Family symmetries.

G.G.Ross, Valencia, December 2008

Family symmetries.

G.G.Ross, Valencia, December 2008

- $q \leftrightarrow l$

  Neutrino v/s quark masses and mixing?

  See-saw with sequential domination

- Symmetry

  GUT

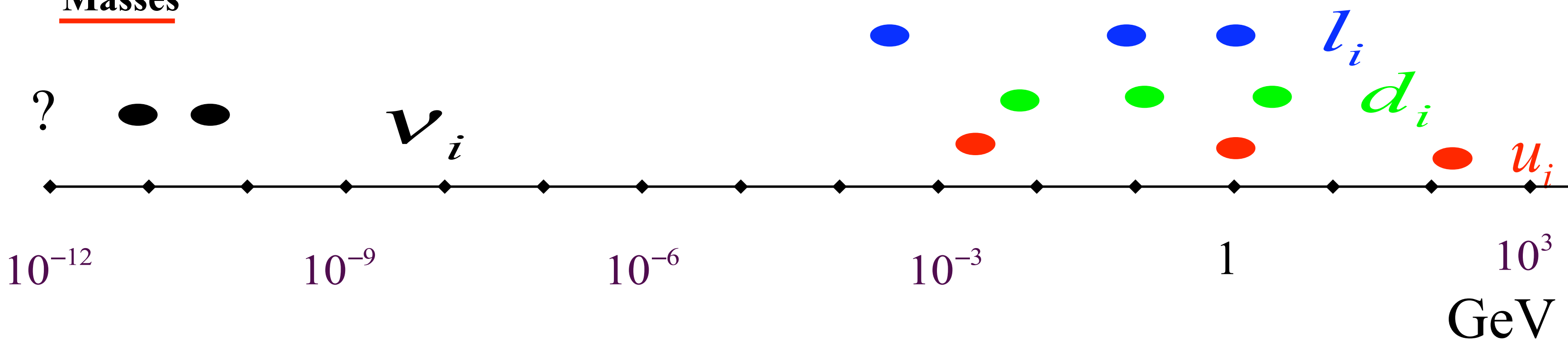
  Family — Abelian, Non-Abelian, Discrete, String?

- Tri-bi-maximal mixing

  Non-Abelian discrete symmetry

DATA :

Masses



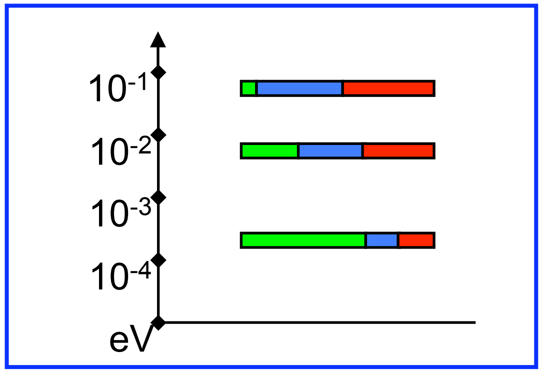
Mixing

Quarks

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

Leptons

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



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

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 :

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

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

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

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

Symmetry 1. GUT relations

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

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

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

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

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

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

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

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

Symmetry 1.

GUT relations

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

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

$$\langle \Sigma_{45} \rangle$$

$$\parallel$$

$$\overline{\psi}^\alpha \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & -3 \end{pmatrix} \psi_\alpha$$

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

Georgi Jarlskog

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

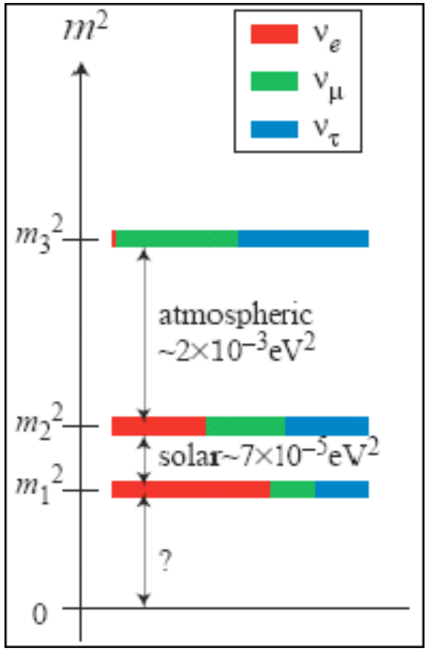
$$\varepsilon^d = 0.15, \quad a^d = 1$$

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

Neutrinos ???

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

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



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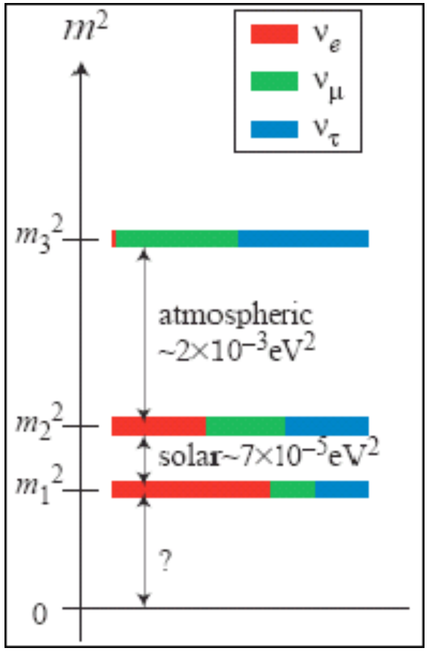

Can one have a unified description of quark, charged lepton and neutrinos?

$$c.f.\ \ L_{Dirac}^{q,l} = m_3\, \bar{\phi}_3^{i} \psi_i \bar{\phi}_3^{j} \psi_j^c + \ldots \qquad <\bar{\phi}_3>^i = (0,0,1) \quad ???$$

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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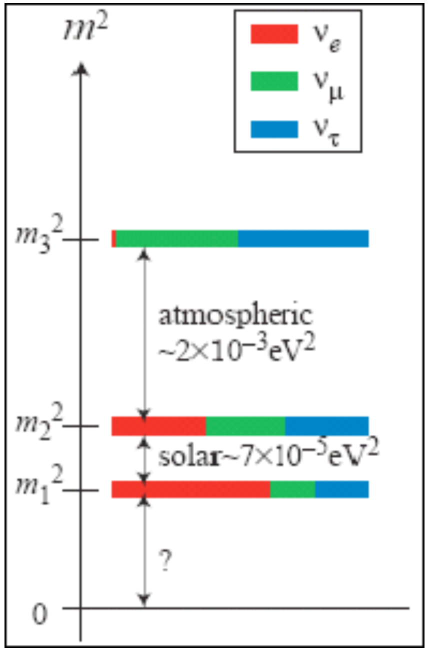


See-Saw

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

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

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

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

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

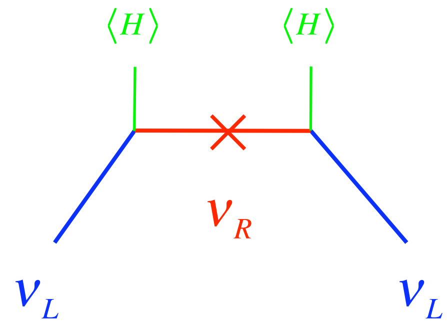
$\varepsilon^u = 0.05, \quad a^u = 1$

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

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

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

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



$$L^\nu_{Dirac} = \alpha\, \psi_i \bar{\phi}^i_3 \psi^c_j \bar{\phi}^j_3 + \beta \left(\psi_i \bar{\phi}^i_{123} \psi^c{}_j \bar{\phi}^j_{23} + \psi_i \bar{\phi}^i_{23} \psi^c{}_j \bar{\phi}^j_{123} \right) \qquad \alpha > \beta$$

$$L^\nu_{eff} = \frac{\beta^2}{M_1} \psi_i \phi^i_{123} \psi_j \phi^j_{123} + \frac{\beta^2}{M_2} \psi_i \phi^i_{23} \psi_j \phi^j_{23} + \frac{(\alpha+\beta)^2}{M_3} \psi_i \phi^i_3 \psi_j \phi^j_3$$

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

Minkowski
Gell-Mann,
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King

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

small

$$L^\nu_{Dirac} = \alpha\, \psi_i \bar{\phi}_3^i \psi^c_j \bar{\phi}_3^j + \beta \left(\psi_i \bar{\phi}^i_{123} \psi^c_j \bar{\phi}^j_{23} + \psi_i \bar{\phi}^i_{23} \psi^c_j \bar{\phi}^j_{123} \right) \qquad \alpha > \beta$$

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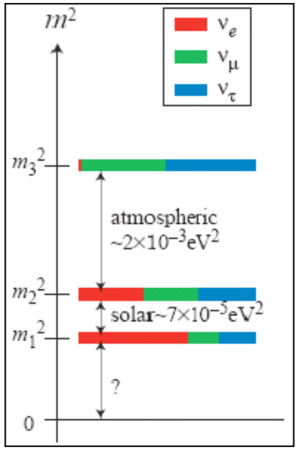
Symmetry 2.

Family symmetry



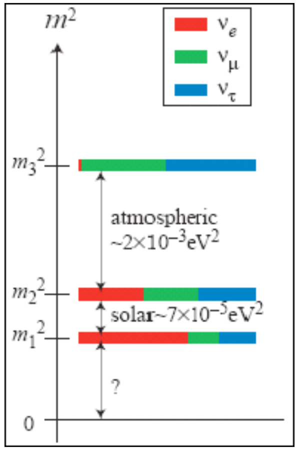
Non-Abelian family symmetry

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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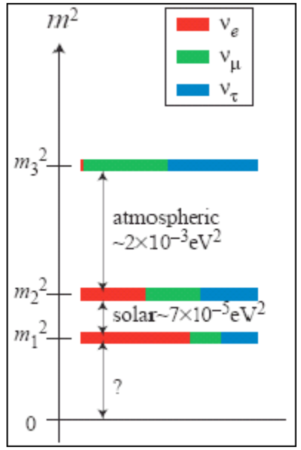
Vacuum alignment ???

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

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

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	$\to \phi_1$	$\to \alpha^{-3}\phi_3$

$$\alpha^n = 1$$

$$\Delta\left(3n^2\right) \qquad n = 2, \quad \Delta\left(12\right) \equiv A_4$$

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

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 : $Z_3 \ltimes Z_n \to \begin{cases} Z_3, & \langle\phi\rangle = (1,1,1)/\sqrt{3} \quad \lambda>0 \\ Z_n, & \langle\phi\rangle = (0,0,1) \quad \lambda<0 \end{cases}$

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

Non Abelian discrete symmetries

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

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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	$Z_3\phi_i$	$Z_n^{'}\phi_i$
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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

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

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

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

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

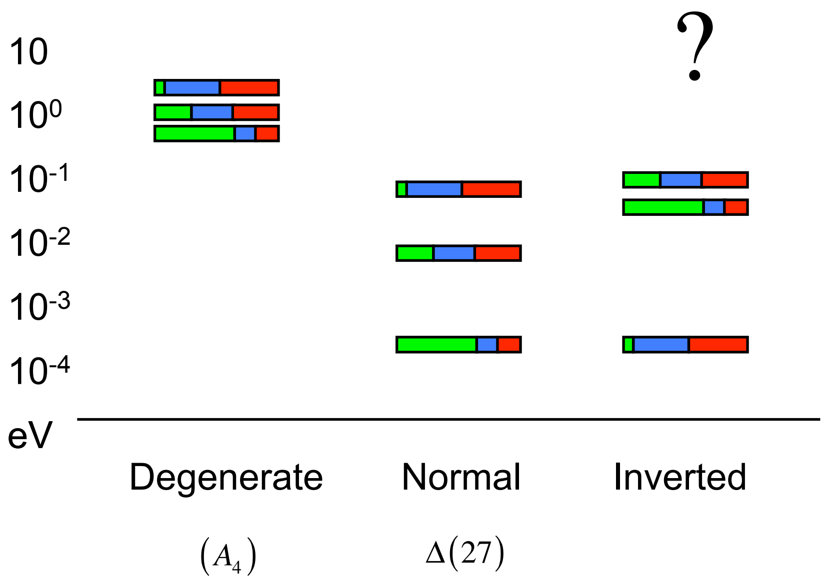
only terms allowed by G

Neutrino Parameters

Neutrino Parameters

- Tri-bi-maximal mixing

  Degenerate and normal spectra favoured



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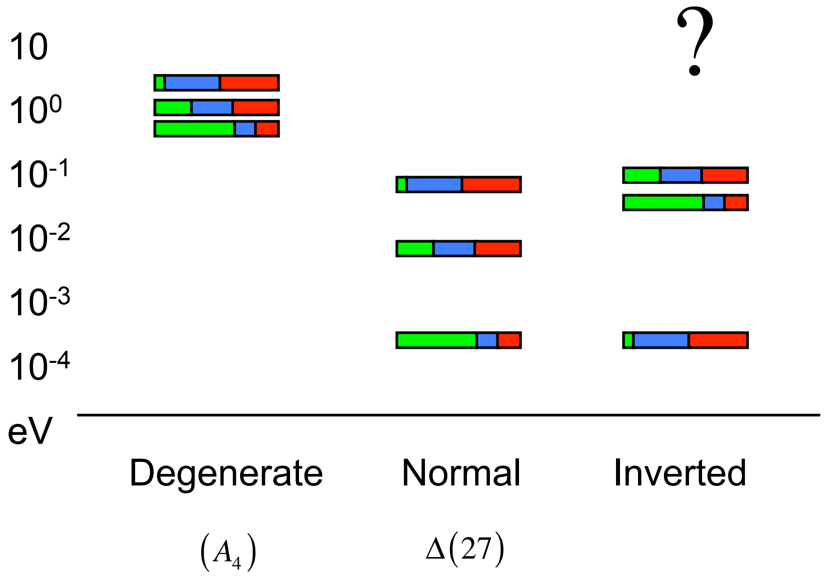

- Mixing angles

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

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

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

From charged lepton mixing

King; GGR, Varzielas

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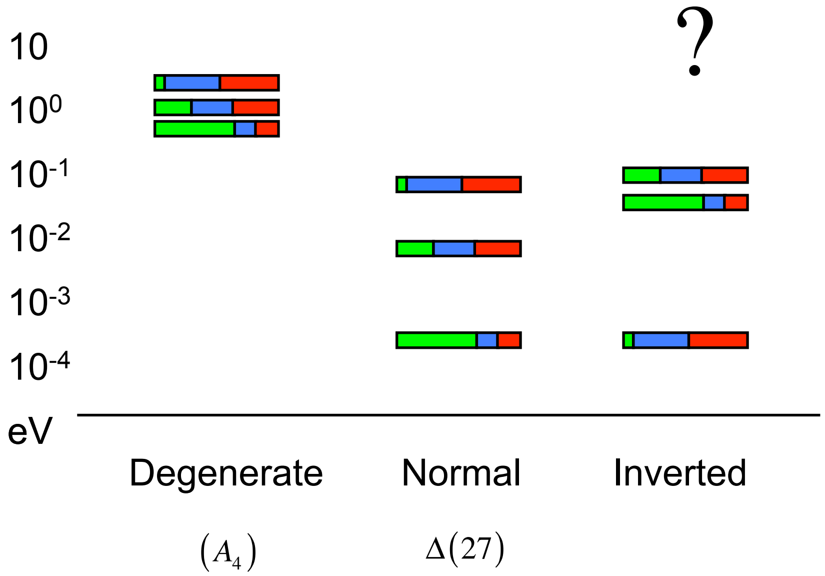

- Mixing angles

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

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

From charged lepton mixing

Antusch, King

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

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

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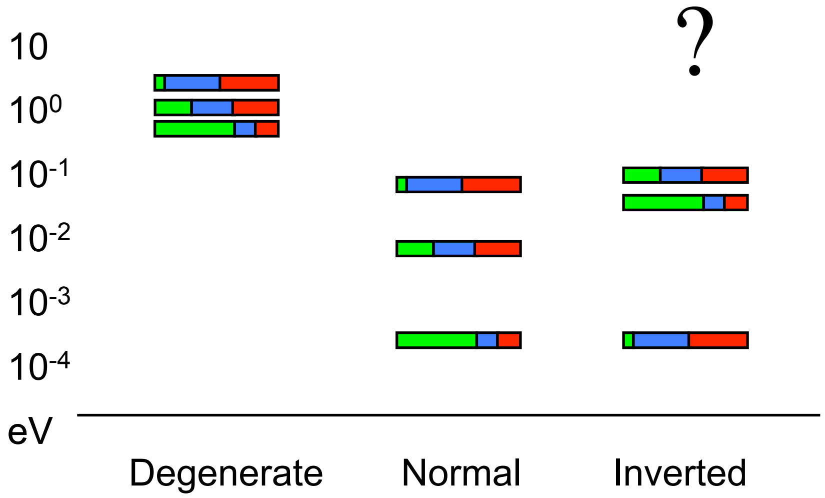
Neutrino Parameters

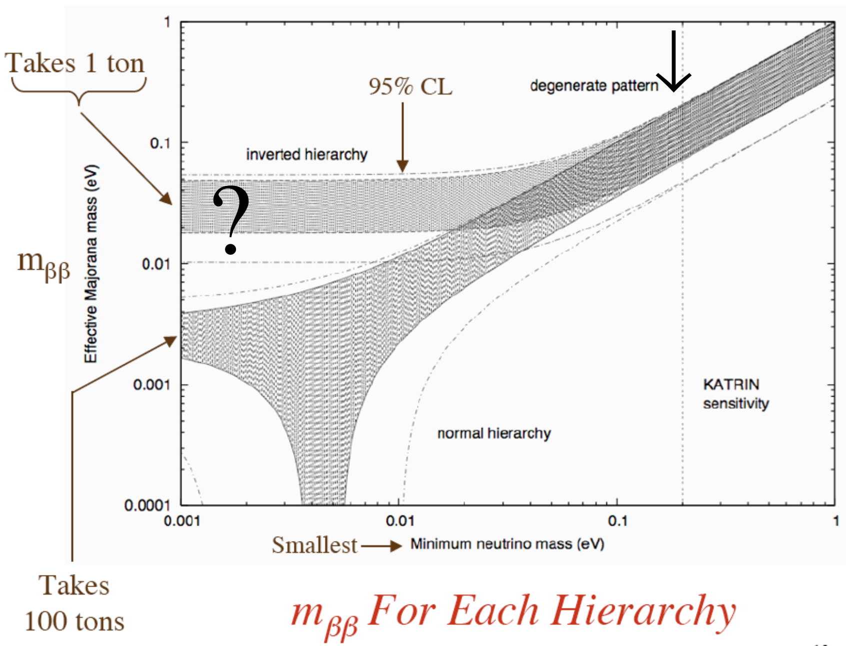
- Tri-bi-maximal mixing

  Degenerate and normal spectra possible

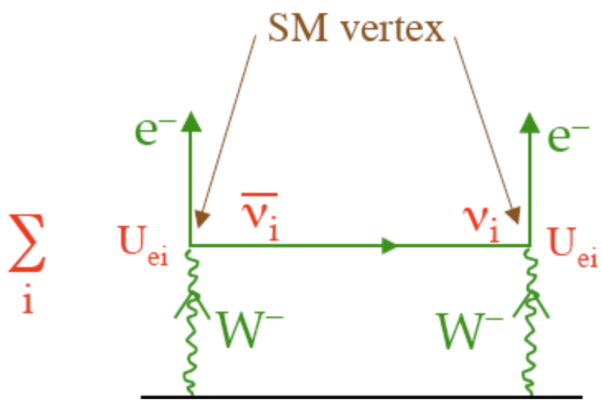


- Neutrinoless double β decay

  (3 light neutrinos) … Ivo's talk



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



Mass (ν_i)

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

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

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

CP ?

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

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

  GGR, Velasco Sevilla, Vives

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Soft masses

$$m^2_{3/2}(\tilde{f}^{i\dagger}\tilde{f}_i + \tilde{f}^{i\dagger}\phi^{\dagger}_{3i}\tilde{f}_j\phi^j_3 + \ldots)$$

Characteristic pattern

CP ?

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

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$$m^2_{3/2}(\tilde{f}^{i\dagger}\tilde{f}_i + \tilde{f}^{i\dagger}\phi^{\dagger}_{3i}\tilde{f}_j\phi^j_3 + \ldots)$$

Characteristic pattern

Soft A-terms

Misalignment of Yukawa and A-terms?

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

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

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

GGR, Vives

Here $\alpha(i,j) = 2$ so Y and A aligned $\left(\text{with } F_\Sigma = 0\right)$ - suppresses FCNC

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

GGR, Velasco Sevilla, Vives

Soft masses

$$m^2_{3/2}(\tilde{f}^{i\dagger}\tilde{f}_i + \tilde{f}^{i\dagger}\phi^\dagger_{3i}\tilde{f}_j\phi^j_3 + \ldots)$$

Characteristic pattern

Soft A-terms: CP violation and FCNC

EDMs

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

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

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

$\mu \to e\gamma$

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

Antusch, King, Malinsky, GGR

Summary

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- Sequential see saw consistent with quark-lepton unification

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  Mixing angles to $\pm 3^o$

  $m_{\beta\beta}$

- CP violation and g-2

  SUSY models: sparticles have related mass structure

  $(m^2 \phi_i^\dagger \phi_i \ldots$ 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)

See saw parameters

Masses + Mixing Angles	6	(15)	(8)
CP violating phases	3	(6)	(3)

$$\kappa = Y_\nu^T M^{-1} Y_\nu$$ Insufficient information

$$P = Y_\nu^\dagger Y_\nu$$ RGE for sleptons (SUSY)

In *principle* all parameters determined by neutrino structure and radiative corrections (assuming degenerate sleptons at GUT scale)

Davidson, Ibarra

Thermal Leptogenesis (Baryogenesis)

Fukugita, Yanagida

$$M_{\nu_R} > 10^9\,GeV, \quad T_{\text{Reheat}} > 10^{10}\,GeV \quad \text{(hierarchical spectrum)}$$

$$\not{CP} = \not{CP}(\delta, \phi', \phi_{i=1,2,3})$$

$\beta\beta$ phase (→ ϕ')

see saw phases (→ $\phi_{i=1,2,3}$)

ν factory phase (→ δ)

Sequential see saw and symmetry (texture zero) simplifies structure…