Dirac vs Majorana

Now that neutrinos appear massive

ν_L 

because $m_\nu \neq 0$, $v < c$

you can pass it and look back

"ν_R" 

what is this state??

two possibilities:

Dirac neutrino

This is a new state:

"right-handed neutrino"

We didn't know this state existed but it must be there.

Majorana neutrino

This is a known state:

"right-handed anti-neutrino"

We thought ν + $\bar{\nu}$ are different, but they must be the same particle (L violatio

What about massive particles? e, u, d, μ, ...

CC weak interaction acts

only on left-handed particles

appears inconsistent if massive

Resolution in the Standard Model:

Universe is filled with Higgs boson

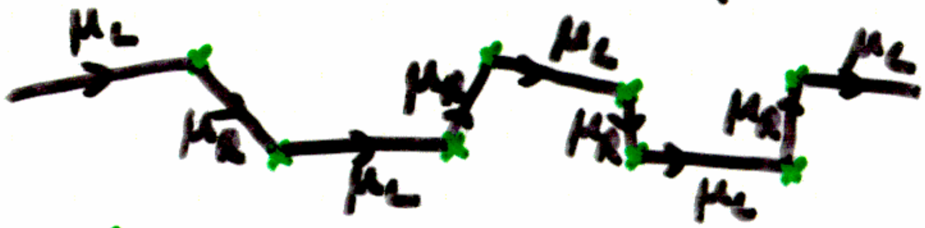
⇒ left-handed + right-handed mix

e

0.511 MeV/c^2

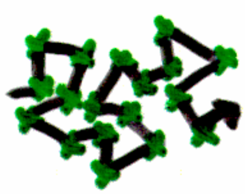
doesn't bump too often

μ



105 MeV/c^2

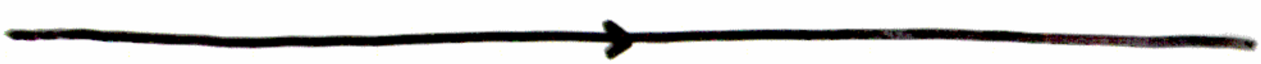
t



175,000 MeV/c^2

bumps all the time

ν_L



no ν_R ⇒ no way to bump + mix

⇒ massless

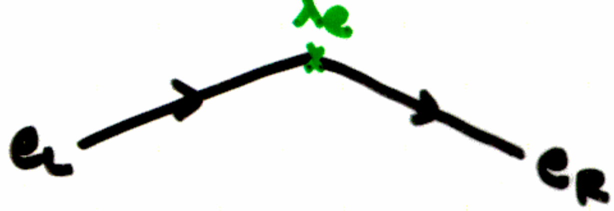
quarks, leptons:

e.g. $[(e^-)_L\,,\ (e^+)_R]$

$[(e^-)_R\,,\ (e^+)_L]$

mix due to Higgs

$$m_e = \lambda_e v$$



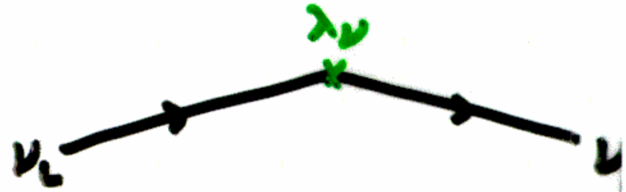
they are all Dirac type

Dirac neutrinos?

$[\,(\nu)_L\,,\,(\bar{\nu})_R\,]$

NEW: $[\,(\nu)_R\,,\,(\bar{\nu})_L\,]$ } mix

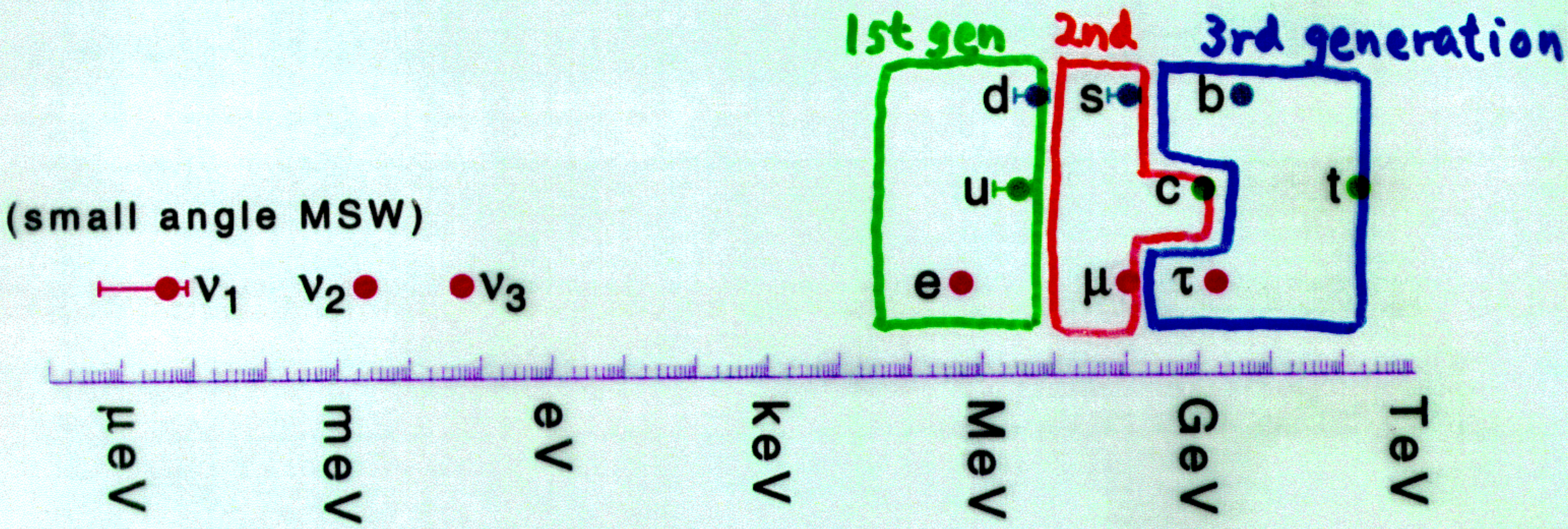
$m_\nu = \lambda_\nu v$



$\Rightarrow$ naively, we expect

$m_\nu \sim m_\ell \sim m_q$

fermion masses



H. Murayama, SSI 2000

$< 10^{-12}$

$\times$

$\ll$

hard to accept this unless

$\exists$ reason why $h_\nu \ll h_e, h_q$ esp. 3rd gen

Theoretical bias against light ν_R

$SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge int.

Q_L	$(3, 2, \frac{1}{6})$
u_R	$(3, 1, \frac{2}{3})$
d_R	$(3, 1, -\frac{1}{3})$
L_L	$(1, 2, -\frac{1}{2})$
e_R	$(1, 1, -1)$
ν_R	$(1, 1, 0)$

no gauge int. at all!

need $\mathcal{L} \ni \lambda_e \bar{L}_L e_R H \Rightarrow m_e = \lambda_e v$

can understand why $m_e < v \ll M_{Pl}$

can write $\mathcal{L} \ni M \nu_R \nu_R$

M does not have to be small

why not $M \sim M_{Pl}$?

Seesaw mechanism

ν_R can be heavy $\quad M \gg v$

not allowed due to gauge inv.

$$\mathcal{L} \ni (\bar{\nu}_L \;\; \nu_R) \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \bar{\nu}_L \\ \nu_R \end{pmatrix}$$

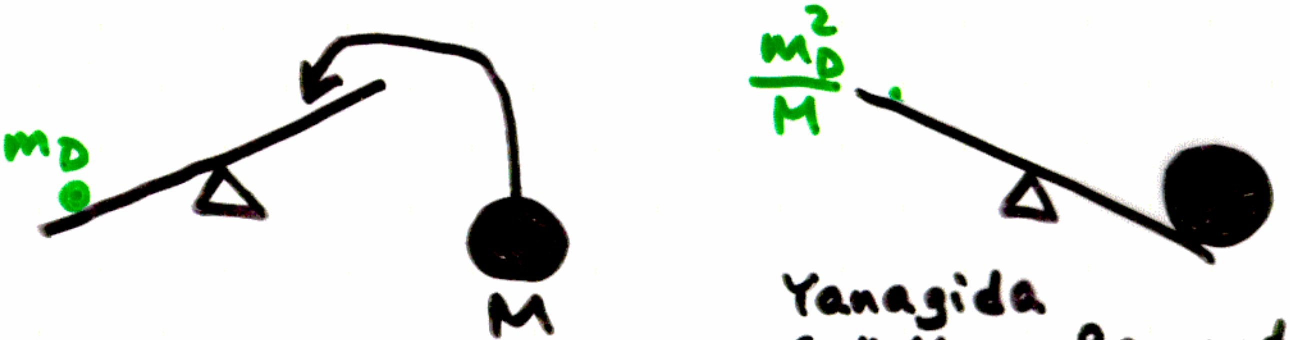
expect $m_D \sim m_t$ for 3rd gen.

two eigenvalues:

$$M, \; -\frac{m_D^2}{M}$$

if $M \gg v$

$\Rightarrow$ naturally explains why neutrinos light



Yanagida
Gell-Mann, Ramond, Slansky

three generations:

$$-\frac{m_D^2}{M} \Rightarrow -(m_D)(M)^{-1}(m_D)^T$$

m_D, M 3x3 matrices

SO(10) GUT

$$\underline{16} = \begin{pmatrix} u_L & u_L & u_L & \nu_L \\ d_L & d_L & d_L & e_L \\ u_R & u_R & u_R & \nu_R \\ d_R & d_R & d_R & e_R \end{pmatrix}$$

all fermions in a single multiplet

SO(10): the smallest anomaly-free gauge group with chiral fermions

$SO(10) \to SU(3) \times SU(2) \times U(1) \qquad \langle \phi \rangle = M_{GUT}$

$\mathcal{L} \ni \phi \nu_R \nu_R \quad \Rightarrow \quad M \sim M_{GUT}$

cf. if $m_{\nu_3} = (\Delta m^2_{\oplus})^{1/2} \simeq 0.05\,\text{eV}$

$$\simeq \frac{m_t^2}{M}$$

$\Rightarrow M \simeq 10^{15}\,\text{GeV}$

Possible reasons why $h_\nu < 10^{-12}$

However, "naive SO(10)" dead

$\mathcal{L} \ni 16\,16\,H$

$$\underbrace{\lambda_u \sim \lambda_d \sim \lambda_e}_{\text{all hierarchical, small mixing}} \sim \lambda_\nu$$

$$M \sim M_{GUT} \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}$$

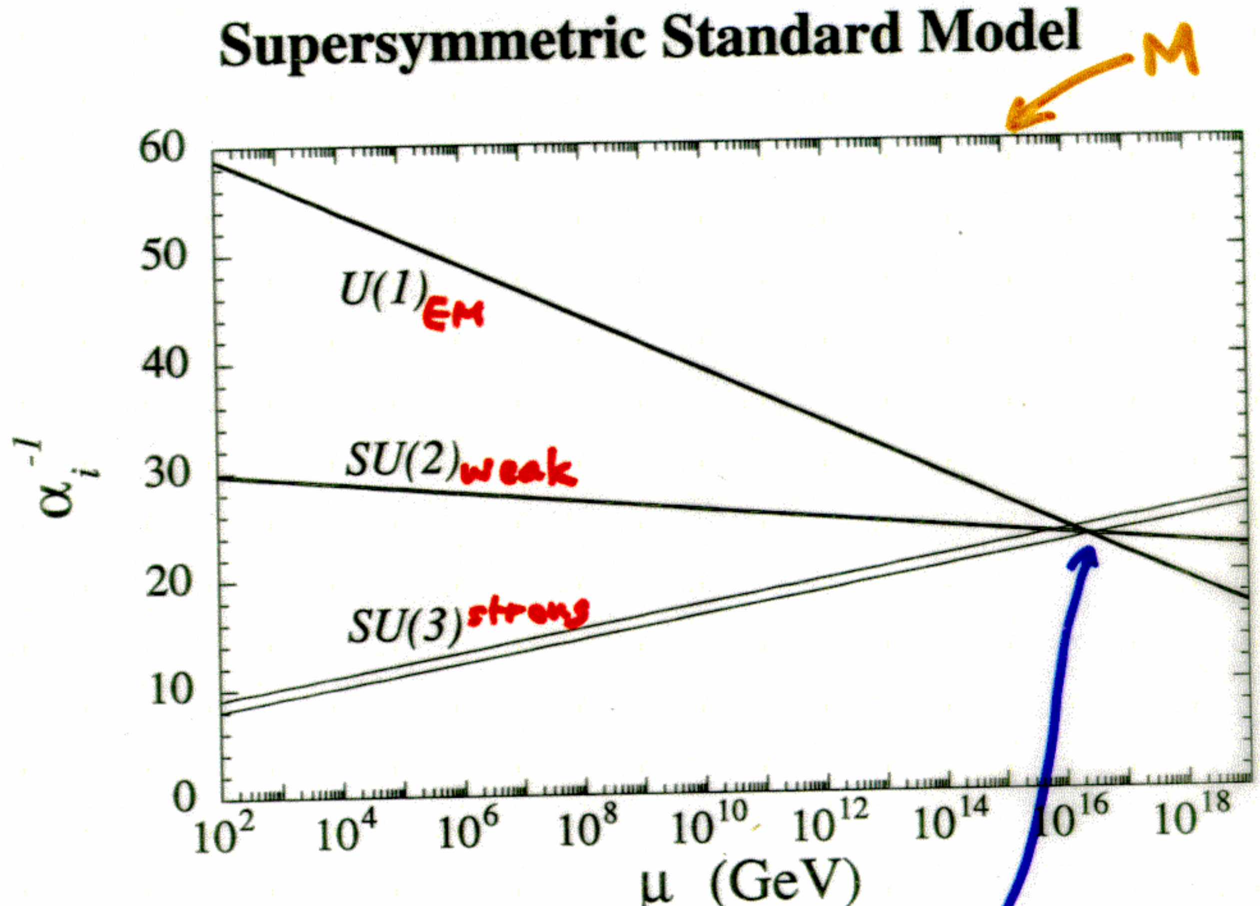
$$(m_\nu) = (\lambda_\nu v) M^{-1} (\lambda_\nu^T v)$$

$$\sim \frac{v^2}{M_{GUT}} \underbrace{\lambda_\nu \lambda_\nu^T}_{\text{also hierarchical, small mixing}}$$

SuperK killed it!

$\Rightarrow$ "not-so-naive SO(10)"

alternative ideas

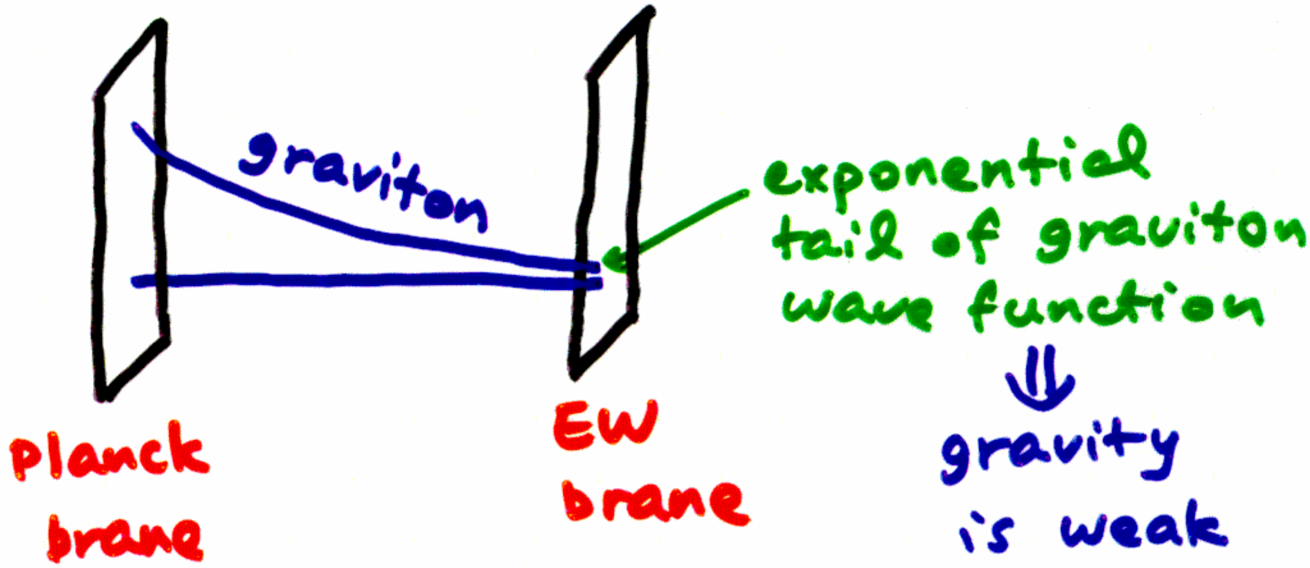


Grand Unification?

Dimopoulos
Raby
Wilczek

Dine
Fischler

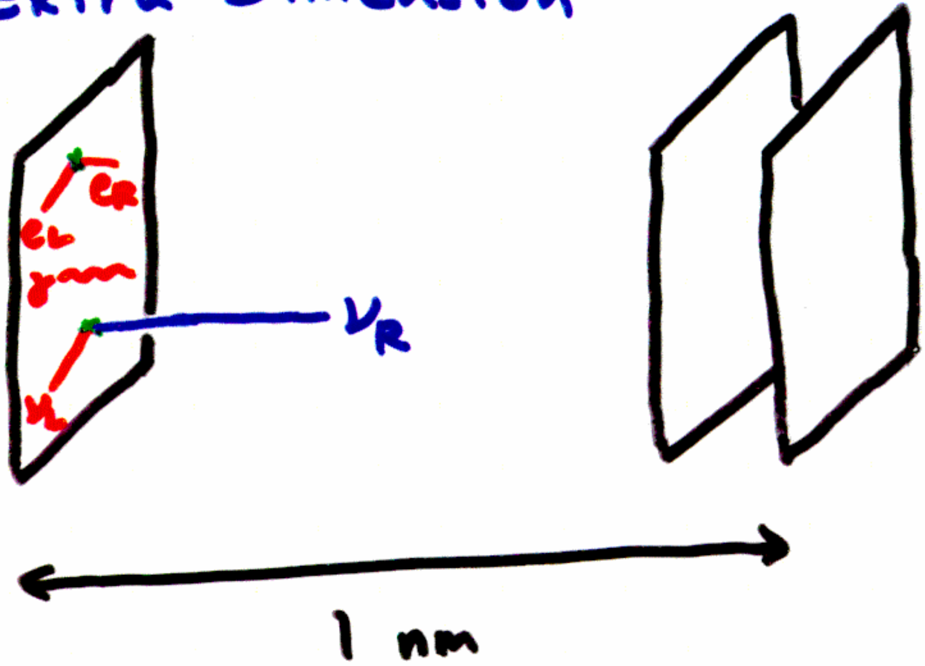
Warped Extra Dimension



ν_R Yukawa is weak

Grossman, Neubert

Large Extra Dimension



even if $h_\nu \sim h_t \sim O(1)$

ν_R is spread out and doesn't come on top of our brane so often

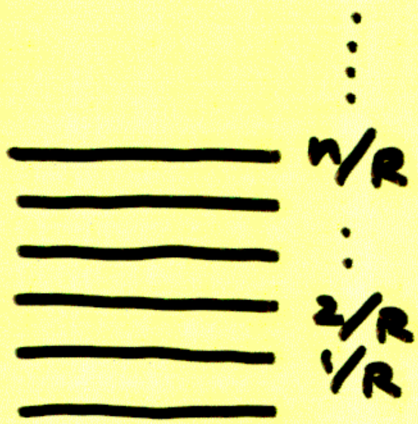
all particles with gauge interaction confined on the brane

but ν_R is gauge singlet is allowed to escape from the brane

Dienes, Dudas, Gherghetta

Arkani-Hamed, Dimopoulos, Dvali, March-Russell not only

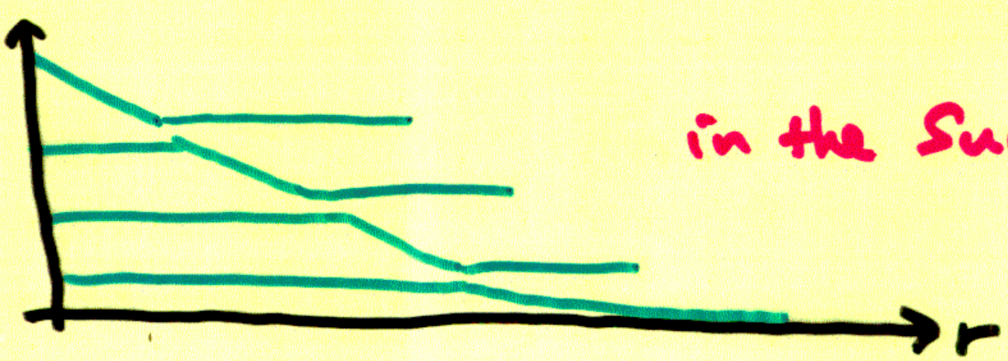
$\exists\, \nu_R$ in addition to ν_L



energy levels
= mass

infinite tower of
light sterile neutrinos

Dvali, Smirnov



in the Sun

MSW multiple resonances

Protected by new symmetries

e.g. new U(1) charge + SUSY

$$U(1)_{L'} \times U(1)_N \to U(1)_L$$

$$\begin{array}{llll} L & (1, & 0) & \to 1 \\ N & (0, & -1) & \to -1 \\ \chi & (1, & -1) & \to 0 \qquad \langle \chi \rangle \neq 0 \end{array}$$

$$\int d^4\theta \, \frac{\chi^+}{M_{Pl}^2} L N H_u$$

$$\Rightarrow h_\nu \sim \frac{m_{SUSY}}{M_{Pl}}$$

$\tilde{N}$: right-handed sneutrinos $\lesssim$ TeV

may even be dark matter

Arkani-Hamed,
Hall,
HM,
Smith,
Weiner

if L further violated

e.g. $U(1)_{B-L}$ gauged

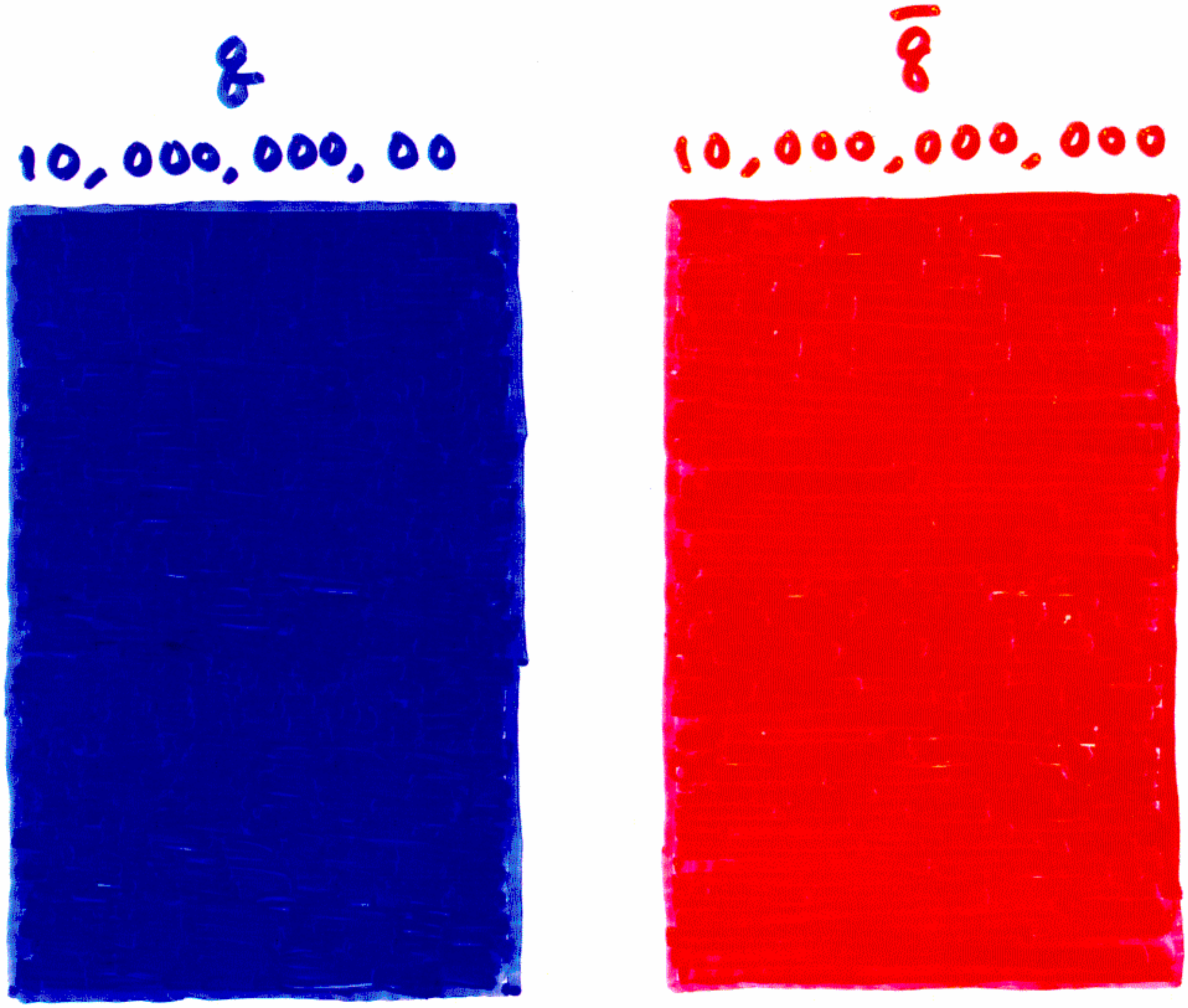
broken ~ TeV $\langle\phi\rangle \neq 0$

$B-L=1$

$$\mathcal{L} \ni \frac{\phi\phi}{M_{Pl}} NN$$

3 N's
3 ν_L's
] all mix

$\Rightarrow$ 3 active neutrinos
3 sterile neutrinos



Early Universe

$T \gtrsim 1$ GeV

cosmic baryon asymmetry

1

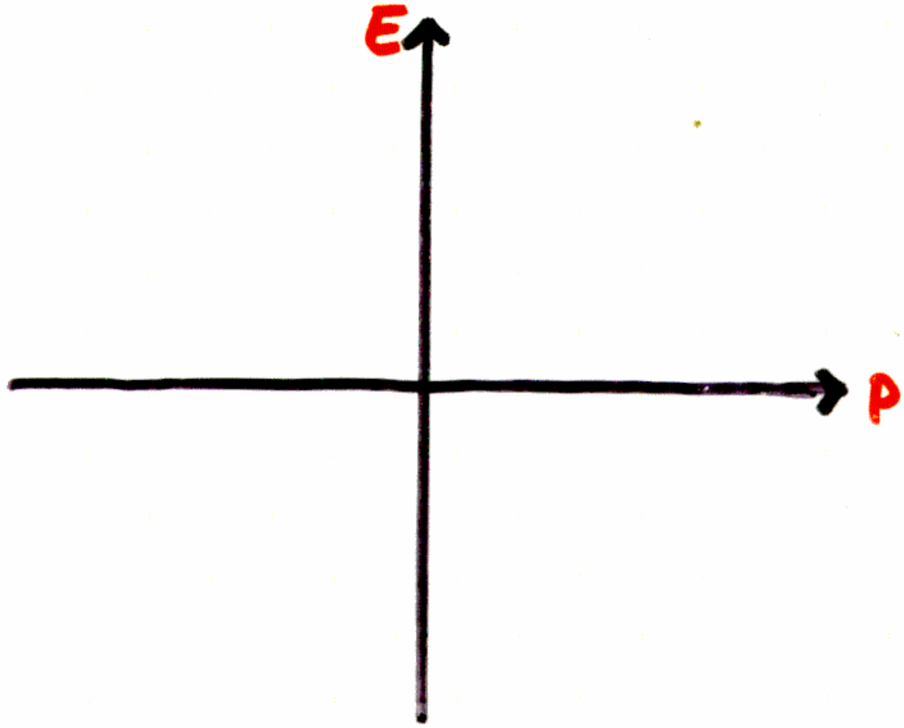
us

<u>now</u>

lepton-number violation

$\underset{SM}{\Longrightarrow}$ baryon-number violation

$i\gamma^\mu(\partial_\mu - ieW_\mu)\psi = 0$ Dirac eq.



T > 200 GeV

W massless ~ EM field

"W-plasma" W always

ends up w/ a gauge equivalent config.

creats $\Delta l_L = \Delta q_L = \Delta q_L = \Delta q_L = 1$

violates B+L, preserves B−L

⇓

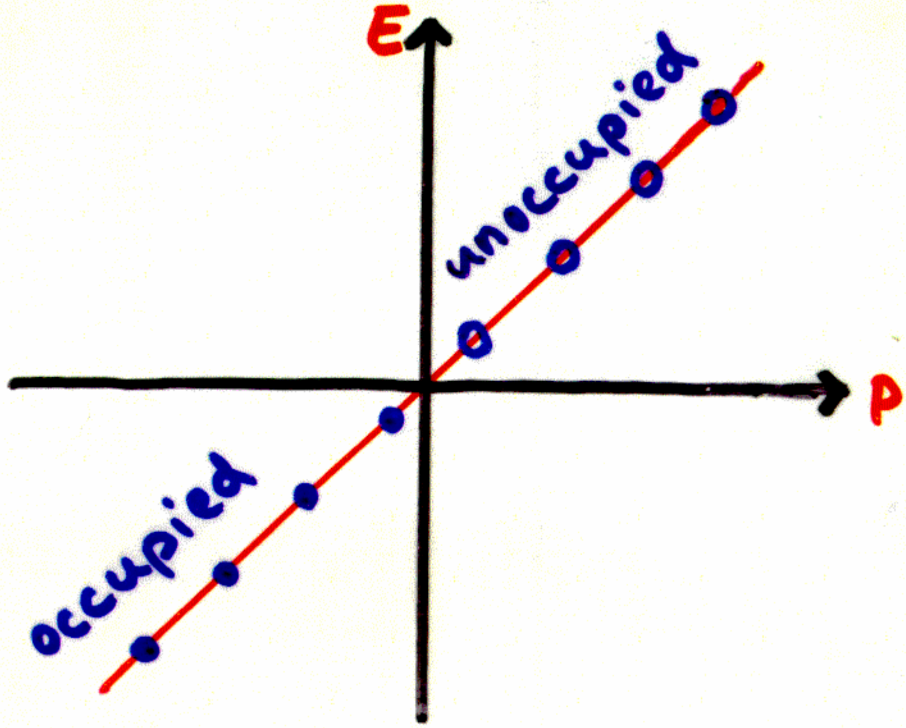
+ Majorana ν: violates B−L

"anomaly"

lepton-number violation

$\xRightarrow{SM}$ baryon-number violation

$i\gamma^\mu(\partial_\mu - ieW_\mu)\psi = 0$ Dirac eq.



T > 200GeV

W massless ~ EM field

"W-plasma" W always fluctuate

ends up w/ a gauge equivalent config.

creats $\Delta l_L = \Delta q_L = \Delta q_L = \Delta q_L = 1$

violates B+L, preserves B−L

⇓

+ Majorana ν: violates B−L

"anomaly"

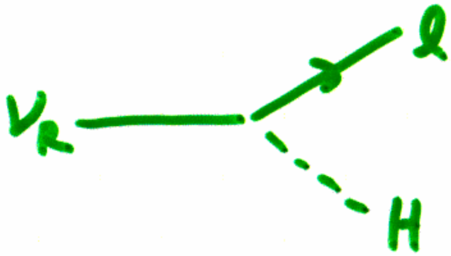
Leptogenesis

Fukugita, Yanagida

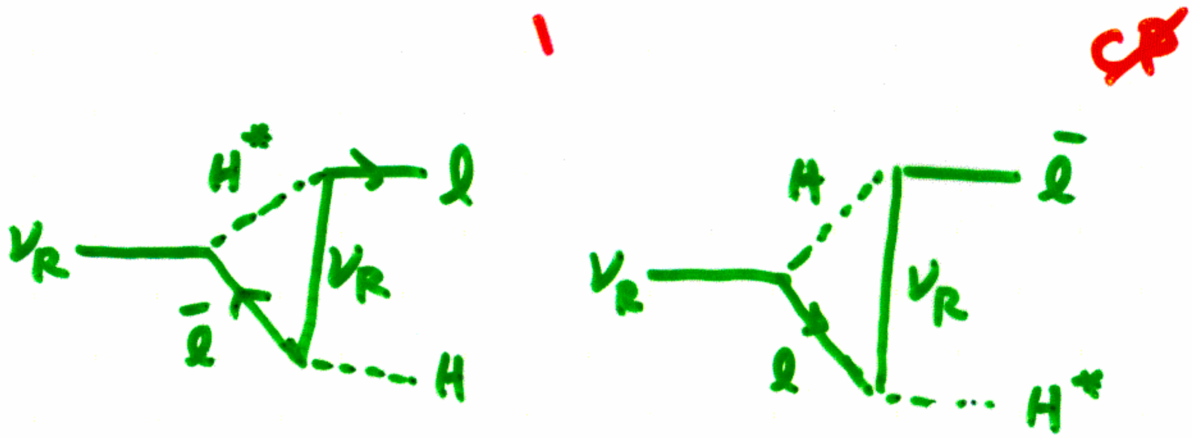
ν_R's in thermal equilibrium

@ $T > M$

once $T < M$, ν_R's no longer produced



$$\Gamma(\nu_R \to l H) = \Gamma(\nu_R \to \bar{l} H^*)$$



decay of ν_R produces net $L \neq 0$

lepton number created

$\Downarrow$ SM anomaly

chemical equilibrium between B & L

$$B \simeq 0.35\,(B-L)$$

$$L \simeq -0.75\,(B-L)$$

baryon asymmetry created

$\not{CP}$ in ν sector may explain cosmic baryon asymmetry

caveat there are three $\not{CP}$ phases relevant to this issue, but only one of them can affect ν oscillation.

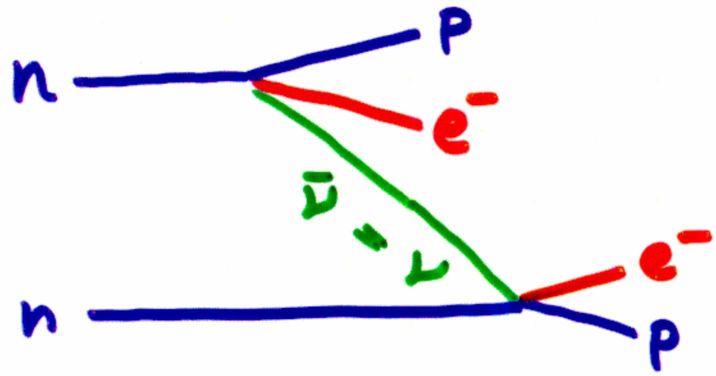
MODELS

seesaw mechanism

$\Rightarrow$ Majorana neutrinos

$\Rightarrow$ lepton number violation

$0\nu\beta\beta$ (neutrinoless double beta) decay?



$$(A, Z) \longrightarrow (A, Z+2) + e^- + e^- + 0\nu$$

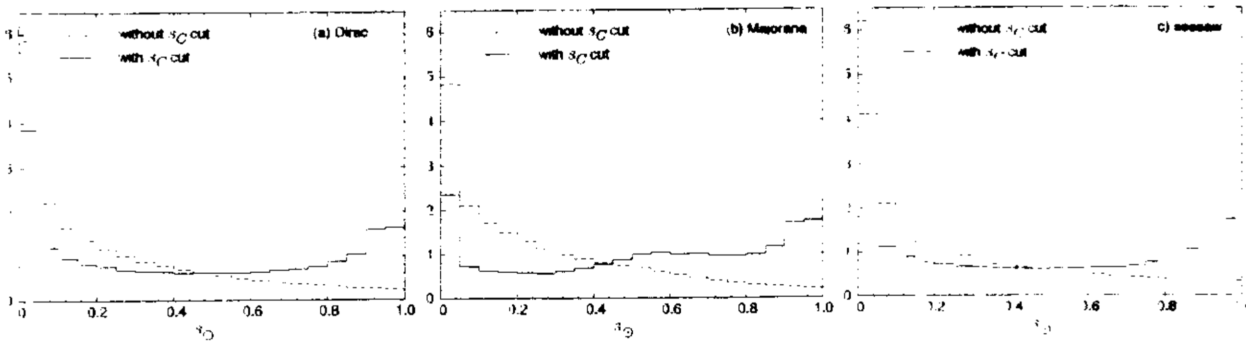


FIG. 3. Plots of the normalized, binned distributions of $s_\odot$ for Dirac (a), Majorana (b), and seesaw (c) cases. The distribution after imposing the s_C cut (solid) shows a greater preference for large $s_\odot$ compared with the original distribution (dashed).

symmetry models, there is no reason to expect U_{e3} is particularly small, and long baseline experiments which probe Δm^2_{atm}, such as K2K and MINOS, will likely see large signals in $\bar{\nu}_e$ appearance. If Δm^2_{atm} is at the lower edge of the current Superkamiokande limit, this could be seen at a future extreme long baseline experiment with a muon source. Furthermore, in this scheme $\Delta m^2_\odot$ is large enough to be probed at KamLAND, which will measure large $\bar{\nu}_e$ disappearance.

ACKNOWLEDGMENTS

This work was supported in part by the Director, Office of Science, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098 and in part by the National Science Foundation under grant PHY-95-14797.

[1] Super-Kamiokande Collaboration (Y. Fukuda et al.), Phys.Rev.Lett. **81** (1998) 1562, hep-ex/9807003.

[2] Y. Suzuki, talk at the "XIX International Symposium on Lepton and Photon Interactions at High Energies", Stanford University, August 9-14, 1999.

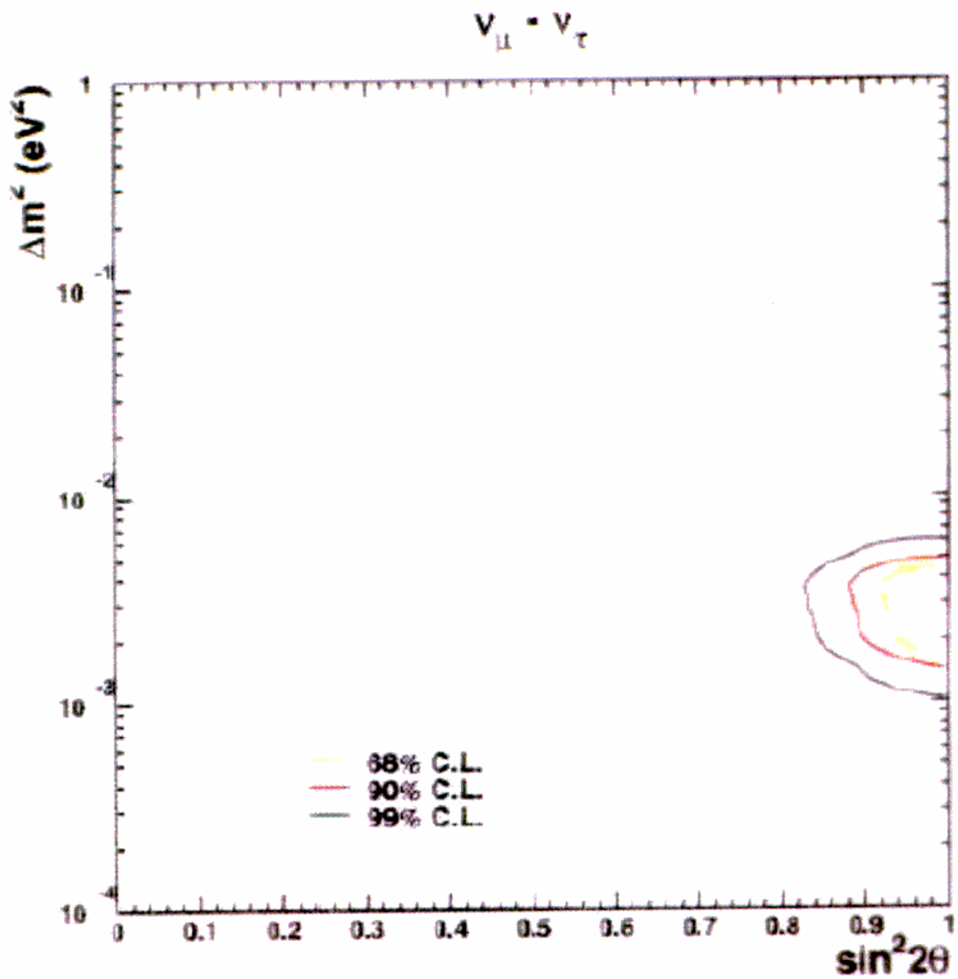
[3] For a recent fit, see M.C. Gonzalez-Garcia et al., hep-ph/9906469.

[4] For papers after the Superkamiokande result, see, for instance, C.H. Albright, S.M. Barr, Phys.Lett. **B461** (1999) 218, hep-ph/9906297; C.H. Albright, S.M. Barr, Phys.Lett. **B452** (1999) 287, hep-ph/9901318; G. Altarelli, F. Feruglio, Phys.Lett. **B439** (1998) 112, hep-ph/9807353; G. Altarelli, F. Feruglio, JHEP **9811** (1998) 021, hep-ph/9809596; G. Altarelli, F. Feruglio, Phys.Lett. **B451** (1999) 388, hep-ph/9812475; A. Aranda, C. Carone, R.F. Lebed, hep-ph/9910392; K.S. Babu, J.C. Pati, F. Wilczek, hep-ph/9812538; R. Barbieri, L.J. Hall and A. Strumia, Phys.Lett. **B445** (1999) 407, hep-ph/9808333; R. Barbieri, P. Creminelli, A. Romanino, hep-ph/9903460; T. Blazek, S. Raby, K. Tobe, Phys.Rev. **D60** (1999) 113001, hep-ph/9903340; K. Choi, E.J. Chun, K. Hwang, Phys.Rev. **D60** (1999) 031301, hep-ph/9811363; R. Dermisek, S. Raby, hep-ph/9911275; J. Ellis, G.K. Leontaris, S. Lola, D.V. Nanopoulos, Eur.Phys.J. **C9** (1999) 389, hep-ph/9808251; J.K. Elwood, N. Irges, P. Ramond, Phys.Rev.Lett. **81** (1998) 5064, hep-ph/9807228; P.H. Frampton, A. Rasin, hep-ph/9910522; P.H. Frampton, S.L. Glashow, Phys.Lett. **B461** (1999) 95, hep-ph/9906375; H. Fritzsch, Z.Z. Xing, Phys.Lett. **B440** (1998) 313, hep-ph/9808272; C.D. Froggatt, M. Gibson, H.B. Nielsen, Phys.Lett. **B446** (1999) 256, hep-ph/9811265; M. Fukugita, M. Tanimoto, T. Yanagida, Phys.Rev. **D59** (1999) 113016, hep-ph/9809554; H. Georgi, S.L. Glashow, hep-ph/9808293; M.E. Gomez, G.K. Leontaris, S. Lola and J.D. Vergados, Phys.Rev. **D59** (1999) 116009, hep-ph/9810291; L.J. Hall, N. Weiner, Phys.Rev. **D60** (1999) 033005, hep-ph/9811299; L.J. Hall, D. Smith, Phys.Rev. **D59** (1999) 113013, hep-ph/9812308; N. Irges, S. Lavignac, P. Ramond, Phys.Rev. **D58** (1998) 035003, hep-ph/9802334; A.S. Joshipura, Phys.Rev. **D59** (1999) 077301, hep-ph/9808261; A.S. Joshipura, S.D. Rindani, hep-ph/9811252; S. King, Phys.Lett. **B439** (1998) 350, hep-ph/9806440; S.K. Kang, C.S. Kim, Phys.Rev. **D59** (1999) 091302, hep-ph/9811379; G.K. Leontaris, S. Lola, C. Scheich and J.D. Vergados, Phys.Rev. **D53** 6381(1996); S. Lola, J.D. Vergados, Prog.Part.Nucl.Phys. **40** (1998) 71; S. Lola, G.G. Ross, Nucl.Phys. **B553** (1999) 81, hep-ph/9902283; R.N. Mohapatra, S. Nussinov, Phys.Rev. **D60** (1999) 013002, hep-ph/9809415; N. Nomura, T. Yanagida, Phys.Rev. **D59** (1999) 017303, hep-ph/9807325; T. Yanagida, J. Sato, Nucl.Phys.Proc.Suppl. **77** (1999) 293, hep-ph/9809307; M. Tanimoto, hep-ph/9807517.

[5] M. Apollonio et al., hep-ex/9907037.

[6] M. Gell-Mann, P. Ramond, R. Slansky, in Supergravity, ed. by F. van Nieuwenhuizen and D. Freedman (Amsterdam, North Holland, 1979) 315; T. Yanagida, in Proc. of the workshop on the unified Theory and Baryon Number in the Universe, eds. O. Sawada and A. Sugamoto (KEK, Tsukuba, 1979) 95.

FC,PC,UpMu



Result of Oscillation Analysis (FC + PC + Upmu)

- Assuming $\nu_\mu \leftrightarrow \nu_\tau$ oscillation

Best fit :

χ^2_{min} = 135.3 / 152 d.o.f

at ($\sin^2 2\theta, \Delta m^2$) = (1.01 , 3.2×10^{-3} eV^2)

(Including unphysical region)

χ^2_{min} = 135.4 / 152 d.o.f

at ($\sin^2 2\theta, \Delta m^2$) = (1.00 , 3.2×10^{-3} eV^2)

(Physical region)

- Assuming null oscillation

strikingly maximal mixing

$\Rightarrow$ must be special structures

permutation symmetry S_3

Fukugita, Tanimoto, Yanagida

$$(\bar{L}_1\ \bar{L}_2\ \bar{L}_3)\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}\begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix} H$$

$(S_3)_L \times (S_3)_E \Rightarrow$ democracy

$\Rightarrow$ hierarchy $m_\tau \neq 0$

$m_e, m_\mu \ll m_\tau$

large rotation of L's

$$(L_1\ L_2\ L_3)\begin{pmatrix} & & \\ & & \\ & & \end{pmatrix}\begin{pmatrix} L_1 \\ L_2 \\ L_3 \end{pmatrix} \frac{H^2}{M}$$

two possible matrices

$$\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}, \quad \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}$$

choose only this

$\Rightarrow$ no rotation of neutrinos

big rotation of leptons

$\Rightarrow \sin^2 2\theta_{23} = 1, \ \sin^2 2\theta_{12} = \frac{4}{9}, \ \sin^2\theta_{13} = 0$

maximal mixing

$$m_\nu = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \rightarrow 45°$$

but

$$\rightarrow \begin{pmatrix} -1 & \\ & 1 \end{pmatrix} \qquad \Delta m^2 = 0$$

add $\begin{pmatrix} 1 & \\ & 1 \end{pmatrix}$

$$m_\nu = \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \rightarrow \begin{pmatrix} 0 & \\ & 2 \end{pmatrix}$$

3 generations

$$m_\nu = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \rightarrow \begin{pmatrix} 0 & & \\ & 0 & \\ & & 3 \end{pmatrix}$$

democracy hierarchy

how do we justify it?

Minimal Higgs sector of SO(10)

Albright, Barr

$$\lambda_u = \begin{pmatrix} \eta & 0 & 0 \\ 0 & 0 & \frac{1}{3}\epsilon \\ 0 & -\frac{1}{3}\epsilon & 1 \end{pmatrix}$$

$$\lambda_d = \begin{pmatrix} 0 & \delta & \delta' \\ \delta & 0 & \sigma + \frac{1}{3}\epsilon \\ \delta' & -\frac{1}{3}\epsilon & 1 \end{pmatrix}$$

$\sigma \simeq 1.8$

$\epsilon \simeq 0.14$

$\delta \simeq |\delta'| \simeq 0.008$

$\eta \simeq 6 \times 10^{-6}$

$A \simeq 0.05$

$$\lambda_\nu = \begin{pmatrix} \eta & 0 & 0 \\ 0 & 0 & -\epsilon \\ 0 & \epsilon & 1 \end{pmatrix}$$

$$\lambda_\ell = \begin{pmatrix} 0 & \delta & \delta' \\ \delta & 0 & -\epsilon \\ \delta' & \sigma + \epsilon & 1 \end{pmatrix}$$

$\Rightarrow$ VAC

$\sin^2 2\theta_{13} = 0.00$

$$M = \begin{pmatrix} 0 & A\epsilon^3 & 0 \\ A\epsilon^3 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

VOLUME 85, NUMBER 2 PHYSICAL RE

TABLE II. Matter superfields in the proposed model.

$\mathbf{16}_1(-\frac{1}{2}-2p)^{+-}$	$\mathbf{16}_2(-\frac{1}{2}+p)^{++}$	$\mathbf{16}_3(-\frac{1}{2})^{++}$
$\mathbf{16}(-\frac{1}{2}-p)^{-+}$	$\mathbf{16}'(-\frac{1}{2})^{-+}$	
$\overline{\mathbf{16}}(\frac{1}{2})^{+-}$	$\overline{\mathbf{16}}'(-\frac{3}{2}+2p)^{+-}$	
$\mathbf{10}_1(-1-p)^{-+}$	$\mathbf{10}_2(-1+p)^{++}$	
$\mathbf{1}_1(2+2p)^{+-}$	$\mathbf{1}_2(2-p)^{++}$	$\mathbf{1}_3(2)^{++}$
$\mathbf{1}_1^c(-2-2p)^{+-}$	$\mathbf{1}_2^c(-2)^{+-}$	$\mathbf{1}_3^c(-2-p)^{++}$

In terms of these fermion fields and the Higgs fields previously introduced, one can then spell out all the terms in the Yukawa superpotential which follow from their SO(10) and $U(1)\times Z_2\times Z_2$ assignments:

$$\begin{aligned}
W_{\rm Yukawa} = {} & \mathbf{16}_3\cdot\mathbf{16}_3\cdot T_1+\mathbf{16}_2\cdot\mathbf{16}\cdot T_1 \\
& +\mathbf{16}'\cdot\mathbf{16}'\cdot T_1+\mathbf{16}_3\cdot\mathbf{16}_1\cdot T_0' \\
& +\mathbf{16}_2\cdot\mathbf{16}_1\cdot T_0+\mathbf{16}_3\cdot\overline{\mathbf{16}}\cdot A \\
& +\mathbf{16}_1\cdot\overline{\mathbf{16}}'\cdot Y'+\mathbf{16}\cdot\overline{\mathbf{16}}\cdot P \\
& +\mathbf{16}'\cdot\overline{\mathbf{16}}'\cdot S+\mathbf{16}_3\cdot\mathbf{10}_2\cdot C' \\
& +\mathbf{16}_2\cdot\mathbf{10}_1\cdot C+\mathbf{10}_1\cdot\mathbf{10}_2\cdot Y \\
& +\mathbf{16}_3\cdot\mathbf{1}_3\cdot\overline{C}+\mathbf{16}_2\cdot\mathbf{1}_2\cdot\overline{C} \\
& +\mathbf{16}_1\cdot\mathbf{1}_1\cdot\overline{C}+\mathbf{1}_3\cdot\mathbf{1}_3^c\cdot Z \\
& +\mathbf{1}_2\cdot\mathbf{1}_2^c\cdot P+\mathbf{1}_1\cdot\mathbf{1}_1^c\cdot X \\
& +\mathbf{1}_3^c\cdot\mathbf{1}_3^c\cdot V_M+\mathbf{1}_2^c\cdot\mathbf{1}_2^c\cdot V_M\,, \qquad (2)
\end{aligned}$$

where the coupling parameters have been suppressed. T...

following values are obtained compared with experiment [12] in parentheses:

$$
\begin{aligned}
m_c(m_c) &= 1.23 \text{ GeV}, & (1.27 \pm 0.1 \text{ GeV}), \\
m_b(m_b) &= 4.25 \text{ GeV}, & (4.26 \pm 0.11 \text{ GeV}), \\
m_s(1 \text{ GeV}) &= 148 \text{ MeV}, & (175 \pm 50 \text{ MeV}), \\
m_d(1 \text{ GeV}) &= 7.9 \text{ MeV}, & (8.9 \pm 2.6 \text{ MeV}), \\
|V_{ub}/V_{cb}| &= 0.080, & (0.090 \pm 0.008),
\end{aligned}
\tag{15}
$$

where finite SUSY loop corrections for m_b and m_s have been scaled to give $m_b(m_b) \simeq 4.25$ GeV for $\tan\beta = 5$.

The effective light neutrino mass matrix of Eq. (10) leads to bimaximal mixing with a large angle solution for atmospheric neutrino oscillations [13] and the "just-so" vacuum solution [14] involving two pseudo-Dirac neutrinos, if we set $\Lambda_R = 2.4 \times 10^{14}$ GeV and $A = 0.05$. We then find

$$
\begin{aligned}
& m_3 = 54.3 \text{ MeV}, \quad m_2 = 59.6\ \mu\text{eV}, \quad m_1 = 56.5\ \mu\text{eV}, \\
& U_{e2} = 0.733, \quad U_{e3} = 0.047, \quad U_{\mu 3} = -0.818, \\
& \delta'_{CP} = -0.2^\circ, \\
& \Delta m^2_{23} = 3.0 \times 10^{-3} \text{ eV}^2, \quad \sin^2 2\theta_{\text{atm}} = 0.89, \\
& \Delta m^2_{12} = 3.6 \times 10^{-10} \text{ eV}^2, \quad \sin^2 2\theta_{\text{solar}} = 0.99, \\
& \Delta m^2_{13} = 3.0 \times 10^{-3} \text{ eV}^2, \quad \sin^2 2\theta_{\text{reac}} = 0.009.
\end{aligned}
\tag{16}
$$

The effective scale of the right-handed Majorana mass contribution occurs 2 orders of magnitude lower than the

TABLE I. **Higgs superfields in the proposed model.**

	Higgs fields needed to solve the 2-3 problem:
$\mathbf{45}_{B\text{-}L}$:	$A(0)^{+-}$
16:	$C(\frac{3}{2})^{-+}, C'(\frac{3}{2}-p)^{++}$
$\overline{\mathbf{16}}$:	$\overline{C}(-\frac{3}{2})^{++}, \overline{C}'(-\frac{3}{2}-p)^{-+}$
10:	$T_1(1)^{++}, T_2(-1)^{+-}$
1:	$X(0)^{++}, P(p)^{+-}, Z_1(p)^{++}, Z_2(p)^{++}$
	Additional Higgs fields for the mass matrices:
10:	$T_0(1+p)^{+-}, T_0'(1+2p)^{+-}$, $\overline{T}_0(-3+p)^{-+}, \overline{T}_0'(-1-3p)^{-+}$
1:	$Y(2)^{-+}, Y'(2)^{++}, S(2-2p)^{--}, S'(2-3p)^{--}$, $V_M(4+2p)^{++}$

0031-9007/00/85(2)/244(4)$15.00

$$
\begin{aligned}
W_{\rm Higgs} &= W_A + W_{CA} + W_{2/3} + W_{H_D} + W_R\,,\\
W_A &= trA^4/M + M_A trA^2,\\
W_{CA} &= X(\overline{C}C)^2/M_C^2 + F(X) + \overline{C}'(PA/M_1 + Z_1)C\\
&\quad + \overline{C}(PA/M_2 + Z_2)C',\\
W_{2/3} &= T_1AT_2 + Y'T_2^2\,,\\
W_{H_D} &= T_1\overline{C}\,\overline{C}Y'/M + \overline{T}_0CC' + \overline{T}_0(T_0S + T_0'S')\,,\\
W_R &= \overline{T}_0\overline{T}_0'V_M\,.
\end{aligned}
\tag{1}
$$

Do we really need such a rigid structure

do nothing ⇒ "anarchy"   Hall, HM, Weiner

if there is no particular structure in a mass matrix

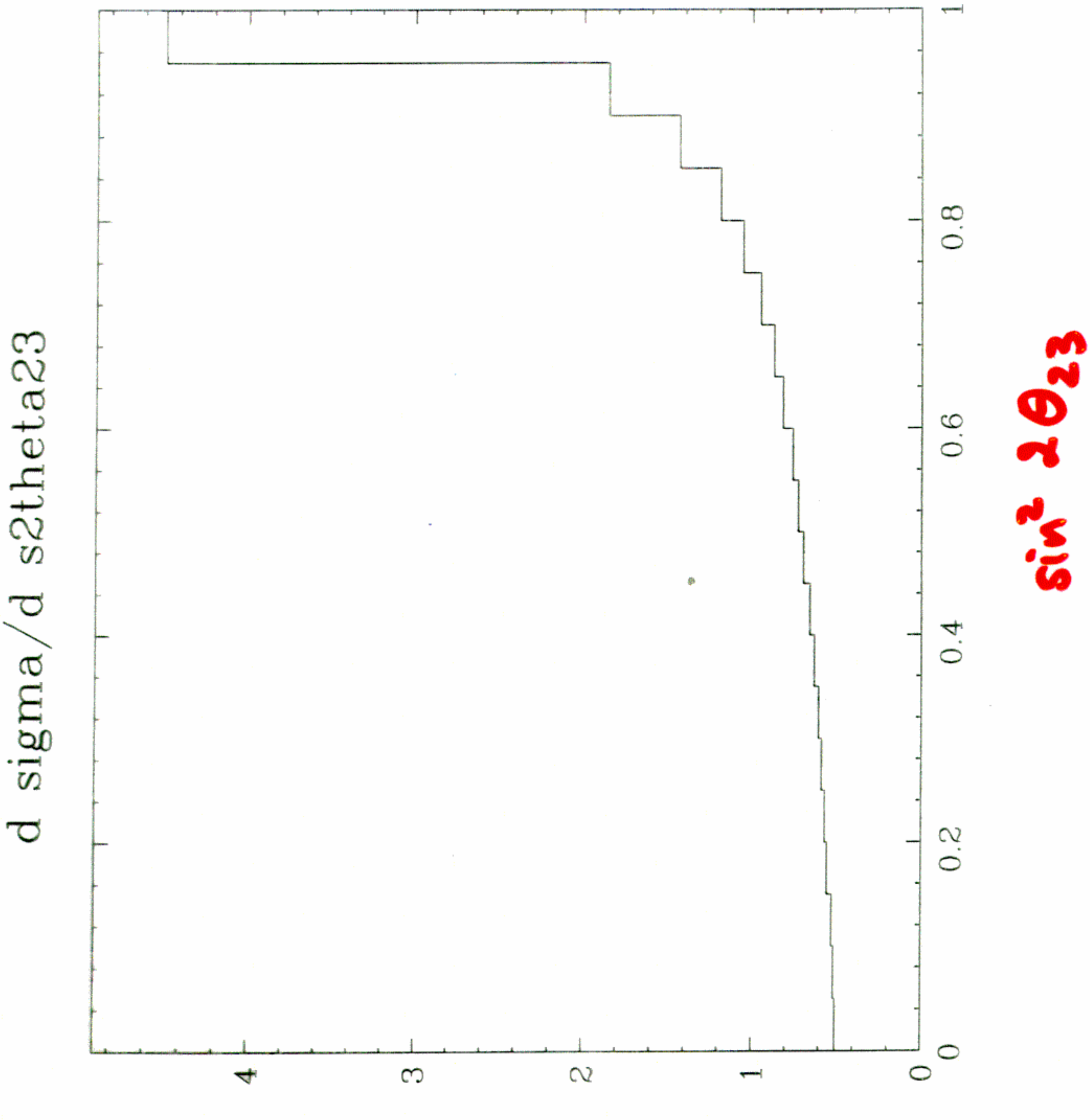
each element would appear random

throw dice

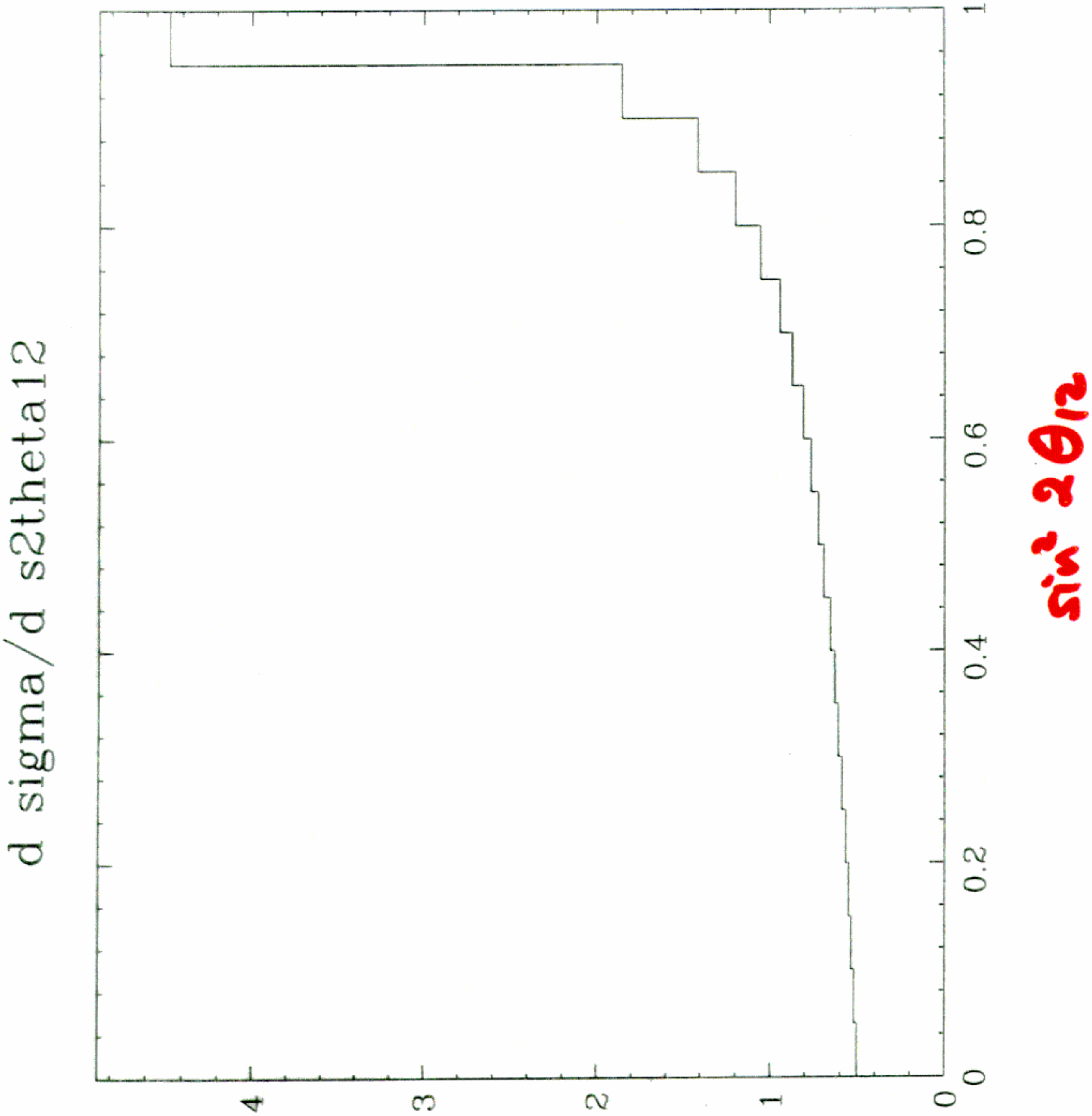
⇒ see if near-maximal mixing is really so special

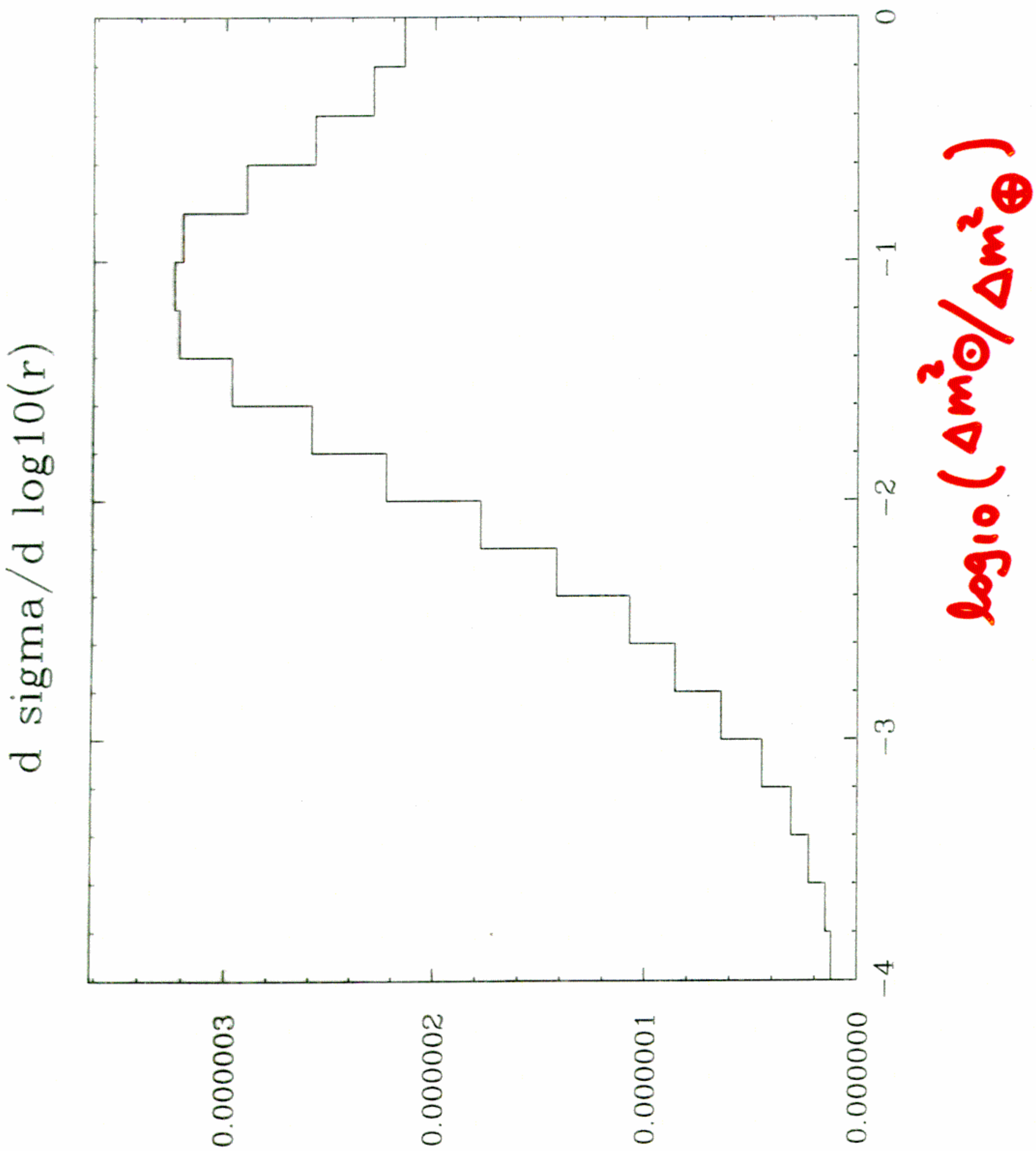
$$M_\nu = \left(m_D \right) \left(M \right)^{-1} \left(m_D \right)^T$$

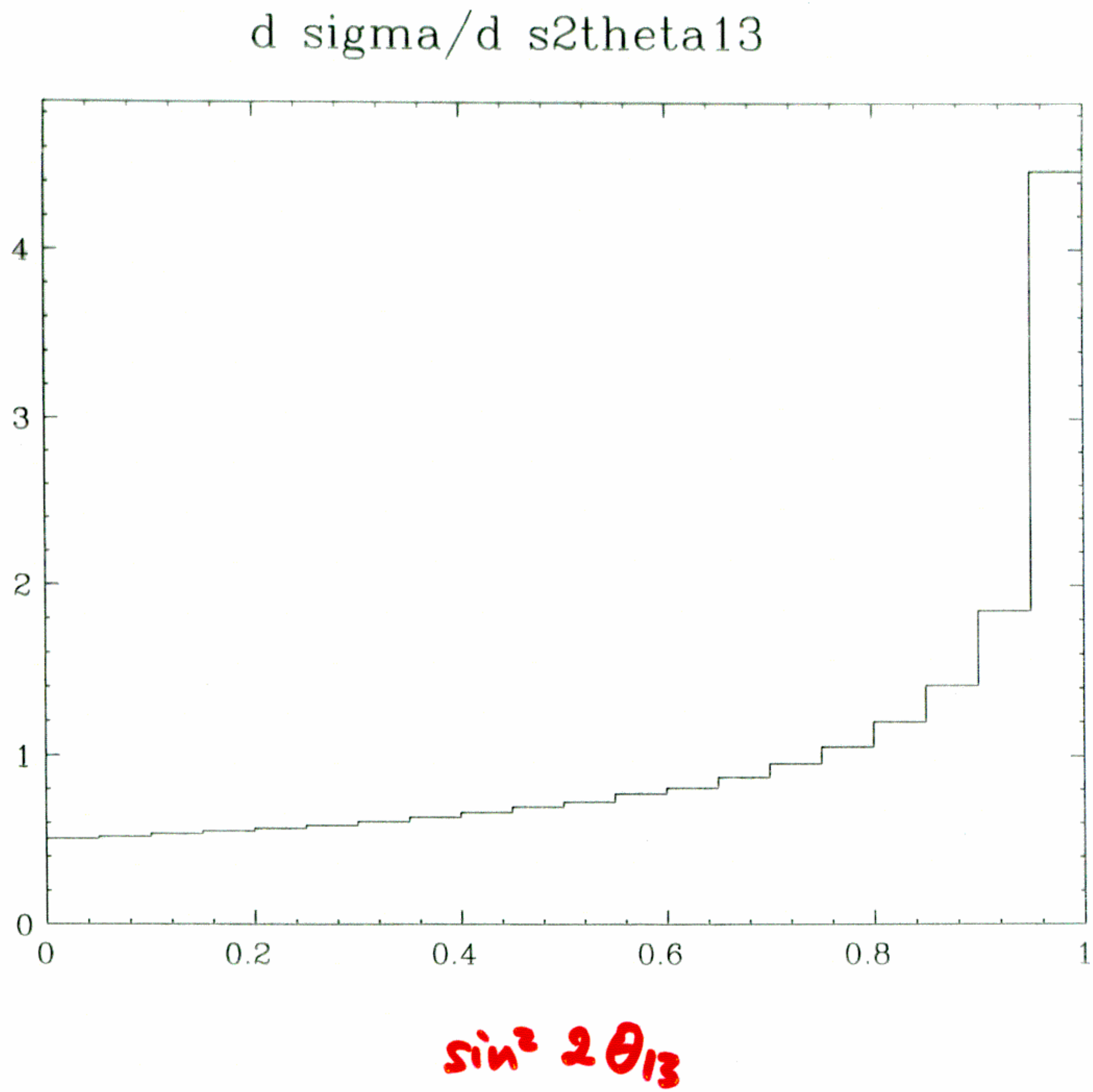
m_D, M random 3×3


d sigma/d s2theta23
0
1
2
3
4
0
0.2
0.4
0.6
0.8
1
sin² 2θ₂₃

H. Murayama, SSI 2000




d sigma/d log10(r)
0.0000003
0.0000002
0.0000001
0.0000000
−4
−3
−2
−1
0
$\log_{10}(\Delta m^2_\odot/\Delta m^2_\oplus)$


d sigma/d s2theta13
0
1
2
3
4
0
0.2
0.4
0.6
0.8
1
$\sin^2 2\theta_{13}$

do nothing

$\Rightarrow$ all angles tend to be near maximal

$\Rightarrow$ $\Delta m^2_\odot / \Delta m^2_\oplus \sim \frac{1}{20}$

perfect for LMA

price:

only 10% chance to satify CHOOZ limit $\sin^2 2\theta_{13} \lesssim 0.2$

does not appear particularly damaging

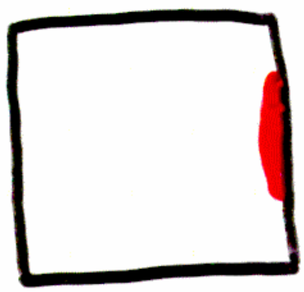
we don't seem to need any particular (i.e. artificial, engineered) structure in ν mass + mixing distributions in angles:

consequence of basis independence

$\Rightarrow$ group Haar measure

flat in $\sin^2\theta_{12}$, $\sin^2\theta_{23}$, $\cos^4\theta_{13}$

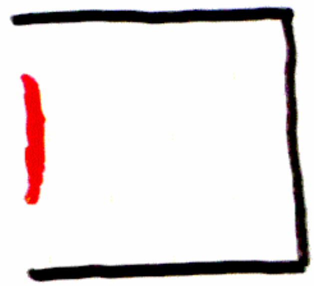
Haba, HM



$\sin^2 2\theta_{23}$

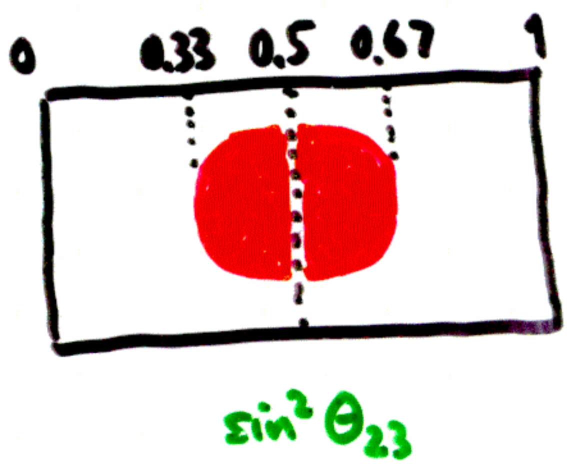
$\sin^2 2\theta_{23} > 0.88$
(90% CL)

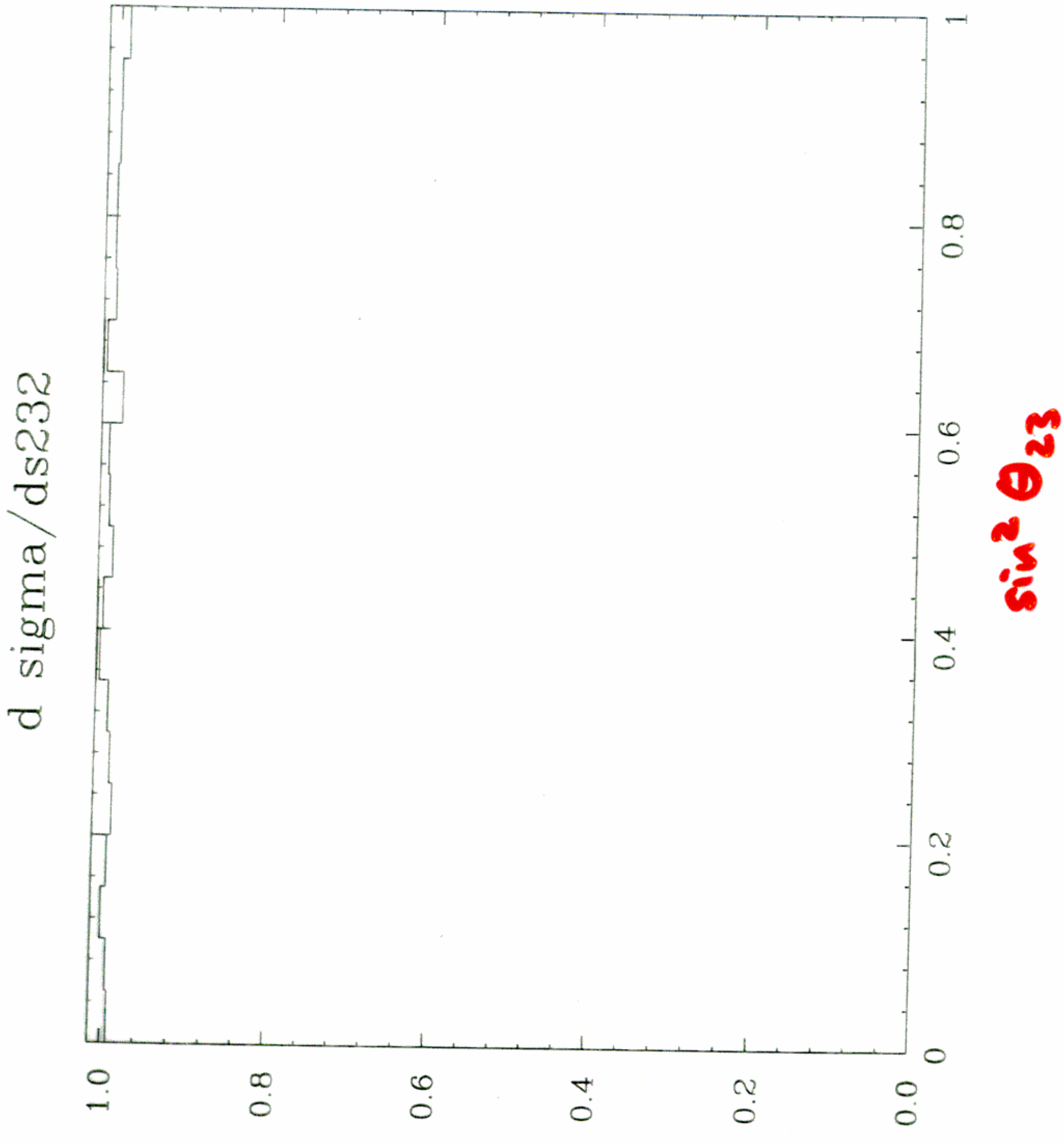
special, large
at the boundary of physical region

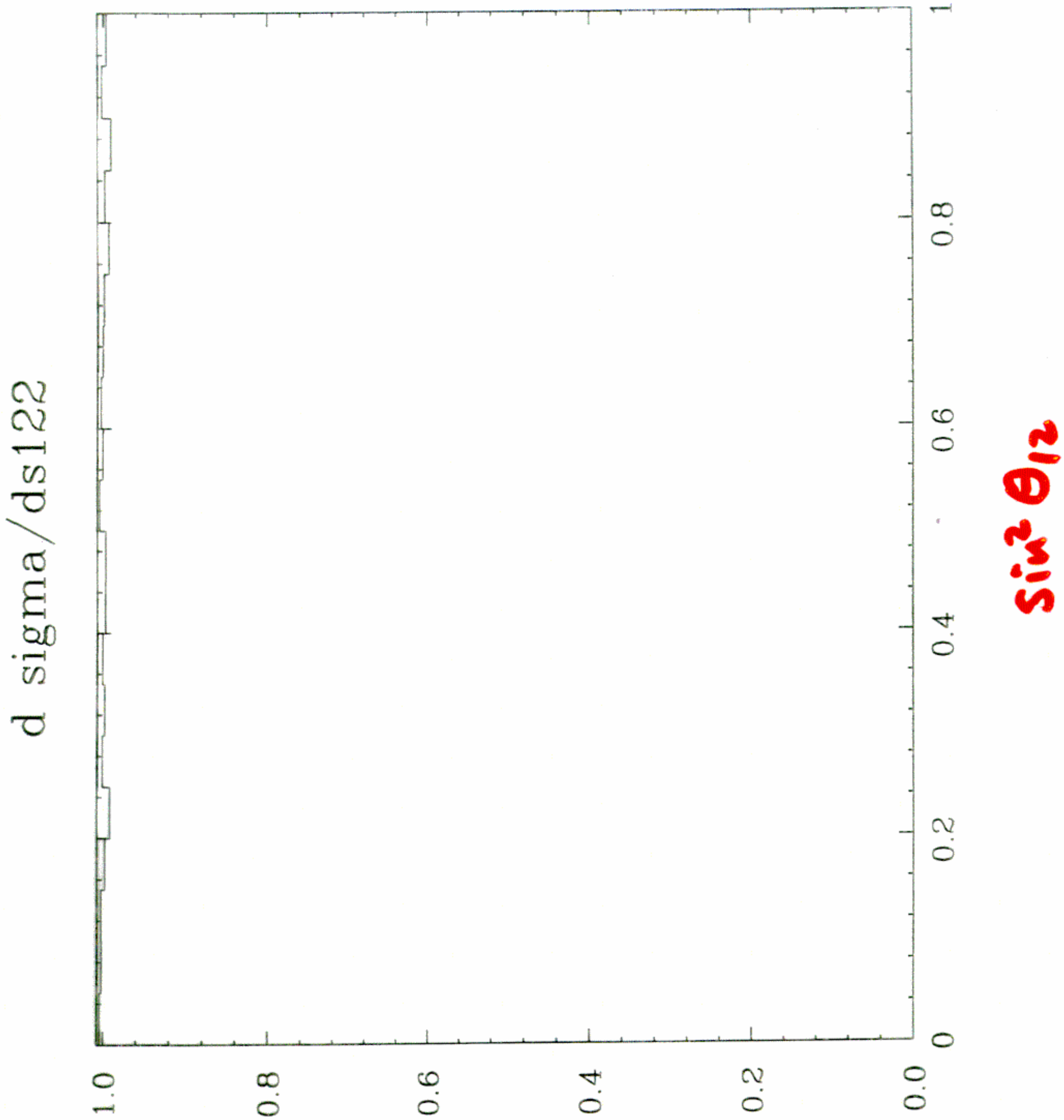


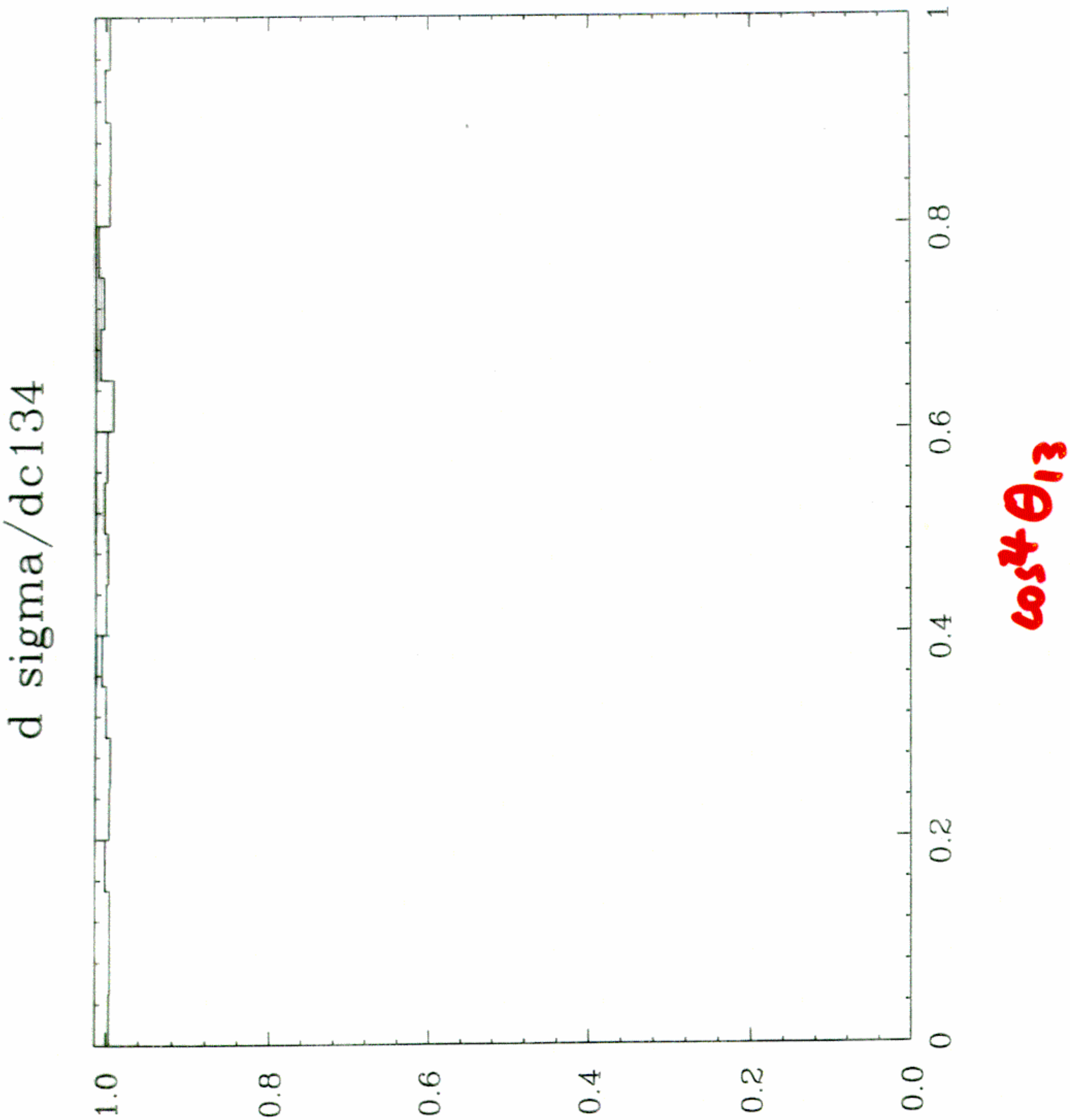
center

moderate




d sigma/ds232
0.0
0.2
0.4
0.6
0.8
1.0
0
0.2
0.4
0.6
0.8
1
$\sin^2\theta_{23}$


d sigma/ds122
1.0
0.8
0.6
0.4
0.2
0.0
0
0.2
0.4
0.6
0.8
1
$\sin^2\theta_{12}$


d sigma/dc134
1.0
0.8
0.6
0.4
0.2
0.0
0
0.2
0.4
0.6
0.8
1
cos θ13

§ signature of anarchy

- LMA

  $\Rightarrow$ testable by KamLAND

- U_{e3}

  probably not too small

  $\Rightarrow$ MINOS, ICANOE

  $\nu_\mu \to \nu_e$

  $\Delta m^2 = \Delta m^2_{atm} + \Delta m^2_\odot$

  $\simeq \Delta m^2_{atm}$

- $0\nu\beta\beta$

  set the scale s.t. $\Delta m^2_{atm} = 3 \times 10^{-3}$ eV²

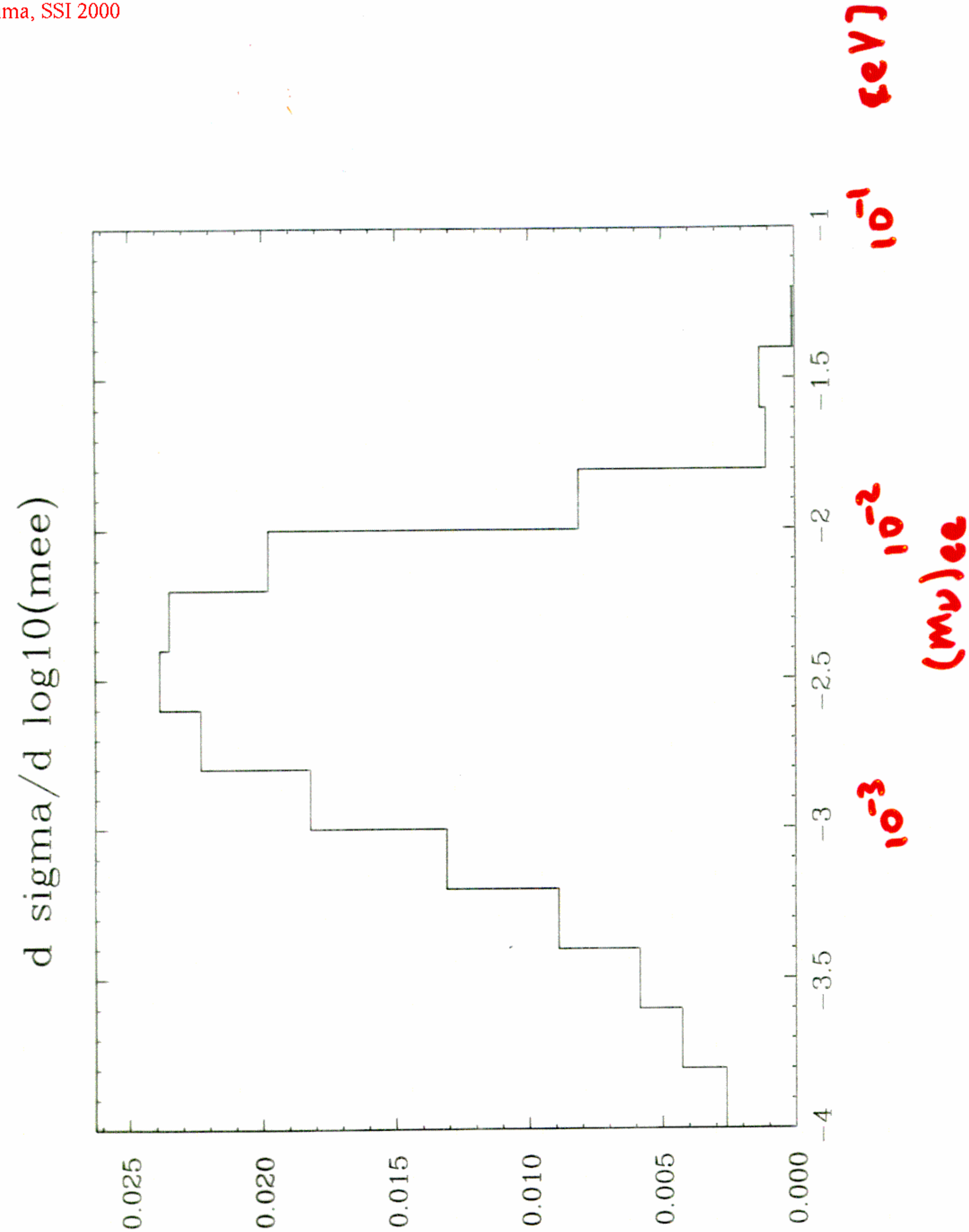
  (superK best fit FC

  $\Rightarrow (m_M)_{ee}$

  usually considered sizable only for degenerate neutrinos

  practically zero for SMA, LOW, VAC

- CP̸ in ν oscillation


d sigma/d log10(mee)
0.025
0.020
0.015
0.010
0.005
0.000
−4
−3.5
−3
−2.5
−2
−1.5
−1
10^{-3}
10^{-2}
10^{-1}
[eV]
$(m_\nu)_{ee}$

FUTURE

IS BRIGHT