Family symmetries.

G.G.Ross, Ringberg Castle, April 2009

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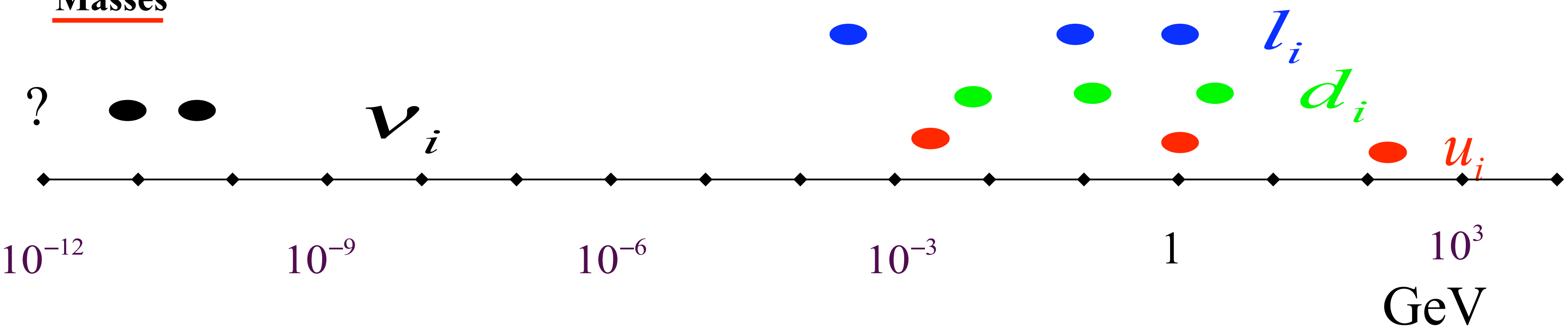
- $q \leftrightarrow l$ — Neutrino v/s quark masses and mixing?
  See-saw with sequential domination
- Symmetry — GUT
  Family — Abelian, Non-Abelian, Discrete, String?
- Tri-bi-maximal mixing — Non-Abelian discrete symmetry

DATA :

Masses



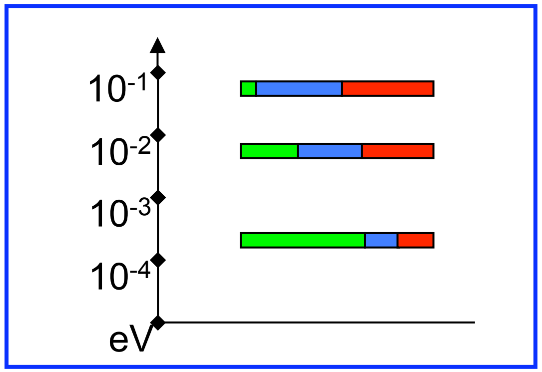
Mixing

Quarks

Leptons

$$V_{CKM} \approx \begin{pmatrix} 1 & 0.218-0.224 & 0.002-0.005 \\ 0.218-0.224 & 1 & 0.032-0.048 \\ 0.004-0.015 & 0.03-0.048 & 1 \end{pmatrix}$$

$$V_{MNS} = \begin{pmatrix} 0.79-0.88 & 0.48-0.61 & <0.2 \\ 0.27-0.49 & 0.45-0.71 & 0.52-0.82 \\ 0.28-0.5 & 0.51-0.65 & 0.57-0.81 \end{pmatrix}$$



$$\approx \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & \sim 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Bi-Tri Maximal Mixing …

Discrete Non Abelian Structure?

DATA :

$$L_{Yukawa} = Y^u_{ij}\, Q^i u^{c,j} H + Y^d_{ij}\, Q^i d^{c,j}\, \overline{H}$$

$$M^u_{ij} = Y^u_{ij} < H^0 > \qquad M^d_{ij} = Y^d_{ij} < \overline{H}^0 >$$

$$M^u = V_L^\dagger\, \underline{M^u_{Diag}}\, V_R$$

$$M^d = U_L^\dagger\, \underline{M^d_{Diag}}\, U_R$$

$$\underline{V_{CKM}} = V_L^\dagger U_L$$

The data for quarks is *consistent* with a very symmetric structure :

$$\frac{M^{d,u}}{m^{b,t}} \simeq \begin{pmatrix} < \varepsilon^4 & \varepsilon^3 & \varepsilon^3 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon^3 & \varepsilon^2 & 1 \end{pmatrix} \qquad \varepsilon^{d} = 0.15 \qquad \varepsilon^{u} = 0.05$$

O(1) coefficients suppressed

$q \leftrightarrow l$ symmetry?

Charged leptons are consistent with a similar form

$$\frac{M^{d,l,u}}{m^{b,\tau,t}} \simeq \begin{pmatrix} <\varepsilon^4 & \varepsilon^3 & \varepsilon^3 \\ \varepsilon^3 & a\varepsilon^2 & a\varepsilon^2 \\ \varepsilon^3 & a\varepsilon^2 & 1 \end{pmatrix}$$

$$\varepsilon^{d} = 0.15, \quad a^{d} = 1$$
$$\varepsilon^{l} = 0.15, \quad a^{l} = -3$$
$$\varepsilon^{u} = 0.05, \quad a^{u} = 1$$

Symmetry 1.

GUT relations

$$e.g. \quad SU(4) \subset SO(10)$$

$$\psi_\alpha = \begin{pmatrix} d \\ d \\ d \\ l \end{pmatrix}$$

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GUT relations

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$$\psi_\alpha = \begin{pmatrix} d \\ d \\ d \\ l \end{pmatrix}$$

$$Det(M^l) = Det(M^d)|_{M_X}$$

$$\overline{\psi}^\alpha \psi_\alpha$$

$$\frac{m_b}{m_\tau}(M_X) = 1$$

$$\frac{M^{d,l}}{m_3} = \begin{pmatrix} <\varepsilon^4 & \varepsilon^3 & \varepsilon^3 \\ \varepsilon^3 & a\varepsilon^2 & a\varepsilon^2 \\ \varepsilon^3 & a\varepsilon^2 & 1 \end{pmatrix}$$

$$\varepsilon^d = 0.15, \quad a^d = 1$$

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Symmetry 1.

GUT relations

$e.g.\quad SU(4) \subset SO(10)$

$$\psi_\alpha = \begin{pmatrix} d \\ d \\ d \\ l \end{pmatrix}$$

$$\langle \Sigma_{45} \rangle = \overline{\psi}^{\alpha} \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & -3 \end{pmatrix} \psi_\alpha$$

$$\frac{m_s}{m_\mu}(M_X) = \frac{1}{3}$$

Georgi Jarlskog

$$\frac{M^{d,l}}{m_3} = \begin{pmatrix} < \varepsilon^4 & \varepsilon^3 & \varepsilon^3 \\ \varepsilon^3 & a\varepsilon^2 & a\varepsilon^2 \\ \varepsilon^3 & a\varepsilon^2 & 1 \end{pmatrix}$$

$$\varepsilon^{d} = 0.15, \quad a^{d} = 1$$

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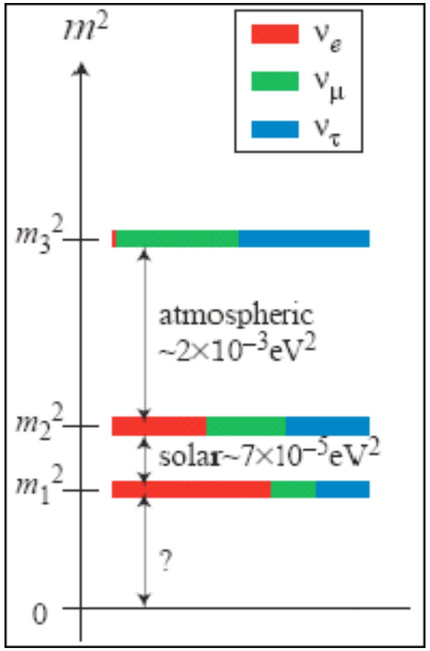
Neutrinos ???

$$L^{\nu}_{eff} = m_3\, \bar{\phi}^{i}_{23}\nu_i \bar{\phi}^{j}_{23}\nu_j + m_2\, \bar{\phi}^{i}_{123}\nu_i \bar{\phi}^{j}_{123}\nu_j$$

$$<\bar{\phi}_{23}>^i = (0,-1,1), \quad <\bar{\phi}_{123}>^i = (1,1,1)$$



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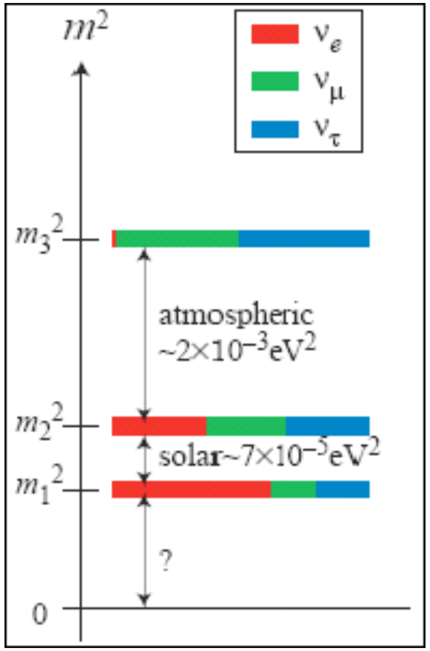

Can one have a unified description of quark, charged lepton and neutrinos?

$$c.f.\ \ L^{q,l}_{Dirac} = m_3\, \bar{\phi}^{i}_{3}\psi_i \bar{\phi}^{j}_{3}\psi^{c}_{j} + \ldots \qquad <\bar{\phi}_{3}>^{i} = (0,0,1) \quad ???$$

Neutrinos ???

$$L^{\nu}_{eff} = m_3\, \bar{\phi}^i_{23} \nu_i \bar{\phi}^j_{23} \nu_j + m_2\, \bar{\phi}^i_{123} \nu_i \bar{\phi}^j_{123} \nu_j$$

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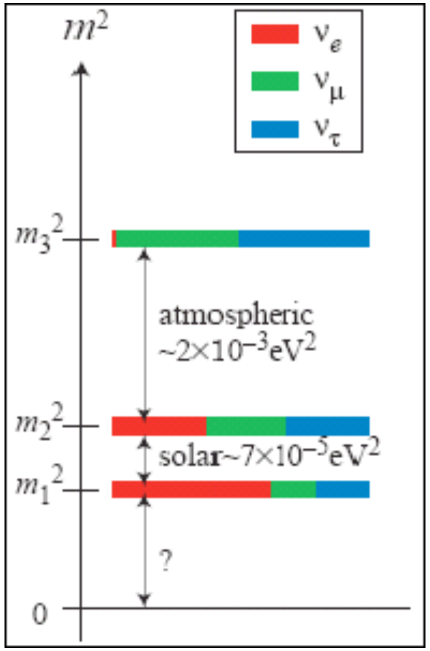


See-Saw

Quarks, charged leptons, neutrinos can have similar Dirac mass :

$$L^{q,l,\nu}_{Dirac} = \alpha\, \psi_i \bar{\phi}^i_3 \psi^c_j \bar{\phi}^j_3 + \beta \left(\psi_i \bar{\phi}^i_{123} \psi^c_j \bar{\phi}^j_{23} + \psi_i \bar{\phi}^i_{23} \psi^c_j \bar{\phi}^j_{123} \right) + \gamma\, \psi_i \bar{\phi}^i_{23} \psi^c_j \bar{\phi}^j_{23} \Sigma_{45} \qquad \alpha > \beta$$

$$\frac{M^{Dirac}}{m_3} = \begin{pmatrix} <\varepsilon^4 & \varepsilon^3+\varepsilon^4 & -\varepsilon^3+\varepsilon^4 \\ \varepsilon^3+\varepsilon^4 & a\varepsilon^2+\varepsilon^3 & -a\varepsilon^2+\varepsilon^3 \\ -\varepsilon^3+\varepsilon^4 & -a\varepsilon^2+\varepsilon^3 & 1 \end{pmatrix}$$

$\varepsilon^d = 0.15, \quad a^d = 1$

$\varepsilon^l = 0.15, \quad a^e = -3$

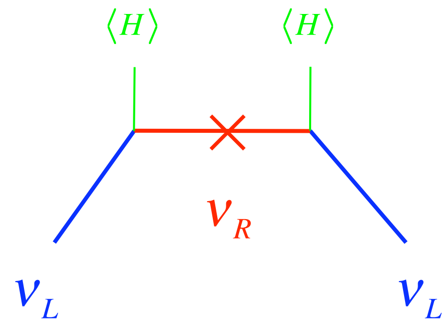
$\varepsilon^u = 0.05, \quad a^u = 1$

$\varepsilon^\nu = 0.05, \quad a^\nu = 0$

- "See-saw" with sequential domination $M_\nu = M_D^\nu \, M_M^{-1} \, M_D^{\nu T}$

Minkowski
Gell-Mann,
Ramond,
Slansky;
Yanagida,
King

$$M_M \approx \begin{pmatrix} M_1 & & \\ & M_2 & \\ & & M_3 \end{pmatrix} \qquad M_1 < M_2 << M_3$$



$$L_{Dirac}^\nu = \alpha \, \psi_i \bar{\phi}_3^i \psi_j^c \bar{\phi}_3^j + \beta \left(\psi_i \bar{\phi}_{123}^i \psi^c{}_j \bar{\phi}_{23}^j + \psi_i \bar{\phi}_{23}^i \psi^c{}_j \bar{\phi}_{123}^j \right) \qquad \alpha > \beta$$

$$L_{eff}^\nu = \frac{\beta^2}{M_1} \psi_i \phi_{123}^i \psi_j \phi_{123}^j + \frac{\beta^2}{M_2} \psi_i \phi_{23}^i \psi_j \phi_{23}^j + \frac{(\alpha+\beta)^2}{M_3} \psi_i \phi_3^i \psi_j \phi_3^j$$

- "See-saw" with sequential domination $M_\nu = M_D^\nu M_M^{-1} M_D^{\nu T}$

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$$M_M \approx \begin{pmatrix} M_1 & & \\ & M_2 & \\ & & M_3 \end{pmatrix} \qquad M_1 << M_2 << M_3$$

small

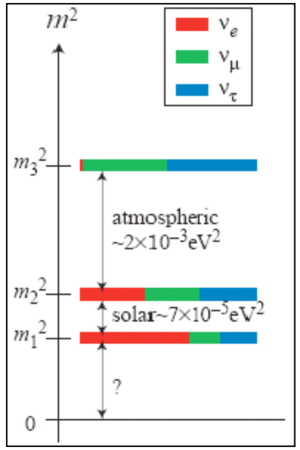
$$L_{Dirac}^\nu = \alpha\, \psi_i \bar{\phi}_3^i \psi_j^c \bar{\phi}_3^j + \beta \left(\psi_i \bar{\phi}_{123}^i \psi^c{}_j \bar{\phi}_{23}^j + \psi_i \bar{\phi}_{23}^i \psi^c{}_j \bar{\phi}_{123}^j \right) \quad \alpha > \beta$$

$$L_{eff}^\nu = \frac{\beta^2}{M_1} \psi_i \phi_{123}^i \psi_j \phi_{123}^j + \frac{\beta^2}{M_2} \psi_i \phi_{23}^i \psi_j \phi_{23}^j + \frac{(\alpha+\beta)^2}{M_3} \psi_i \phi_3^i \psi_j \phi_3^j$$

Symmetry 2. Family symmetry

Non-Abelian family symmetry

Promote ϕ_i to fields transforming under $SU(3)_{family}$

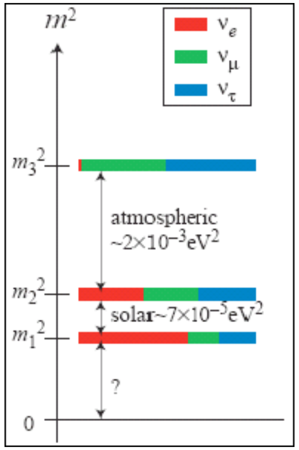


$$\frac{\phi_3}{M} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \qquad \frac{\phi_{23}}{M} = \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix} \varepsilon \qquad \frac{\phi_{123}}{M} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \varepsilon^2$$

Messenger mass

Symmetry 2.

Family symmetry



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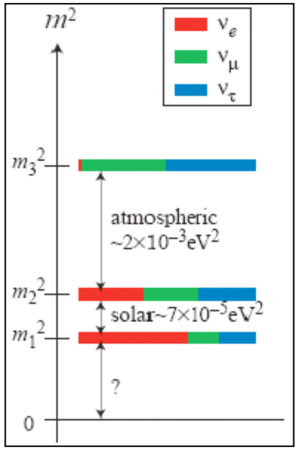
Vacuum alignment ???

Symmetry 2.

Family symmetry



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Vacuum alignment ??? $\Rightarrow$ Discrete non Abelian symmetry

List of models with discrete flavour symmetry

(incomplete, by symmetry)

S_3: Pakvasa et al.(1978), Derman(1979), Ma(2000), Kubo et al.(2003), Chen et al.(2004), Grimus et al.(2005), Dermisek et al (2005), Mohapatra et al.(2006), Morisi(2006), Caravaglios et al.(2006), Haba et al(2006),…Mondragon

S_4: Pakvasa et al.(1979), Derman(1979), Lee et al.(1994), Mohapatra et al.(2004),Ma(2006), Hagedorn et al.(2006), Caravaglios et al.(2006), Lampe(2007), Sawanaka(2007), …

A_4: Wyler(1979), Ma et al.(2001), Babu et al.(2003), Altarelli et al.(2005-8), He et al.(2006), Bazzocchi, Morisi, et al.(2007/8), King et al.(2007),…Luca

D_4: Seidl(2003), Grimus et al.(2003/4), Kobayashi et al.(2005), …

D_5: Ma(2004), Hagedorn et al.(2006), …

D_n: Chen et al.(2005), Kajiyama et al.(2006), Frampton et al.(1995/6,2000), Frigerio et al (2005), Babu et al.(2005), Kubo(2005),...

T': Frampton et al.(1994,2007), Aranda et al.(1999,2000),Feruglio et al.(2007), Chen et al.(2007), …

Δ_n: Kaplan et al.(1994), Schmaltz(1994), Chou et al.(1997), de Madeiros Varzielas et al(2006/7).

T_7: Luhn et al.(2007).

Adapted from Lindner, Manchester

Non Abelian discrete symmetries

$e.g.\quad Z_3 \ltimes Z_n$

ϕ_i	$Z_3\phi_i$	$Z_n^{'}\phi_i$
ϕ_1	$\to \phi_2$	$\to \alpha\,\phi_1$
ϕ_2	$\to \phi_3$	$\to \alpha^2\phi_2$
ϕ_3	$\to \phi_1$	$\to \alpha^{-3}\phi_3$

$\alpha^n = 1$

$\Delta\left(3n^2\right)$

$$n = 2, \quad \Delta\left(12\right) \equiv A_4$$

$$n = 3, \quad \Delta\left(27\right)$$

Non Abelian discrete symmetries

$e.g.$ $Z_3 \ltimes Z_n$

ϕ_i	$Z_3\phi_i$	$Z'_n\phi_i$
ϕ_1	$\to \phi_2$	$\to \alpha\,\phi_1$
ϕ_2	$\to \phi_3$	$\to \alpha^2\phi_2$
ϕ_3	$\to \phi_1$	$\to \alpha^{-3}\phi_3$

$\alpha^n = 1$

Choice of discrete symmetry

- Vacuum structure : $Z_3 \ltimes Z_n \to \begin{cases} Z_3, & \langle\phi\rangle = (1,1,1) \quad \lambda > 0 \\ Z_n, & \langle\phi\rangle = (0,0,1) \quad \lambda < 0 \end{cases}$

$$V(\phi) = -m^2\,\phi^{\dagger i}\phi_i + \ldots + \lambda\, m^2\phi^{\dagger i}\phi_i\phi^{\dagger i}\phi_i$$

Non Abelian discrete symmetries

$e.g.$ $Z_3 \ltimes Z_n$

ϕ_i	$Z_3\phi_i$	$Z_n^{'}\phi_i$
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- Quasi-degenerate neutrinos $D \subset SO(3)$ $e.g.\, A_4$ $m\psi^i\psi^i + ..$

GGR, Serna, Varzielas

Non Abelian discrete symmetries

e.g. $Z_3 \ltimes Z_n$

ϕ_i	$Z_3\phi_i$	$Z_n'\phi_i$
ϕ_1	$\rightarrow \phi_2$	$\rightarrow \alpha\,\phi_1$
ϕ_2	$\rightarrow \phi_3$	$\rightarrow \alpha^2\phi_2$
ϕ_3	$\rightarrow \phi_1$	$\rightarrow \alpha^{-3}\phi_3$

$\alpha^n = 1$

Choice of discrete symmetry

- Vacuum structure : $Z_3 \ltimes Z_n \rightarrow \begin{cases} Z_3, & \langle\phi\rangle = (1,1,1) \\ Z_n, & \langle\phi\rangle = (0,0,1) \end{cases}$
- Quasi-degenerate neutrinos $D \subset SO(3)$ $e.g.\, A_4$ $m\psi^i\psi^i + ..$
- GUT : $A_4 \times SU(5),\quad S_3 \times E_6, \ldots$ $q \leftrightarrow l$ ✗ Altarelli et al, Caravaglios et al

  $\Delta(27) \times SO(10)$ ✔ GGR, Varzielas

A complete model

$$\Delta(27)\otimes SO(10)\otimes G \qquad (G=R\otimes U(1))$$

Varzielas, GGR

- $\psi_i^c,\psi_i \subset (16,3) \Rightarrow$ No mass while SU(3) unbroken

- Spontaneous symmetry breaking

c.f. Georgi-Jarskog

$$\bar{\phi}_3^i, \quad \bar{\phi}_{23}^i, \quad \bar{\phi}_{123}^i, \quad H_{45}$$

$$(1,\bar{3}) \quad (1,\bar{3}) \quad (1,\bar{3}) \quad (45,1)$$

$$\begin{pmatrix}0\\0\\1\end{pmatrix}, \quad \begin{pmatrix}0\\-1\\1\end{pmatrix}\varepsilon M, \quad \begin{pmatrix}1\\1\\1\end{pmatrix}\varepsilon^2 M, \quad M$$

- $$P_Y=\frac{1}{M^2}\bar{\phi}_3^i\psi_i\bar{\phi}_3^j\psi_j^c H+\frac{1}{M^3}\bar{\phi}_{23}^i\psi_i\bar{\phi}_{23}^j\psi_j^c HH_{45}+\frac{1}{M^2}\bar{\phi}_{23}^i\psi_i\bar{\phi}_{123}^j\psi_j^c H+\frac{1}{M^2}\bar{\phi}_{123}^i\psi_i\bar{\phi}_{23}^j\psi_j^c H$$

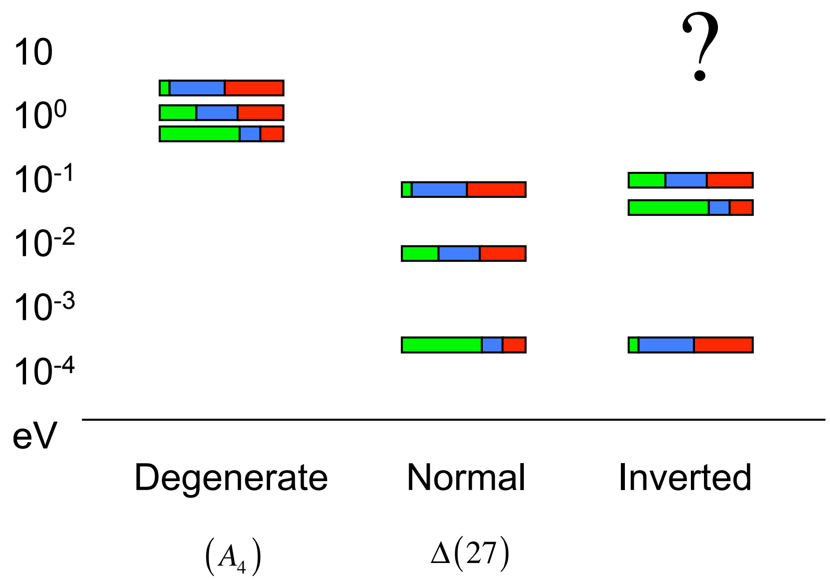
only terms allowed by G

Neutrino Parameters

Neutrino Parameters

- Tri-bi-maximal mixing

  Degenerate and normal spectra favoured



Neutrino Parameters

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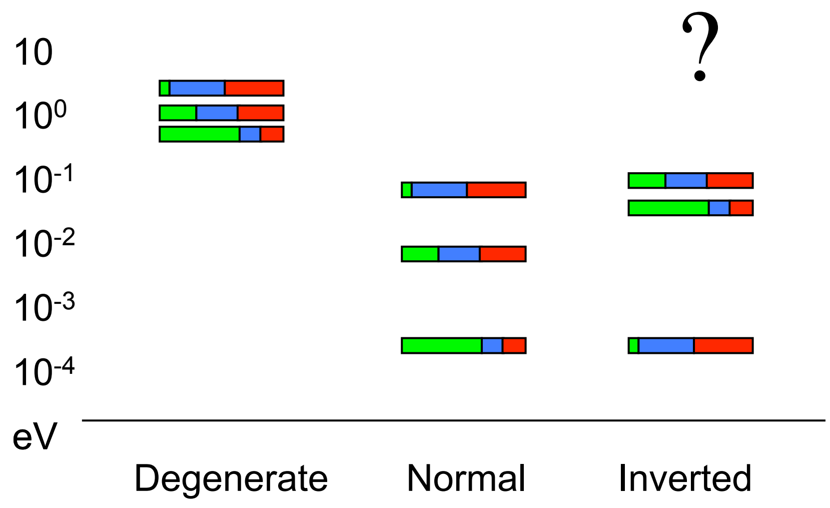

(A_4) $\Delta(27)$

- Mixing angles

$$\sin^2\theta_{12} \approx \frac{1}{3} \pm 0.03$$

$$\sin^2\theta_{23} \approx \frac{1}{2} \pm 0.03$$

$$\sin\theta_{13} \approx \sqrt{\frac{m_e}{2m_\mu}} = 0.053 \pm 0.05 \quad (3 \pm 3^o)$$

From charged lepton mixing

King; GGR, Varzielas

Neutrino Parameters

- Tri-bi-maximal mixing

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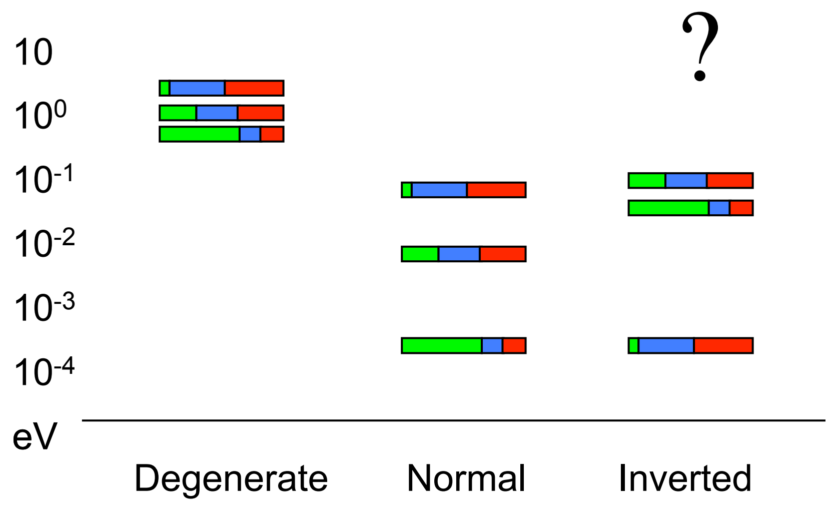


(A_4) $\Delta(27)$

- Mixing angles

$$\sin^2\theta_{12} \approx \frac{1}{3} \pm 0.03 \longrightarrow \theta_{12} + \frac{1}{\sqrt{2}}\frac{\theta_C}{3}\cos(\delta-\pi) \simeq 35.26 \pm 2^o$$

$3\cos(\delta-\pi)$

From charged lepton mixing

Antusch, King

$$\sin^2\theta_{23} \approx \frac{1}{2} \pm 0.03$$

$$\sin\theta_{13} \approx \sqrt{\frac{m_e}{2m_\mu}} = 0.053 \pm 0.05 \quad (3 \pm 3^o)$$

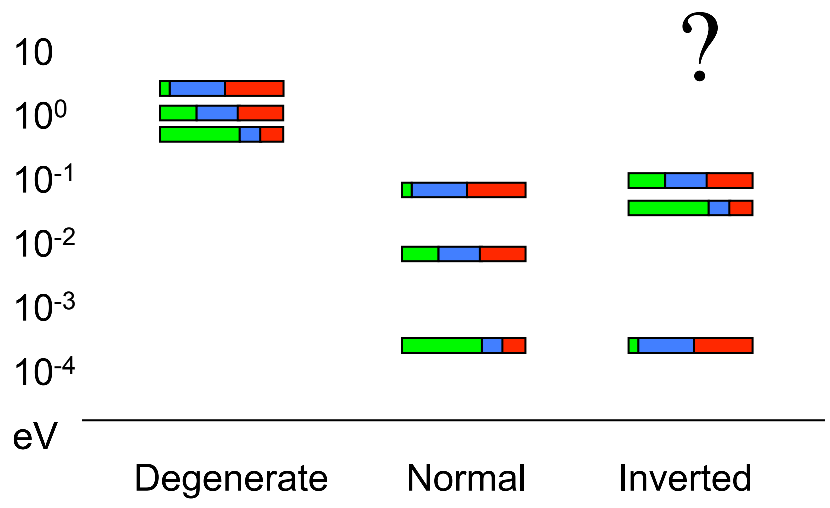
King; GGR, Varzielas

◆

Neutrino Parameters

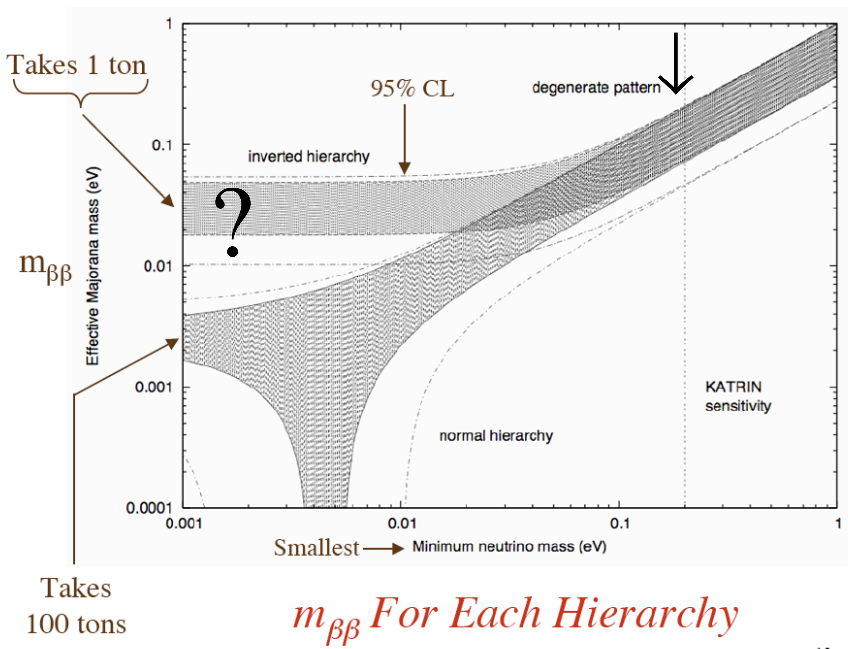
- Tri-bi-maximal mixing

  Degenerate and normal spectra possible

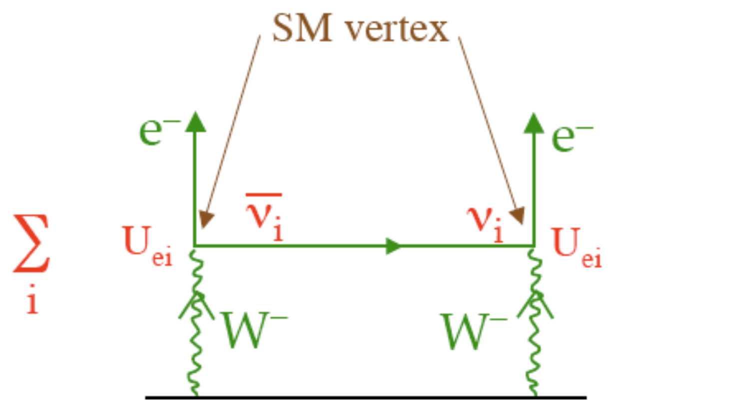


- Neutrinoless double β decay

  (3 light neutrinos) … Ivo's talk



$m_{\beta\beta}$ For Each Hierarchy



Mass (ν_i)

$$\mathrm{Amp}[0\nu\beta\beta] \propto \left|\sum m_i U_{ei}^2\right| \equiv m_{\beta\beta}$$

Sequential see saw and (1,1) texture zero

(1,1) texture zero

$$\frac{M^{Dirac}}{m_3} = \begin{pmatrix} < \varepsilon^4 & \varepsilon^3 + \varepsilon^4 & -\varepsilon^3 + \varepsilon^4 \\ \varepsilon^3 + \varepsilon^4 & a\varepsilon^2 + \varepsilon^3 & -a\varepsilon^2 + \varepsilon^3 \\ -\varepsilon^3 + \varepsilon^4 & -a\varepsilon^2 + \varepsilon^3 & 1 \end{pmatrix}$$

Sequential see saw and (1,1) texture zero

Quark sector zero $\Rightarrow$ $|V_{us}| = \left| \sqrt{\frac{m_d}{m_s}} - e^{i\delta} \sqrt{\frac{m_u}{m_c}} \right|$

(1,1) texture zero

$$\frac{M^{Dirac}}{m_3} = \begin{pmatrix} < \varepsilon^4 & \varepsilon^3 + \varepsilon^4 & -\varepsilon^3 + \varepsilon^4 \\ \varepsilon^3 + \varepsilon^4 & a\varepsilon^2 + \varepsilon^3 & -a\varepsilon^2 + \varepsilon^3 \\ -\varepsilon^3 + \varepsilon^4 & -a\varepsilon^2 + \varepsilon^3 & 1 \end{pmatrix}$$

Sequential see saw and (1,1) texture zero

Lepton sector zero $\Rightarrow \sin^2\theta_{23} \simeq \frac{1}{2}, \quad \sin\theta_{13} \simeq \sqrt{\frac{m_e}{2m_\mu}}$

(1,1) texture zero

$$\frac{M^{Dirac}}{m_3} = \begin{pmatrix} <\varepsilon^4 & \varepsilon^3+\varepsilon^4 & -\varepsilon^3+\varepsilon^4 \\ \varepsilon^3+\varepsilon^4 & a\varepsilon^2+\varepsilon^3 & -a\varepsilon^2+\varepsilon^3 \\ -\varepsilon^3+\varepsilon^4 & -a\varepsilon^2+\varepsilon^3 & 1 \end{pmatrix}$$

SUSY flavour and CP problem : soft SUSY breaking terms

Leading term degenerate

$$(\hat{m}^2_{f,f^c})_{\overline{a}b} = m^2_{3/2}\left[\delta_{\overline{a}b}\left(k_0^{f,f^c} + l_0^{f,f^c}\frac{\langle X^\dagger X\rangle}{M^2_{\rm Pl}} - l_0^{f,f^c}\frac{F_{X^\dagger}F_X}{m^2_{3/2}M^2_{Pl}}\right)\right.$$

$$\left. + \sum_A \frac{\langle\phi^*_A\rangle_{\overline{a}}\langle\phi_A\rangle_b}{M_f^2}\left(k_A^{f,f^c}(1 - x_A x_A^*) - l_A^{f,f^c}\frac{F_{X^\dagger}F_X}{m^2_{3/2}M^2_{Pl}}\right) - k_4^{f,f^c}\delta_{\overline{a}b}\frac{\langle\Sigma^*\rangle\langle\Sigma\rangle}{M^2_\Sigma}x_\Sigma x_\Sigma\right]$$

FCNC

SUSY flavour and CP problem : soft SUSY breaking terms

Leading term degenerate

$$(\hat{m}^2_{f,f^c})_{\overline{a}b} = m^2_{3/2}\left[\delta_{\overline{a}b}\left(k_0^{f,f^c} + l_0^{f,f^c}\frac{\langle X^\dagger X\rangle}{M^2_{\rm Pl}} - l_0^{f,f^c}\frac{F_{X^\dagger}F_X}{m^2_{3/2}M^2_{Pl}}\right)\right.$$

$$\left. + \sum_A \frac{\langle\phi^*_A\rangle_{\overline{a}}\langle\phi_A\rangle_b}{M_f^2}\left(k_A^{f,f^c}(1 - x_A x_A^*) - l_A^{f,f^c}\frac{F_{X^\dagger}F_X}{m^2_{3/2}M^2_{Pl}}\right) - k_4^{f,f^c}\delta_{\overline{a}b}\frac{\langle\Sigma^*\rangle\langle\Sigma\rangle}{M^2_\Sigma}x_\Sigma x_\Sigma\right]$$

FCNC

$$F_\phi = \frac{\partial W}{\partial\phi} + \phi^* W, \quad \langle W\rangle = m_{3/2}$$

Determined by Yukawa structure

$$A_{abc} \propto \left\langle F_X\left(\partial_X\frac{K_{\rm hid}}{M^2_{Pl}}\right)Y_{abc} + \sum_\Phi F_\Phi\partial_\Phi Y_{abc}\right.$$

$$\left. - \left(F_X(\tilde{K}^{-1})_{d\overline{e}}\partial_X\tilde{K}_{\overline{e}a}Y_{dbc} + \sum_\Phi F_\Phi(\tilde{K}^{-1})_{d\overline{e}}\partial_\Phi\tilde{K}_{\overline{e}a}Y_{dbc} + cyclic(a,b,c)\right)\right\rangle$$

SUSY flavour and CP problem : soft SUSY breaking terms

Leading term degenerate

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Misalignment of Yukawa and A-terms?

e.g. $P = Y_{ij} Q_i q^c_j H_a \propto \left(\frac{\theta}{M}\right)^{\alpha(i,j)} Q_i q^c_j H_a$

$A_{ij} Y_{ij} \tilde{Q}_i \tilde{q}^c_j H_a = (3+\alpha(i,j)) m_{3/2} Y_{ij} \tilde{Q}_i \tilde{q}^c_j H_a$

(Here $\alpha(i,j)=2$ so Y and A aligned if $F_\Sigma = 0$)

$F_{\phi,\Sigma} = m_{3/2}\langle\phi,\Sigma\rangle$, "natural" value

GGR, Vives

suppression factor $\left(\frac{m_{3/2}}{M_\phi}\right)^2$ possible

Antusch et al

CP ?

$\phi_A = Arg(Am^*_{1/2}), \quad \phi_B = Arg(Bm^*_{1/2}) < 10^{-2}$?

SUSY CP problem has a simple solution in familon models:

- CP invariant in underlying theory (string compactification)

  Dine, Leigh, MacIntyre

- Spontaneously broken in flavour changing familon sector

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CP violation and FCNC

Mass insertion bounds

$$(\delta^f_{LL})_{ij} = \frac{\left(m^2_{\tilde{f}\,LL}\right)_{ij}}{\langle m_{\tilde{f}}\rangle^2_{LL}}\,, \quad (\delta^f_{RR})_{ij} = \frac{\left(m^2_{\tilde{f}\,RR}\right)_{ij}}{\langle m_{\tilde{f}}\rangle^2_{RR}}\,, \quad (\delta^f_{LR})_{ij} = \frac{\left(m^2_{\tilde{f}\,LR}\right)_{ij}}{\langle m_{\tilde{f}}\rangle^2_{LR}}$$

Most stringent bounds
(Determined by A terms)

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EDMs

$$|\mathrm{Im}(\delta^u_{LR})_{11}| \approx 2\times10^{-7}\frac{A_0}{100\,\mathrm{GeV}}\left(\frac{500\,\mathrm{GeV}}{\langle\tilde m_u\rangle_{LR}}\right)^2\left(\frac{\bar\varepsilon}{0.13}\right)^3\left(\frac{\varepsilon}{0.05}\right)^2|y^f_1+y^f_2|\,|x_{123}-x_{23}-x_\Sigma|\sin\phi_1 \qquad \lesssim 10^{-6}\,|_{Expt}$$

$$|\mathrm{Im}(\delta^d_{LR})_{11}| \approx 5\times10^{-7}\frac{A_0}{100\,\mathrm{GeV}}\left(\frac{500\,\mathrm{GeV}}{\langle\tilde m_d\rangle_{LR}}\right)^2\left(\frac{\bar\varepsilon}{0.13}\right)^5\frac{10}{\tan\beta}|y^f_1+y^f_2|\,|x_{123}-x_{23}-x_\Sigma|\sin\phi_1, (1 \qquad \lesssim 10^{-6}\,|_{Expt}$$

$$|\mathrm{Im}(\delta^\ell_{LR})_{11}| \approx 2\times10^{-7}\frac{A_0}{100\,\mathrm{GeV}}\left(\frac{200\,\mathrm{GeV}}{\langle\tilde m_l\rangle_{LR}}\right)^2\left(\frac{\bar\varepsilon}{0.13}\right)^5\frac{10}{\tan\beta}|y^f_1+y^f_2|\,|x_{123}-x_{23}-x_\Sigma|\sin\phi_1, \qquad \lesssim 10^{-7}\,|_{Expt}$$

$\mu \to e\gamma$

$$|(\delta^\ell_{LR})_{12}| \approx 1\times10^{-4}\frac{A_0}{100\,\mathrm{GeV}}\frac{(200\ \mathrm{GeV})^2}{\langle\tilde m_l\rangle^2_{LR}}\frac{10}{\tan\beta}\left(\frac{\bar\varepsilon}{0.13}\right)^3|y_1|\,|x_{123}-x_{23}-x_\Sigma| \qquad \lesssim 10^{-5}\,|_{Expt}$$

Antusch, King, Malinsky, GGR
Calibbi,Jones-Perez,Vives

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$$|\mathrm{Im}(\delta^u_{LR})_{11}| \lesssim 2\times 10^{-8}\frac{A_0}{100\ \mathrm{GeV}}\left(\frac{500\,\mathrm{GeV}}{\langle\tilde m_u\rangle_{LR}}\right)^2\left(\frac{\bar\varepsilon}{0.15}\right)^3\left(\frac{\varepsilon}{0.05}\right)^3\sin\phi_1 \qquad \le 10^{-6}\,|_{Expt}$$

$$|\mathrm{Im}(\delta^d_{LR})_{11}| \sim 2\times 10^{-7}\frac{A_0}{100\ \mathrm{GeV}}\left(\frac{500\,\mathrm{GeV}}{\langle\tilde m_d\rangle_{LR}}\right)^2\left(\frac{\bar\varepsilon}{0.15}\right)^6\frac{10}{\tan\beta}\sin\phi_1 \qquad \le 10^{-6}\,|_{Expt}$$

$$|\mathrm{Im}(\delta^\ell_{LR})_{11}| \sim 6\times 10^{-8}\frac{A_0}{100\ \mathrm{GeV}}\left(\frac{200\,\mathrm{GeV}}{\langle\tilde m_e\rangle_{LR}}\right)^2\left(\frac{\bar\varepsilon}{0.15}\right)^6\frac{10}{\tan\beta}\sin\phi_1 \qquad \le 10^{-7}\,|_{Expt}$$

$\mu \to e\gamma$

$$|(\delta^e_{LR})_{12}| \lesssim |(\delta^\ell_{LR})_{12}| \sim 3\times 10^{-5}\frac{A_0}{100\,\mathrm{GeV}}\frac{(200\,\mathrm{GeV})^2}{\langle\tilde m_l\rangle^2_{LR}}\frac{10}{\tan\beta}\left(\frac{\bar\varepsilon}{0.15}\right)^4 \qquad \le 10^{-5}\,|_{Expt}$$

Antusch, King, Malinsky, GGR

Summary

- Sequential see saw consistent with quark-lepton unification

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- Discrete non Abelian family symmetry readily generates near Tri-Bi-Maximal mixing

- Neutrino parameters strongly constrained:

  Mixing angles to $\pm 3^o$

  $m_{\beta\beta}$

- Sparticle masses, CP violation and FCNC

  SUSY models: sparticles have related mass structure

  $(m^2\phi_i^\dagger\phi_i \dots$ degeneracy split by small fermion mass related terms)

  $FCNC: \quad L_i, B_i\ violation - close\ to\ present\ bounds$

  ($\mu \to e\gamma$, mercury EDM within a factor of 10 of present limits)

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