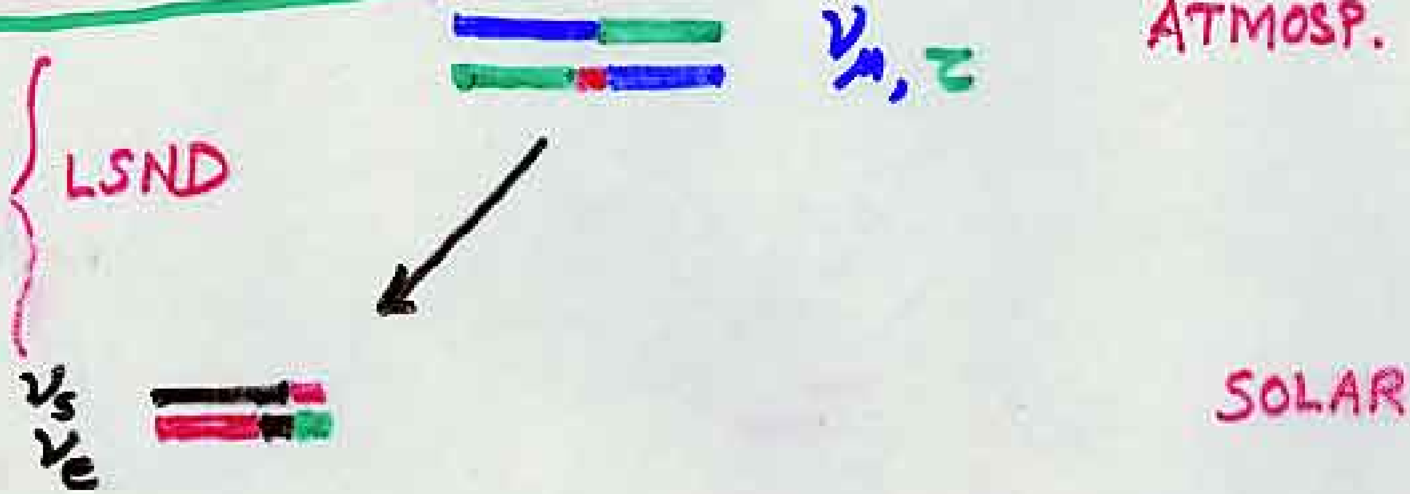
PREDICTED IN STD. MODEL



α-PROBLEM

2. PHENOMENOLOGY:

- MASS PATTERNS:
- 2+2 SCENARIO:

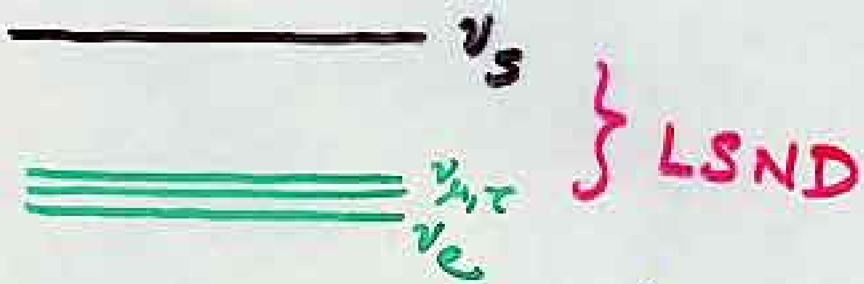


CALDWELL, R.N.M;
PELTONIEMI, VALLE
93

$$\Rightarrow \quad m_{\nu_s} \sim 10^{-3}\,eV$$

• 3 + 1 SCHEME :

MCGLAUGHLIN, BALATENKIN, FULLER, ..
BILENKY, GRIMUS, GIUNTI, SCHWETZ
KAYSER, BARGER, LEARNED, WEILER, WHISNANT.



$$m_{\nu_s} \sim eV$$

⇒ FLAT ENERGY DISTRIBUTION SUGGESTED BY SNO AND SK SUPPORTS BIMAXIMAL MIXING.

$$U = \begin{pmatrix} c & s & 0 \\ \frac{s}{\sqrt{2}} & -\frac{c}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{s}{\sqrt{2}} & -\frac{c}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$

STATUS OF ν_s AFTER SNO

SNO - SK GAP

$\Rightarrow$ PURE $\nu_e - \nu_s$ EXPLANATION OF $\nu_\odot$ PUZZLE RULED OUT.

- A HYBRID SOLUTION STILL VIABLE FOR 2+2 CASE

OR

- 3+1 OK FOR SPECIFIC Δm^2_{LSND}!

  - SPECIAL APPEAL IS:

    BIMAXIMAL FOR $\nu_{e,\mu,\tau}$ FITS NICELY

GRIMUS, SCHWETZ;
MALTONI, SCHWETZ,
VALLE;

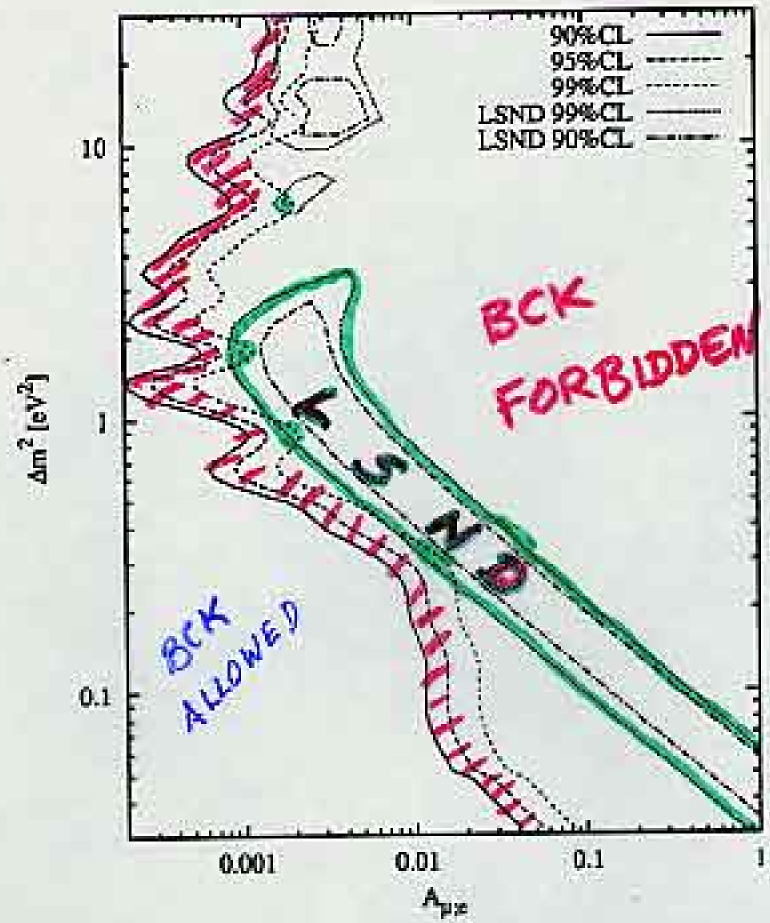


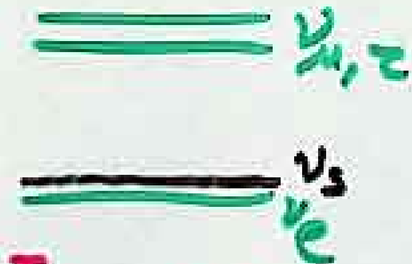
Figure 1: Upper bounds on the transition amplitude $A_{\mu;e}$ in the case of (3+1)-mass spectra for 90%, 95% and 99% CL. These bounds have been calculated with the maximum likelihood approach for the inclusion of the atmospheric up-down inequality (12) and the CHOOZ inequality (23) as described in Section 3.2. Also shown are the regions allowed by the latest LSND results [6] at 90% and 99% CL.

BUGEY, CDHS, KARMEN COMBINED.

(BCK)

(ALLOWED FOR SOME VALUES OF Δm^2_{LSND}).

HYBRID 2+2 SCENARIO



$$
\begin{array}{cccc}
e & s & \mu & \tau \\
\end{array}
$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & 0 & 0 \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \end{pmatrix}$$

SUM RULE PROBLEM ?

IF $U_{\mu 1} = U_{\mu 2} = 0$; $\eta_s = \dfrac{\nu_s}{\nu_s + \nu_a}$ $a \equiv e$ $\odot$
$\equiv \mu$ AT.

$$\Rightarrow \quad \eta_s^{\odot} + \eta_s^{ATM} = 1 \quad (?)$$

PEREZ, SMIRNOV.

SK: $\eta_s^{ATM} < 25\%$

SNO: $\eta_s^{\odot} < 75\%$

SLIGHT $U_{\mu 1}, U_{\mu 2}$ EFFECTS SUMRULE A LOT !! SO 2+2 IS OK.

WITH $U_{\mu 1}, U_{\mu 2} \neq 0$ AND $U_{s3}, U_{s4} \neq 0$,

2+2 PERFECTLY CONSISTENT WITH DATA:

GONZALEZ-GARCIA, MALTONI, PENAGARAY (01).

SOLAR: $\nu_e \to c_{23}c_{24} \nu_s + \sqrt{1-c_{23}^2 c_{24}^2}\, \nu_{\mu,2}$

$$U_{s3}^2 + U_{s4}^2 = \sqrt{1 - c_{23}^2 c_{24}^2}$$

$c_{23}c_{24} \downarrow$ SOLAR FITS BETTER !!

$c_{23}c_{24} \uparrow$ ATMOS. FITS BETTER

MIN. χ^2 FOR $c_{23}^2 c_{24}^2 \simeq .2 - .4$

SOLAR

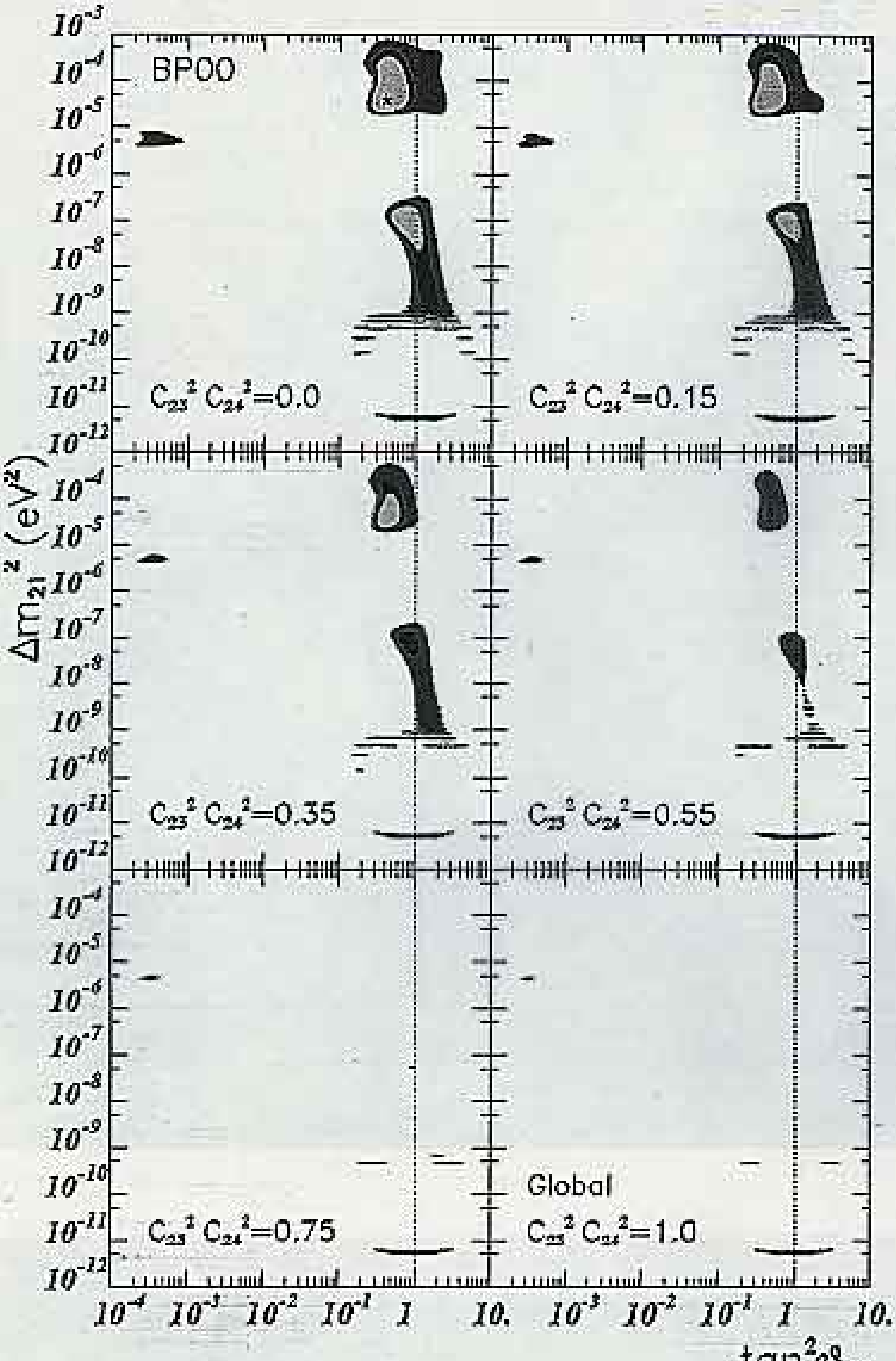


FIG. 2. Results of the global analysis of solar neutrino data for the allowed regions in Δm^2_{21} and $\tan^2\vartheta_{12}$ for the four-neutrino oscillations. The different panels represent sections at a given value of the active–sterile admixture $|U_{s1}|^2 + |U_{s2}|^2 = c^2_{23}c^2_{24}$ of the three-dimensional allowed regions at 90%, 95% and 99% CL. The best-fit point in the three-parameter space is plotted as a star.

GONZALEZ-GARCIA et al

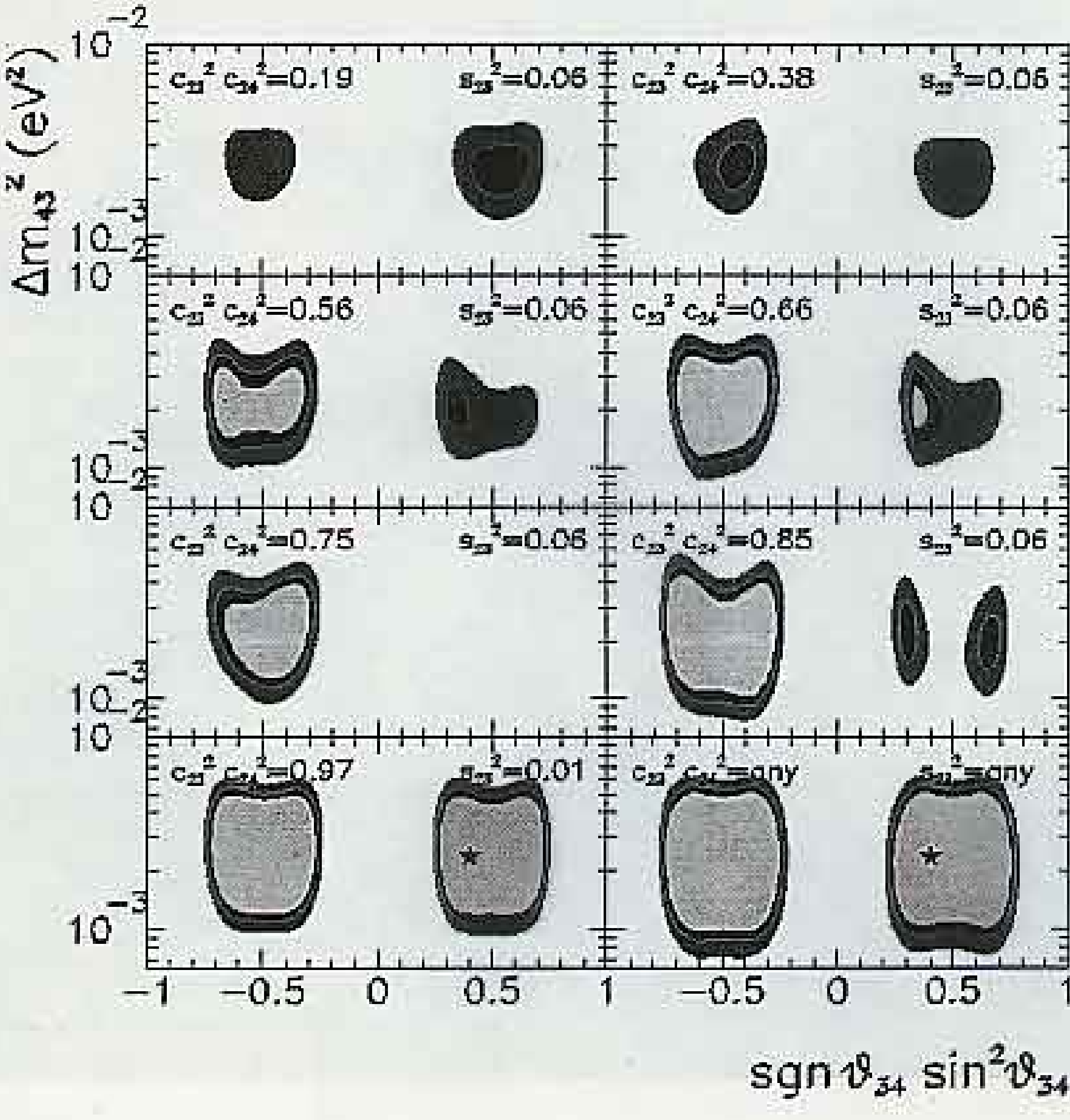


FIG. 4. Results of the analysis of atmospheric neutrino data for the allowed regions in Δm^2_{43} and ϑ_{34} for the four-neutrino oscillations. The different panels represent sections at given values of the ν_μ projection $|U_{\mu 1}|^2+|U_{\mu 2}|^2 = s^2_{23}$ and the active–sterile admixture $|U_{s1}|^2+|U_{s2}|^2 = c^2_{23}c^2_{24}$ of the four-dimensional allowed regions at 90%, 95% and 99% CL. The best-fit point in the four-parameter space is plotted as a star. The last panel corresponds to the case in which χ^2 has also been minimized with respect to s^2_{23} and $c^2_{23}c^2_{24}$.

THEORY:

$m_\nu \neq 0$ AND SMALL IS A NEW WINDOW TO NEW SYMMETR[IES]

$m_{\nu_{e,\mu,\tau}} \ll m_\ell$

$\Rightarrow$ ADD $\nu_{e,\mu,\tau\,R}$

(i) SMALL $m_{\nu_{e,\mu,\tau}}$

$\Rightarrow$ NATURE LEFT-RIGHT SYM AT HIGH ENERGIES.

(ii) BIMAXIMAL $\Rightarrow$

$L_e - L_\mu - L_\tau$

(iii) LIGHT STERILE

$\Rightarrow$ MIRROR WORLD

STD MODEL (NO ν_R)

$SU(2)_L \times U(1)_Y$ LOCAL SYM.

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} ; \quad \begin{matrix} u_R \\ d_R \end{matrix} \; ; \quad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} ; \quad e_R ;$$

$m_\nu = 0$.

ADD ν_R

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \xleftrightarrow{P} \begin{pmatrix} u_R \\ d_R \end{pmatrix} ; \quad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \leftrightarrow \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

- NEW LOCAL SYM:

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

- ALL INT. CONSERVE PARITY FOR $E \gg M_Z$

$$W_L^\pm, Z \; ; \; W_R^\pm, Z' \; ; \; \gamma$$

- WHY LOW ENERGY V-A ?
- WHY $m_\nu \ll m_{\ell,q}$

$$\mathcal{L}_{WK} = \frac{g}{2\sqrt{2}}\left(\vec{J}_{\mu L}\cdot\vec{W}_L^\mu + \vec{J}_{\mu R}\cdot\vec{W}_R^\mu\right)$$

$$M_{W_R, Z_R} \gg M_{W_L, Z_L} \Rightarrow V-A$$

SYM. BREAKING

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\begin{array}{cc} \nu_L & \nu_R \\ \multicolumn{2}{c}{\begin{pmatrix} 0 & 0 \\ 0 & M_R \end{pmatrix}} \end{array}$$

$$\Big\downarrow M_{W_R}$$

$$SU(2)_L \times U(1)_{Y \equiv I_{3R} + \frac{B-L}{2}}$$

$$\begin{array}{cc} \nu_L & \nu_R \\ \multicolumn{2}{c}{\begin{pmatrix} - & m_\ell \\ m_\ell & M_R \end{pmatrix}} \end{array}$$

$$\Big\downarrow$$

$$U(1)_{em}$$

$$m_\nu \simeq f\frac{k^2}{M_R} - \frac{m_\ell^2}{M_R} \ll m_\ell \text{ ; SEESAW}$$

Gell-Mann, Ramond, Slansky
Yanagida
R.N.M., Senjanovic '79

- MORE DETAILS CAN REVEAL MORE NEW SYMMETRIES:

EX. BIMAXIMAL MIXING

$$m_\nu \equiv \begin{pmatrix} 0 & m_1 & m_2 \\ m_1 & \delta & 0 \\ m_2 & 0 & 0 \end{pmatrix}$$

$\delta \ll m_{1,2}$

$\delta = 0$

$\Rightarrow$ NEW SYM. OF LEPTONS

$$L_e - L_\mu - L_\tau$$

PREDICTIONS:

1. INVERTED SPECTRUM

SOLAR

$$\Delta m^2_{23} > 0$$

2. $U_{e3} \simeq \dfrac{\Delta m^2_{\odot}}{\Delta m^2_{A}}$

U_{e3} PROBES HOW $L_e - L_\mu - L_\tau$ IS BROKEN !!

3. $\sin^2 2\theta_{\odot} \simeq 1 - \frac{1}{2} \dfrac{\Delta m^2_{\odot}}{\Delta m^2_{ATM}}$

ν_s AND MORE NEW SYMMETRIES:

MIRROR UNIVERSE MODEL

OUR WORLD	MIRROR WORLD
$W^\pm, Z, \gamma, \ldots$	$W^{\pm\prime}, Z', \gamma', \ldots$
$u, d, e, \nu \ldots$	$u', d', e', \nu' \ldots$

GRAVITY

"STERILE UNIVERSE"

TWO VERSIONS:

FOOT & VOLKAS '95

SYMMETRIC

$M_{W,Z} = M_{W',Z'}$

BEREZHIANI, R.N.M. '95

ASYMMETRIC

$M_{W',Z'} \simeq (10-20) M_{W,Z}$

$M_{q',\ell'} \simeq (10-20) M_{q,\ell}$

BOTH VERSIONS PREDICT ULTRALIGHT STERILE ν's:

$\nu_e, \nu_\mu, \nu_\tau \xleftrightarrow{\text{GRAVITY}} \nu_e', \nu_\mu', \nu_\tau'$

LIGHT DUE TO $B-L$ | LIGHT DUE TO $B'-L'$

BIG PICTURE:

STD MODEL $\oplus$ $\left(\text{STD MODEL}\right)'$

$\big\downarrow$ $\mu \gg M_{W_L}$

LEFT-RIGHT FOR SEESAW $\oplus$ (LEFT-RIGHT)'

$(L_e - L_\mu - L_\tau) \times (L'_e - L'_\mu - L'_\tau) \Rightarrow 3+1$

OR

$(L_e + L_\mu - L_\tau) \times (L'_e + L'_\mu - L'_\tau) \Rightarrow 2+2$

(BABU, RNM '01, '02)

A CONCRETE MODEL FOR HYBRID 2+2 SCENARIO:

K.S. BABU & R.N.M.
'01.

MIRROR MODEL

$$+ (L_e + L_\mu - L_\tau) \otimes (L'_e + L'_\mu - L'_\tau)$$

$$\downarrow$$

$$(L_e + L_\mu - L_\tau - L'_e)$$

$$\Rightarrow \quad M_\nu = m_0 \begin{array}{c} \begin{array}{cccc} \nu_e & \nu_\mu & \nu_\tau & \nu'_e \end{array} \\ \begin{pmatrix} 0 & 0 & \epsilon_2 & \epsilon_1 \\ 0 & 0 & 1 & a \\ \epsilon_2 & 1 & 0 & 0 \\ \epsilon_1 & a & 0 & \delta \end{pmatrix} \end{array}$$

5-PARAMETER FOR ALL DATA:

- $a > 1 \gg \epsilon_{1,2}, \delta$

$\Delta m^2_{LSND} \simeq m_0^2(1+a^2)$; $\theta_{LSND} \simeq \epsilon$

$\Delta m^2_{ATM} \Rightarrow \delta$; $\Delta m^2_{\odot} \Rightarrow \epsilon_2$

$$U_{s1}^2 + U_{s2}^2 \equiv c_{23}^2 c_{24}^2 \simeq \frac{1}{1+a^2}$$

$a \simeq \cancel{1}\text{-}2$ (HYBRID SOLN.)

$\eta_\odot^s \approx .2 - .5$

PREDICTIONS:

a) $|U_{e3}^{eff}| \gtrsim \theta_{LSND} \simeq .02 - .03$

b) A SUM RULE:

$$\Delta m_\odot^2 \cos 2\theta_\odot \simeq \frac{\Delta m_{AT}^2}{2\Delta m_{LSND}^2} \cdot \frac{1}{x(1-x)^2}$$

$$x = U_{s1}^2 + U_{s2}^2$$

c) $\frac{NC}{CC} \approx 2.2 - 1.8$ (STD LMA $\simeq$ 3.5)

A MIXING MATRIX

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} .91 & .4 & .016 & .016 \\ .016 & -.018 & .71 & .70 \\ -.29 & -.65 & .5 & .5 \\ .29 & .65 & .49 & .51 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$$\Delta m^2_{LSND} \simeq .4 \text{ eV}^2$$

$$\Delta m^2_{ATM} \simeq 6 \times 10^{-3} \text{ eV}^2$$

$$\Delta m^2_{\odot} \simeq 2 \times 10^{-4} \text{ eV}^2$$

TESTS

- MINI-BOONE
- DISAPPEARANCE EXPTS:

  KAMLAND, BOREXINO

  (WILL TEST BIMAXIMAL; CANNOT TEST FOR ν_s) EITHER VERSION.
- APPEARANCE:

  SNO $\frac{NC}{CC}$ (~ 2 VRS ~ 3)

  2+2   3+0 OR 3+1 ν'S
- U_{e3} TEST (MINOS, ...)

  $$2+2 \Rightarrow |U_{e3}^{eff}| \geq \theta_{LSND}$$

  $$3+0 \quad 0 \leq |U_{e3}| \leq .16$$
- INVERTED SPECTRUM (ν-FACT, ...)

  TEST FOR $L_e - L_\mu - L_\tau$ SYM
- $\beta\beta_{0\nu}$: BIMAX $\oplus$ $m_1 \ll m_2 \ll m_3$.

  OR $L_e - L_\mu - L_\tau$

CONCLUSION

1. PRESENT SOLAR ν DATA DOES NOT RULE OUT THE STERILE ν_s. BOTH 2+2 & 3+1 OK AND TESTABLE (i.e. $\frac{NC}{CC}$)
2. NEW SYMMETRIES ARE REVEALED BY MAXIMAL MIXING
   - 3ν BIMAXIMAL $L_e - L_\mu - L_\tau$
   - 3+1 $L_e - L_\mu - L_\tau \oplus$ MIRROR WORLD
   - 2+2 $L_e + L_\mu - L_\tau \oplus$ MIRROR WORLD
3. MIRROR H' CAN BE A VIABLE DARK MATTER CANDIDATE.