Mohap--01

STERILE NEUTRINOS AND PHYSICS BEYOND THE STANDARD MODEL

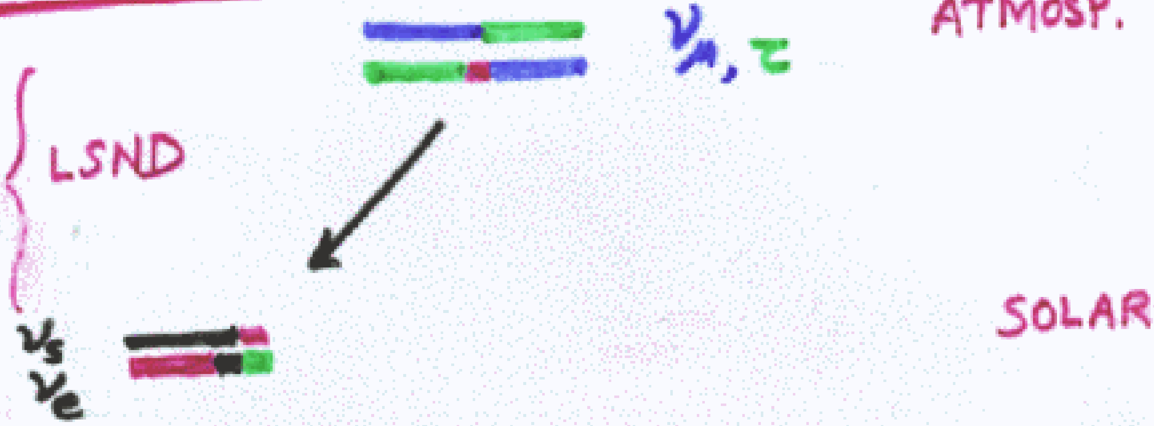
———— X ————

NEUTRINO TELESCOPE, 2001.

R.N. MOHAPATRA

• IF LSND IS CONFIRMED BY MINIBOONE, THERE MUST BE ONE OR MORE STERILE NEUTRINOS (ν_s).

SCENARIO



CALDWELL, R.N.M
PELTONIEMI, VALLE [93]
PELTO., TOMASINI, VALLE

• ULTRA LIGHT STERILE ν NEEDED : $m_{\nu_s} \sim 10^{-3} - 10^{-5}$ eV

ANOTHER HINT FOR ν_s

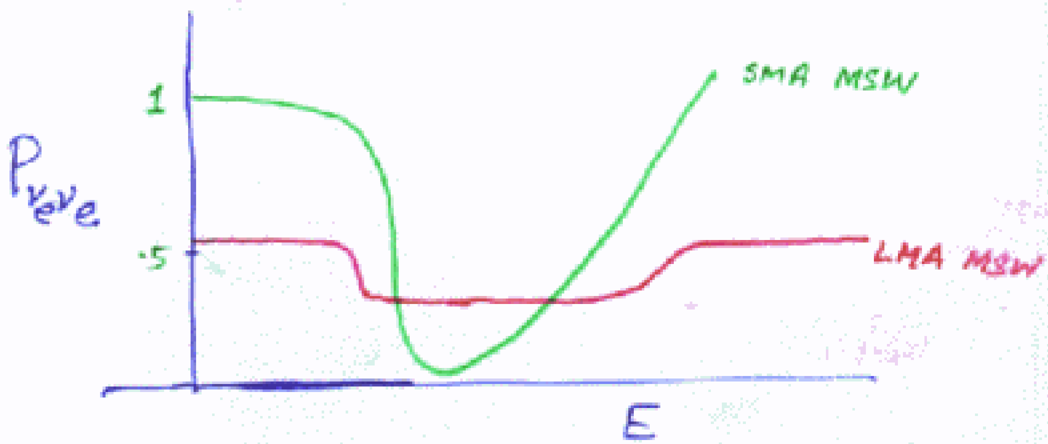
"ALPHA PROBLEM" IN SN r-PROCESS NUCLEOSYNTHESIS CAN BE SOLVED IN THE ABOVE SCENARIO :

CALDWELL, FULLER, QIAN '95
MCGLAUGHLIN et. al.

FITTING SOLAR ν DATA WITH $\nu_{STERILE}$

A) SMALL ANGLE MSW

RATES FIT BUT NOT E_ν DISTRIBUTION!



B) LARGE ANGLE MSW

RATES DON'T FIT SINCE NO N.C. CONTRIBUTION TO WATER.

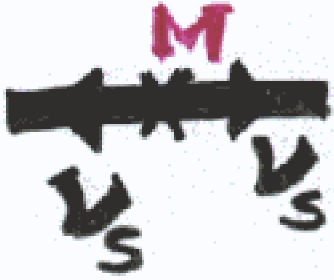
C) VACUUM OSC.: SAME AS B)

CRISIS FOR SINGLE ν_s ?

WHY ARE STERILE ν'S LIGHT ?

$\Rightarrow \quad \nu_1 = \nu_s$ $\quad SU(2)_L \times U(1)_Y$ SINGLET (STERILE ν)

m_ν TOO LARG



m_{ν_s} TOO LARG

TWO POSSIBLE WAYS
TO UNDERSTAND
ULTRA LIGHT STERILE ν_s'

(i) MIRROR UNIVERSE

(ii) LARGE EXTRA
DIMENSIONS

MIRROR UNIVERSE :

$\times$

BEREZHIANI, R.N.M. } '95
FOOT, VOLKAS

u, d, ν, e	u', d', ν', e'
W, Z, γ	W', Z', γ'
G	G'

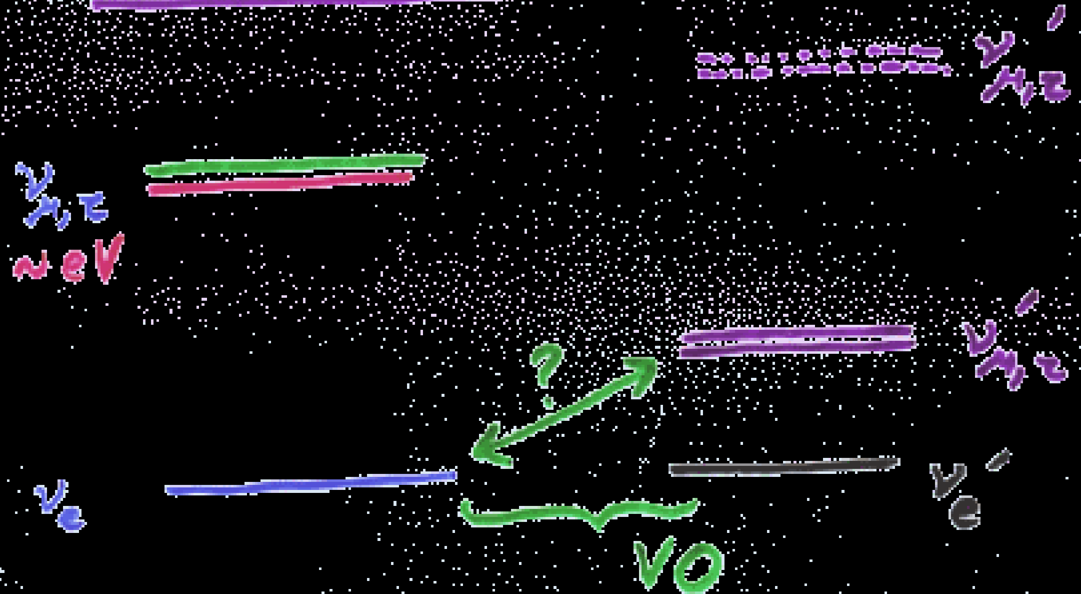
← GRAVITY →

- 3 STERILE ν_s's ($\nu_e', \nu_\mu', \nu_\tau'$).
- LAGRANGIAN PRIOR TO SYM. BREAKING IS MIRROR SYM.
- WHATEVER EXPLAINS THE LIGHTNESS OF $\nu_{e,\mu,\tau}$ ALSO EXPLAINS THAT OF $\nu_e', \nu_\mu', \nu_\tau'$

B-L

SPECTRUM DETAILS

ARE MODEL DEPENDENT *



- ν_e, ν_e' MASS COULD COME FROM GRAVITY
- $\nu_{\mu,\tau}$, $\nu'_{\mu,\tau}$ MASSES FROM SEE-SAW

$\nu_e - \nu_e'$ MIXING ARISES FROM GRAVITY :

OPERATORS

$$\frac{(LH)^2}{M_{P\ell}}, \quad \frac{LH \cdot L'H'}{M_{P\ell}}, \quad \frac{(L'H')^2}{M_{P\ell}} \Rightarrow$$

DEF. $\quad \langle H' \rangle / \langle H \rangle \simeq \zeta$

$$\begin{array}{ccc} & \nu_e & \nu_s \\ M_\nu = 10^{-5}\,\text{eV} \cdot & \left(\begin{array}{c} 1 \\ \lambda\zeta \end{array} \right. & \left. \begin{array}{c} \lambda\zeta \\ \zeta^2 \end{array} \right) \end{array}$$

- $\lambda \sim 1$; $\zeta \sim 20 \Rightarrow$ MSW SMALL ANGLE

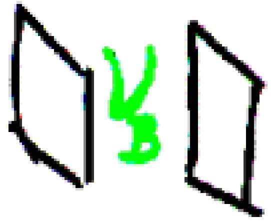
$\lambda \sim 1$; $\zeta \sim 1 \Rightarrow \nu_e - \nu_s$ VO .

INTERESTING COSMO...

- MIRROR MATTER IS DARK MATTER.
- DARK MATTER IS SELF INTERACTING
- EXPLAINS MACHO'S ($\sim \frac{1}{2} M_\odot$)
- γ-γ' MIXING

R.N.M., TEPLITZ 98-0...
BLINNIKOV, KHLOP...
BLINNIKOV, SILAGADZE,
FOOT,
GLASHOW, ...

LARGE EXTRA DIMENSIONS



KK MODES OF ν_B:

$$m_{KK}^{(n)} \sim \frac{n}{R}$$

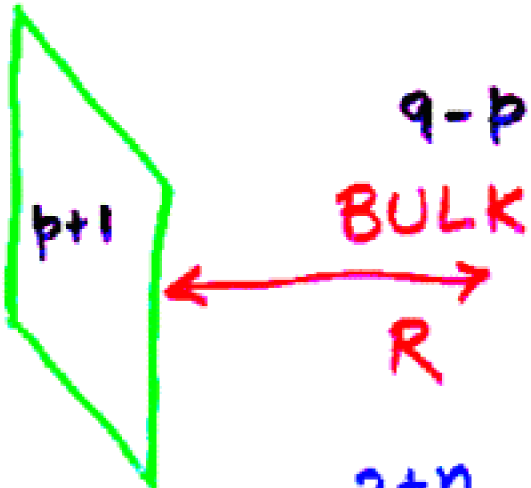
IF $R^{-1} \sim 10^{-3}\,eV$ $\left(\sim (mm)^{-1}\right)$

$\Rightarrow$ $m_{KK}^{(n)}$ ARE NATURALLY LIGHT!!

$\nu_B^{(n)} \equiv$ STERILE ν's:

STRING THEORIES

(NON-PERURBATIVE) $D=10$



$$M_{Pl}^2 \simeq M_{STR.}^{2+n} R_1 R_2 \cdots R_n .$$

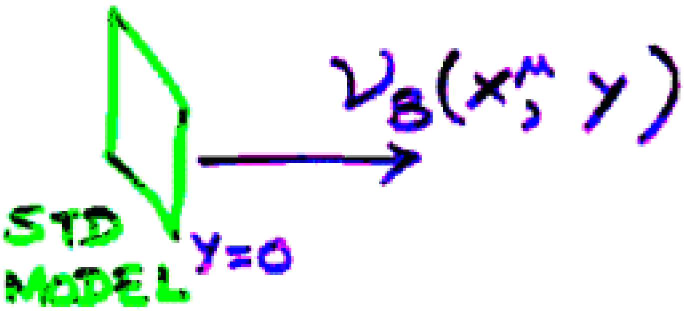
ASSUME ONLY 2 SCALES : (M_{STR}, R^{-1})

(i) $n \geq 2$; FOR $n=2$
$M_{STR.} \sim$ few TeV's
$R \sim .1$ mm

(ii) $n=1$; $R \simeq .1$ mm
$M_{STR} \sim 10^9$ GeV

MASSES :

DIENES, DUDAS, GHERGHETTA
ARKANI-HAMED, DVALI, DIMOPOULOS & MARCH-RUSSELL '98



$$\psi_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad ; \quad H = \begin{pmatrix} H^0 \\ H^- \end{pmatrix}$$

$$\mathcal{L} = \frac{1}{\sqrt{M_{st.}}} \bar{\psi}_L H \nu_B(x^\mu, y)\Big|_{y=0} + h.c.$$

$\nu^{(\pm)}_{B,L}$ + : EVEN FOURIER IN y

$\nu^{(\pm)}_{B,R}$ − : ODD " "

$$\mathcal{L} = \frac{1}{\sqrt{M_{st.} R}} \bar{\psi}_L H \left[\sum_{n=0}^{\infty} \nu^{(+)}_{B,R} \right] + h.c.$$

$$m = \frac{V_{WK}}{\sqrt{M_{st} R}} = \frac{M_{st.} V_{WK}}{M_{Pl}} \simeq 10^{-4}\, eV$$

ν- MASS MATRIX

$$
\begin{array}{cccccc}
\nu_e & \nu_{B,R}^{(0)} & \nu_{BR}^{(1,+)} & \nu_{BL}^{(1,-)} & \nu_{B,R}^{(2,+)} & \nu_{BL}^{(2-)} \cdots \\
\end{array}
$$

$$
\left(
\begin{array}{cccccc}
0 & m & \sqrt{2}\,m & 0 & \sqrt{2}\,m & 0 \;\cdots \\
m & 0 & 0 & 0 & 0 & 0 \\
\sqrt{2}\,m & 0 & 0 & \mu & 0 & 0 \\
0 & 0 & \mu & 0 & 0 & 0 \\
\sqrt{2}\,m & 0 & 0 & 0 & 0 & 2\mu \\
0 & 0 & 0 & 0 & 2\mu & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots &
\end{array}
\right.
$$

$$\Rightarrow \quad m_{\nu_D \atop \nu_e \nu_B^{(0)}} \sim m \quad ; \quad \theta_{\nu_e \nu_B^{(n)}} \sim \frac{\sqrt{2}\,m}{n\mu} = \frac{\sqrt{2}\,mR}{n}$$

IS SMALL m_ν NATURAL?

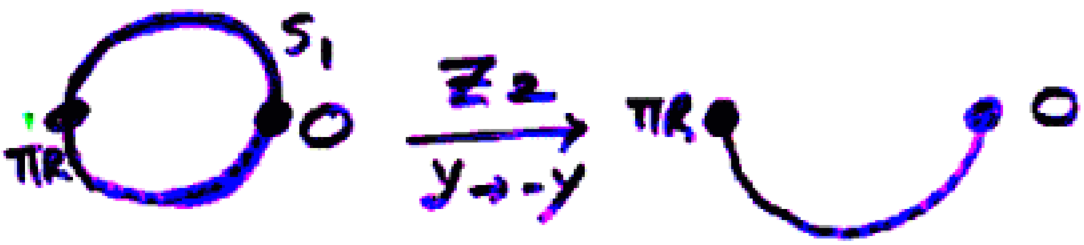
(i) $\dfrac{(\overline{\Psi}_L H)^2}{M_{str}}$ ALLOWED $\Rightarrow$ MUCH LARGER m_ν

IMPOSE GLOBAL B-L - BUT STRING THEORIES MAY NOT ALLOW GLOBAL SYM. ☹

(ii) $M_{str.} \overline{\nu}_B \nu_B$ DIRAC MASS ?

STRING TH. FORBIDS THIS:

$\dfrac{S_1}{Z_2}$



$$\mathcal{L}_{KIN.}(\nu_B) = i\,\overline{\nu}_B \gamma^\mu \partial_\mu \nu_B + i\,\overline{\nu}_{BL} \partial_y \nu_{BR}$$

$$y \longrightarrow -y, \quad \nu_{BL} \longrightarrow +\nu_{BL}, \quad \nu_{BR} \longrightarrow -\nu_{BR}$$

FORBIDS $\overline{\nu}_B \nu_B$!!

TeV SCALE STRING MODELS HAVE "NATURALNESS" PROBLEM FOR ν-MASSES !!

OUR SUGGESTION

USE MODELS WITH LOCAL $B-L$ + $M_{STR.} \sim 10^9\,GeV$

$\Rightarrow$ SEE-SAW IN THE BRANE + BULK $\nu_B \supset \nu_{STERILE}$!!

ULTRALIGHTNESS GUARANTEED BY **STRING** PROPERTIES !!

INTERMEDIATE STRING SCALE LOCAL B-L MODELS:

R.N.M., NANDI, PEREZ-LOR ZAN,

R.N.M., A. PEREZ-L

$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ GAUGE GROUP IN THE BRANE + $\nu_B(x,y)$ IN THE BULK.

$$\mathcal{L}' = i\int dy\, \bar{\nu}_{BL}\partial_y \nu_{BR} + \frac{1}{\sqrt{M_*}}\left(\bar{\psi}_L \chi_L + \bar{\psi}_R \chi_R\right)\nu_B(x,0) + \frac{(\bar{\psi}_L \chi_L)^2 + (\bar{\psi}_R \chi_R)^2}{M_*} + \bar{\psi}_L \phi \psi_R$$

BREAK PARITY & $SU(2)_R \times U(1)_{B-L}$ TO $U(1)_Y$!!

PARITY: $x \to -x$

$Z_2 \equiv$ BULK PARITY $y \to -y$.

UNDER Z_2, $\nu_{B,L}^{(x,y)} \to \nu_{BL}^{(x,-y)}$

$\nu_{B,R}^{(x,y)} \to -\nu_{B,R}^{(x,-y)}$

PARITY $\Rightarrow$ $\chi_R \to +\chi_R$

$(\bar{\Psi}_L \chi_L \nu_{BR} + \bar{\Psi}_R \chi_R \nu_{BL}) \Rightarrow$ $\chi_L \to -\chi_L$

$\Rightarrow$ AT $y=0$ $\Rightarrow$ $\nu_{B,R}(x,0)=0$

$\Rightarrow \langle \chi_L \rangle = 0$; $\langle \chi_R \rangle \simeq M_{STR}$.

- BREAK PARITY & $SU(2)_R \times U(1)_{B-L}$
- BRANE HAS ν_e, $\nu_{B,L}^{(n,+)}$, $\partial_y \nu_{B,R}^{(n,-)}$

$(n = 1, \cdots \infty)$

EFFECTIVE LAGRANGIAN IN THE BRANE :

$$\frac{h}{\sqrt{M_*}}\int d^4x \left[\bar{\nu}_R^{(e)} \chi_R^0 \, \nu_{BL}(x,0) + h \bar{\nu}_L^{(e)} \nu_R^{(e)} \phi^0 \right.$$

$$\left. + \frac{\bar{\nu}_R^{(e)} \bar{\chi}_R \, \nu_R^{(e)} \bar{\chi}_R}{M_*} + n\mu \, \bar{\nu}_{B,L}^{(+,n)} \nu_{B,R}^{(+,n)} \right]$$

- $\nu_R^{(e)} \nu_R^{(e)}$: $\sim V_R^2 / M_* \sim 10^9\,\mathrm{GeV}$
- $\bar{\nu}_L^{(e)} \nu_R^{(e)}$: $m \equiv h\, v_{WK}$ (1-10 MeV)
- $\nu_R^{(e)} \nu_B$: $\alpha \simeq \frac{M_*}{M_{Pl}} \cdot V_R$ (1-10 MeV)

DECOUPLE ν_R : $\Rightarrow$ SEESAW SUPPRESSION OF $m_{\nu_e}, \nu_\mu, \nu_\tau$

ν_R (… '01)

$$
\begin{array}{c|cccc}
 & \nu_L^{(0)} & \nu_{BL}^{(0)} & \nu'_{BL} & \nu'_{BR} \\
\hline
\nu_L^{(0)} & m(1+\epsilon) & \alpha(1+\epsilon') & \sqrt{2}\,\alpha \cdots & 0 \\
\nu_{BL}^{(0)} & \alpha(1+\epsilon') & \frac{\alpha^2}{m} & \sqrt{2}\,\frac{\alpha^2}{m} & 0 \\
\nu'_{BL} & \sqrt{2}\,\alpha & \frac{\sqrt{2}\,\alpha^2}{m} & \frac{2\alpha^2}{m} & \frac{M}{m}\partial_5 \\
\nu'_{BR} & 0 & 0 & \frac{M}{m}\partial_5 & 0
\end{array}
\quad \left(\frac{m}{M}\right)
$$

ϵ = RADIATIVE CORRECTIONS

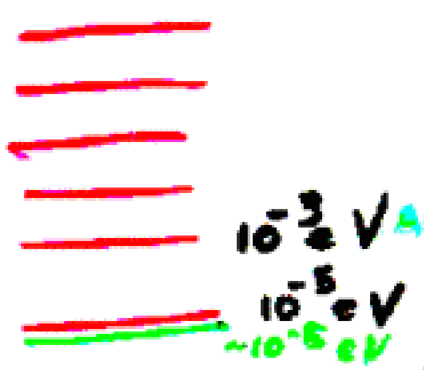
* LIGHTEST MODE : $m_0 = 0 + \frac{m^2}{M}\epsilon$

* FOR OTHERS,

$$\frac{m^2}{M} + \frac{\alpha^2}{M} \cdot \frac{\pi m_n}{\mu} \cot \frac{\pi m_n}{\mu} = m_n$$

$m = 10\,\mathrm{MeV}$

$R^{-1} \sim 10^{-3}\,\mathrm{eV}$



MIXINGS:

$$|\nu_0\rangle = c_\zeta |\nu_e\rangle + s_\zeta |\tilde{\nu}\rangle_B$$

$$\tan\zeta \approx \frac{m}{\alpha}$$

$$\Delta m^2 = m^2_{\nu_B^0} - m^2_{\nu_0} \approx \left(\frac{m^2}{M}\right)^2 \simeq 10^{-10}\ eV^2$$

$\Theta_{\nu_e \nu_B^{(n)}}$:

$$\nu_{B,+}^{(n)} \qquad \theta_+ \sim \frac{m_n}{\mu} \sim \%$$

$$\nu_{B,-}^{(n)} \qquad \theta_- \sim \left(\frac{m_n}{\mu}\right) \sim \%$$

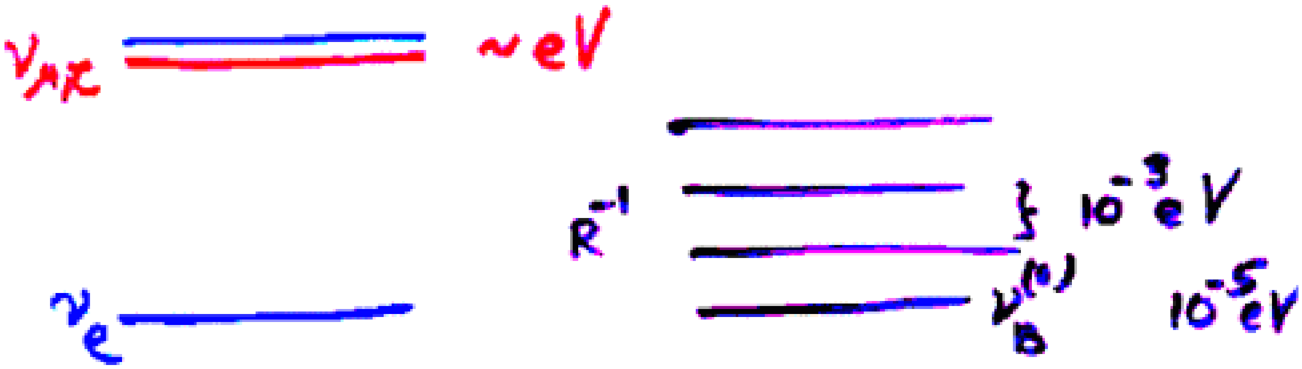
$\Rightarrow$ $\nu_e - \nu_B^{(0)}$ VACUUM OSC.

$\nu_e - \nu_B^{(n)}$ MSW

FITTING SOLAR ν-DATA WITH KK TOWER:

CALDWELL, YELLIN, R.N.M
hep-ph/0102279

SPECTRUM:



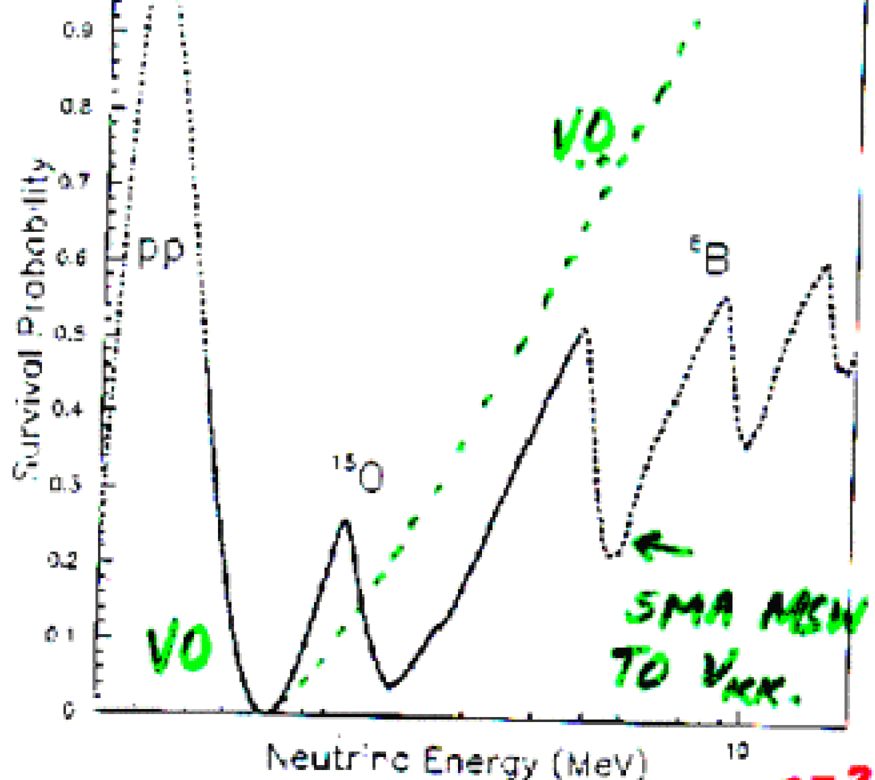
$$\nu_e - \nu_B^{(0)} \Rightarrow \Delta m^2 \simeq 10^{-11}\,\mathrm{eV}^2$$

$$\nu_e - \nu_B^{(n)} \qquad \simeq 10^{-5}\,\mathrm{eV}^2$$

$$\theta_{en} \simeq \sqrt{2}\,\frac{m}{\mu} \sim 1\,\%$$

:3 PARAMETER FIT:

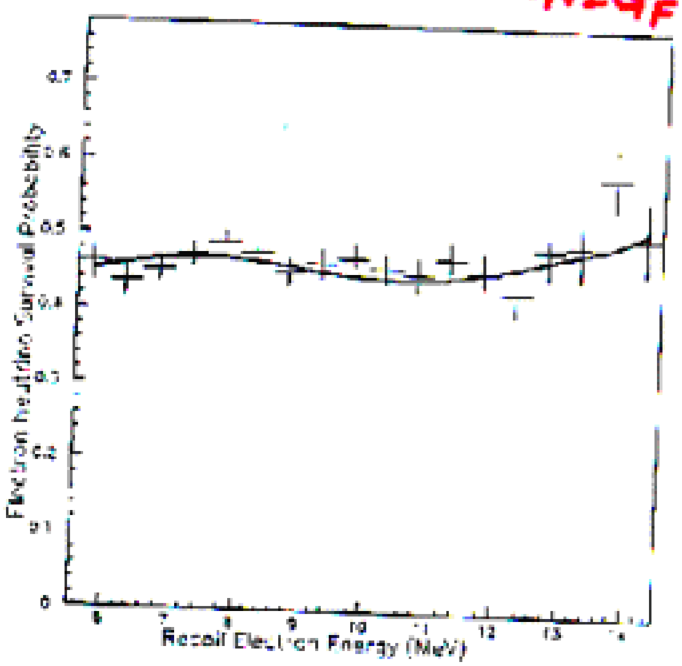
$$\Delta m^2_{\nu_e \nu_B^{(0)}}, \quad R, \quad \theta_{\nu_e \nu^B_{KK}} \sim \sqrt{2}\,\frac{m}{\mu}$$



$\mu = 3.4 \times 10^{-3}$ eV
OR
$R = 58\,\mu m$
$mR = 0.0093$
$\delta_{ee} = .8 \times 10^{-7}$ eV

PEAK SPACING: $E_{n+1} - E_n = \dfrac{R^{-2}}{4\sqrt{2}\, G_F n_e}\left((n+1)^2 - n^2\right)$

$\approx$ few MeVs



CALDWELL, R.N.M., YELLIN.

DIPS :

MSW RESONANCE

$$\Rightarrow \quad m_n^2 \simeq 4 \frac{G_F}{\sqrt{2}} \frac{\rho}{m_p} E_r$$

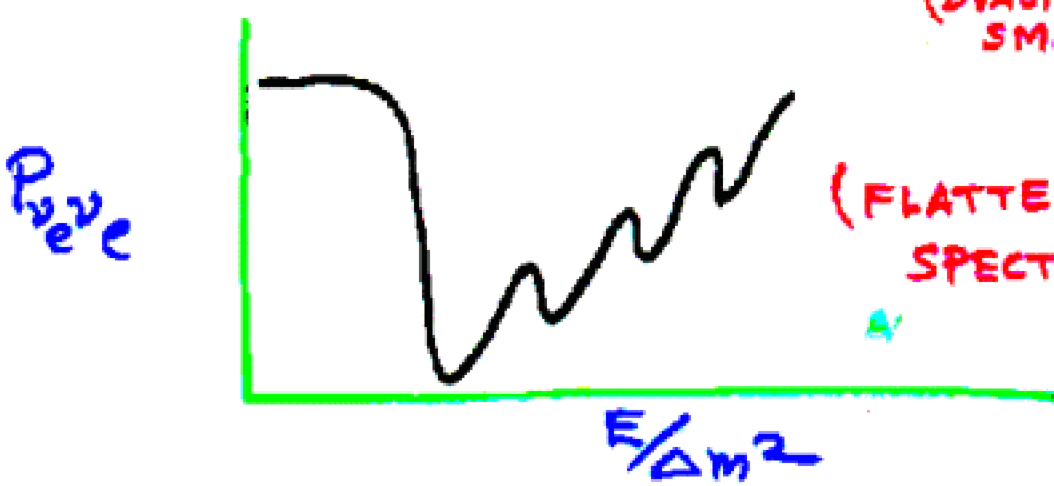
$$P_{SURV.} \simeq e^{-\frac{\pi m_n^2 \sin^2 2\theta}{2E} R_{eff}} \qquad E > E_r$$

$$\simeq 1 \qquad E < E_r$$

MANY RESONANCES :

$$E > E_r \; ; \quad P = P^{(1)} P^{(2)} P^{(3)} \cdots P^{(r)}$$

(DVALI, SMIRNOV '9



(FLATTESIS SPECTRUM !

NO DIPS SEEN

$\Rightarrow$ WILL CONSTRAIN PARAMETE

R AND $m = \frac{M_* V_{WK}}{M_{PL}}$ OF

MODELS WITH LARGE EXTRA DIMENSIONS :

e.g. $\Rightarrow$ m CLOSE TO ZERO

OR $R^{-2} > \frac{2\sqrt{2} G_F \rho}{m_p} (15 \text{ MeV})$

$\gtrsim 10^{-4} \text{ eV}^2$

(CURRENT BOUNDS $> 10^{-6} \text{eV}^2$)

CONCLUSION

- CONFIRMATION OF LSND WILL REVOLUTIONIZE OUR THINKING ABOUT PHYSICS BEYOND THE STANDARD MODEL!!

- MIRROR UNIVERSE AND LARGE EXTRA DIM. MODELS PROVIDE TWO EXAMPLES OF HOW CREATIVE ONE'S THINKING NEEDS TO BE!!

3. ON THE PHENOMENOLOGY SIDE, A FLAT $\nu_\odot$ SPECTRUM CAN BE MIMICED WITH VO + SMA MSW TO EXTRA STERILE ν's AS IN EXTRA D- MODELS.

4. MIRROR MODEL WITH 3 ν_s's NEED ALSO TO BE STUDIED FOR THIS PURPOSE!!