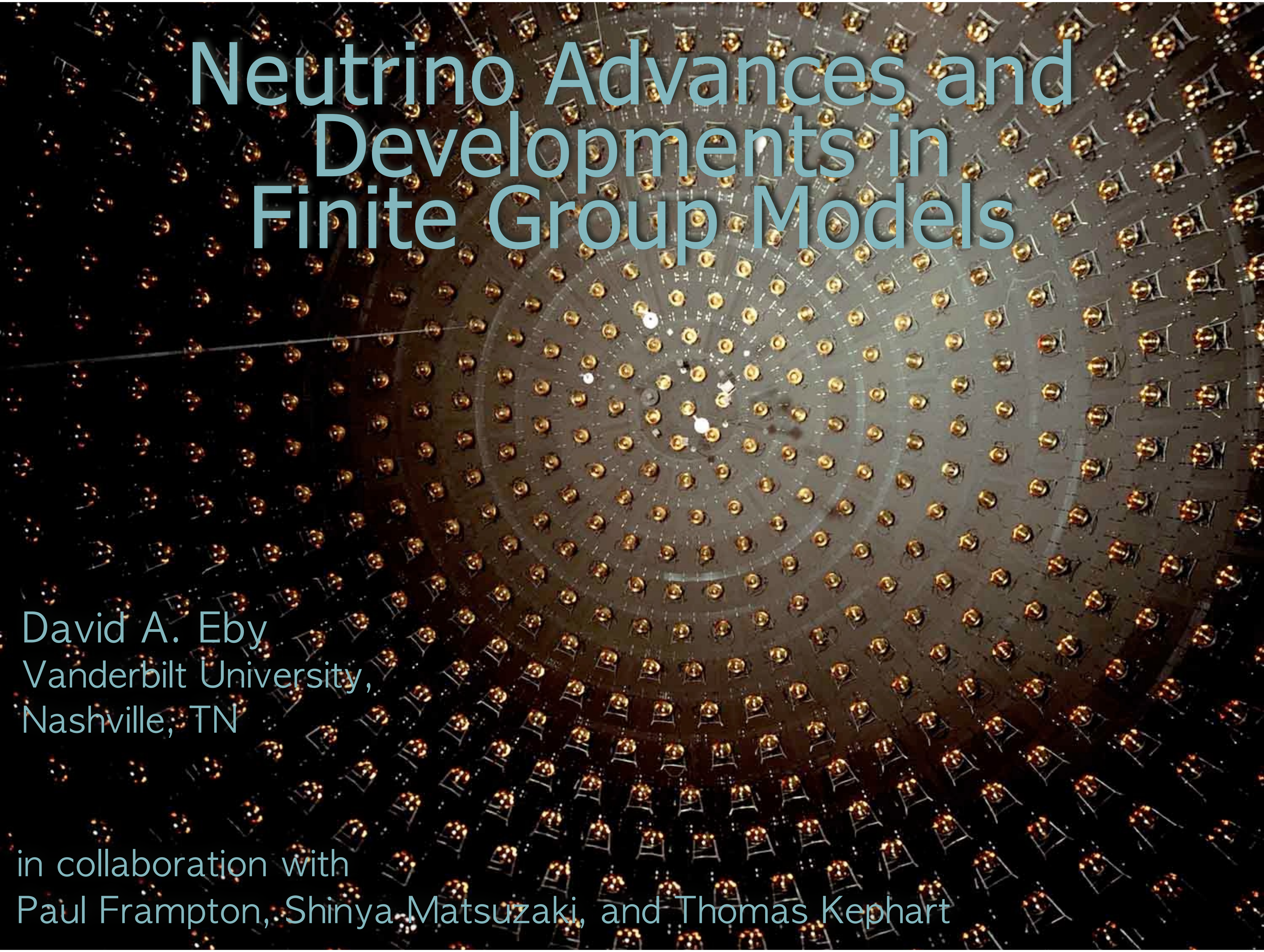

Neutrino Advances and Developments in Finite Group Models

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in collaboration with
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Outline

- Motivation and Neutrino Review
- Building the Minimal Renormalizable T′ Model
- Connections to SM and other BSM physics
- Dark Matter from T′ Symmetry
- Limitations and Future Outlook

Flavor Symmetry Motivations

- Reduction of SM Parameters
- Explain Neutrino behavior: Mixing, Mass Scale, Helicity, etc.
- Connecting Lepton & Quark Properties
- Other Particle Physics questions: Dark Matter, New Symmetries
- Clues to New Physics at the Energy Frontier

"I have done a terrible thing today, something which no theoretical physicist should ever do. I have suggested something that can never be verified experimentally."

-Wolfgang Pauli (1930)

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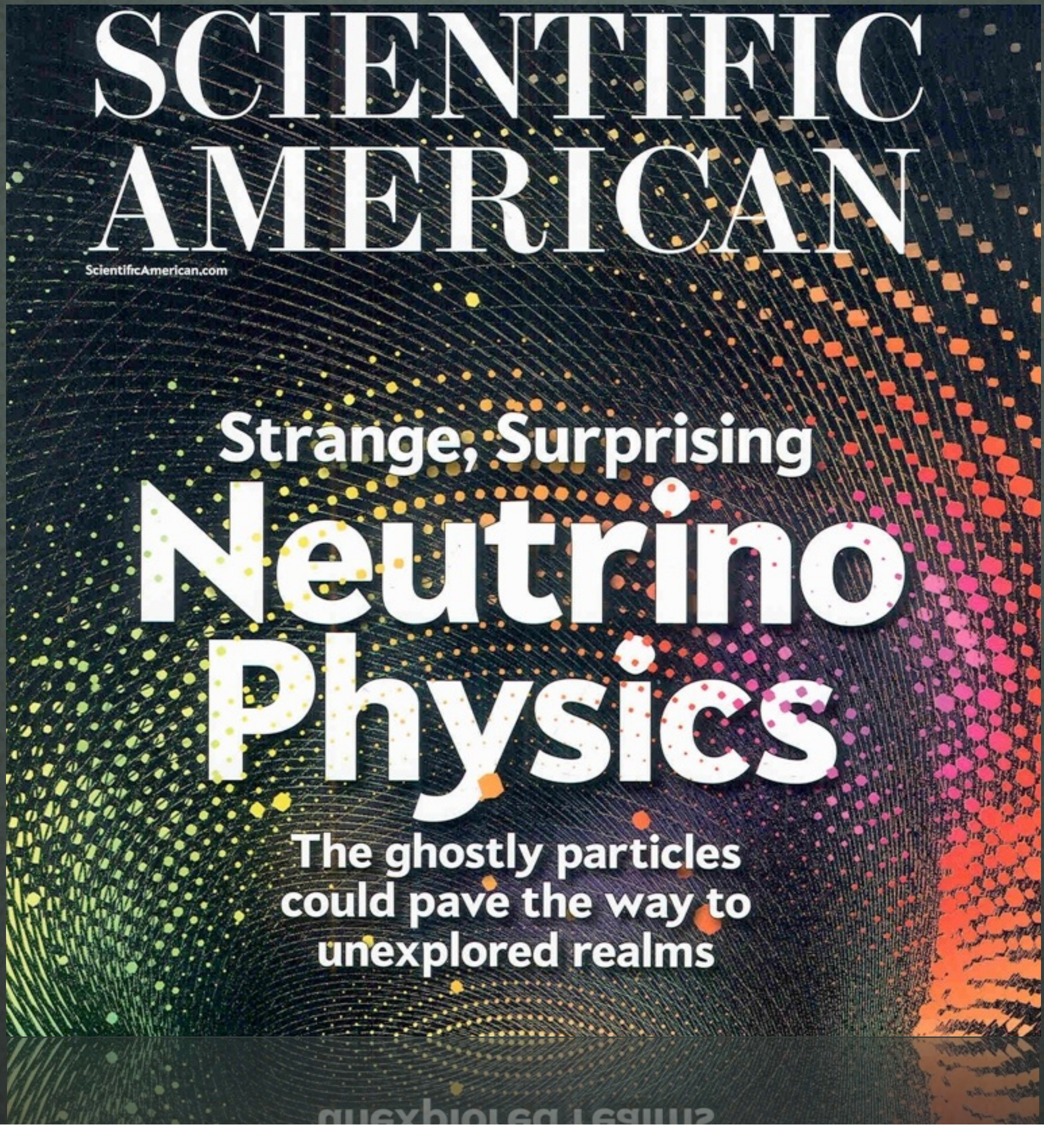

15 years of New Physics from Neutrino Anomalies

Anomalies	New Physics	Been and Gone
Neutrino Oscillation/Mass		
LSND Anomaly		
MINOS Neutrino Anti-Neutrino Asymmetry		
FTL Neutrinos		
Non-zero Reactor Angle		
MiniBooNE low-E ν_e excess		
Missing Reactor/Gallium ν		
IceCube High Energy Events		

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Neutrino Mixing

- Neutrino Oscillation
- PMNS Matrix and Parametrization
- For simplicity we set δ_{CP} to 0
- TBM Symmetry: Tribimaximal Mixing

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

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$$U = \begin{pmatrix} +c_{12}c_{13} & +s_{12}c_{13} & +s_{13} \\ -s_{12}c_{23} + c_{12}s_{23}s_{13} & +c_{12}c_{23} + s_{12}s_{23}s_{13} & +s_{23}c_{13} \\ -s_{12}s_{23} - c_{12}c_{23}s_{13} & +c_{12}s_{23} - s_{12}c_{23}s_{13} & +c_{23}c_{13} \end{pmatrix}$$

$$\text{with } c_{12} \equiv \cos\theta_{12},\ s_{13} \equiv \sin\theta_{13},\ \text{etc.}$$

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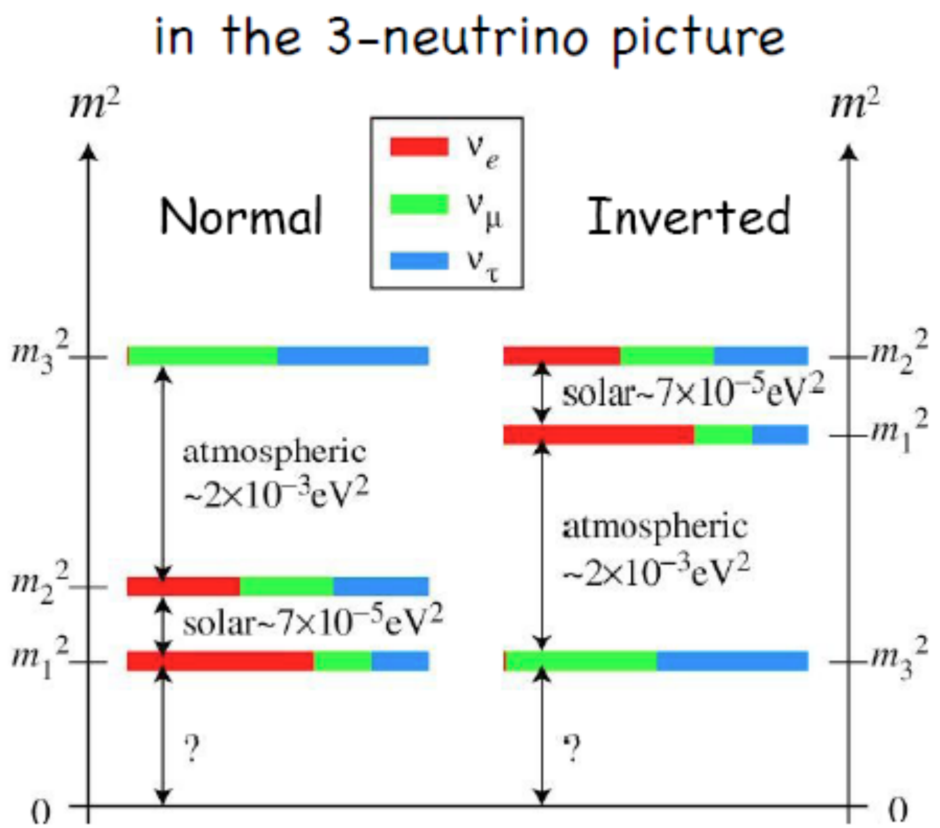
$$\text{with } c_{12} \equiv \cos\theta_{12},\ \ s_{13} \equiv \sin\theta_{13},\ \text{ etc.}$$

$$\theta_{12} \simeq 35.3^\circ,\ \ \theta_{13} = 0^\circ,\ \ \theta_{23} = 45^\circ$$

$$U_{\mathrm{TBM}} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

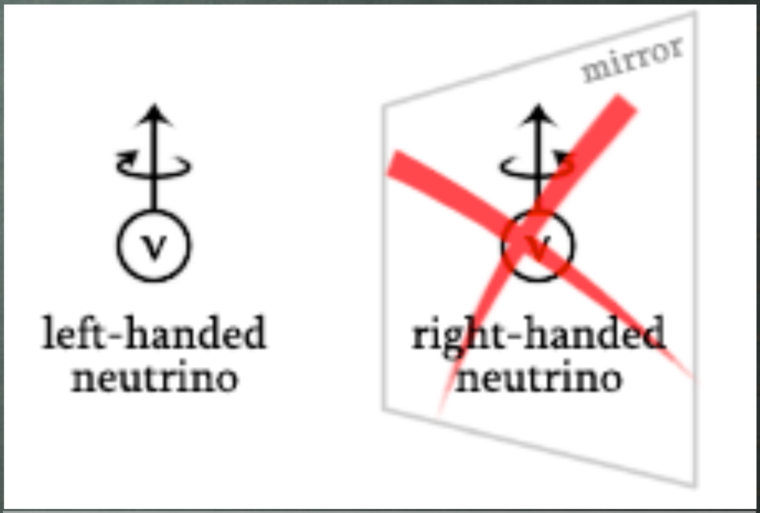
Mass & Hierarchy

- Limited Data leads to complex picture
- Best measurements are Δ^2 between mass eigenstates (sign of atmospheric mass-splitting remains unknown)
- 2 possible orderings: Normal and Inverted
- Quasi-degenerate case (now disfavored)
- Difficult to test, but hopefully next-gen (long baseline) detectors will settle the issue



Helicity and Seesaws

- Nonzero Mass: means Sterile RH Neutrinos are needed
- Dirac—Higgs coupling ($x10^{-12}$)
- Majorana—Possible Seesaw Mechanism
- Loss of Lepton Number Conservation
- Light LH neutrinos explained by making RH neutrinos very heavy
- Equation combines two mass matrices
- Tough to test directly as "heavy" neutrinos could be at GUT scale



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T´ x Z

- Z_2: Cyclic Group
- T´: Binary Tetrahedral Symmetry
- Double-Cover of Tetrahedral Group, A_4, both of which can produce TBM values
- Order 24 Non-Abelian (non-commuting) Finite Group
- Benefits of T´ over A_4: Compatibility with Quark Sector
- First modern use in 1994 as a family symmetry for Quarks

Group Irrep. Multiplication Tables

- Identical singlet and triplet structure allow significant similarities
- T´ is notable for also including doublets

A_4

	1_1	1_2	1_3	3
1_1	1_1	1_2	1_3	3
1_2	1_2	1_3	1_1	3
1_3	1_3	1_1	1_2	3
3	3	3	3	$1_1+1_2+1_3+3+3$

T´

	1_1	1_2	1_3	2_1	2_2	2_3	3
1_1	1_1	1_2	1_3	2_1	2_2	2_3	3
1_2	1_2	1_3	1_1	2_2	2_3	2_1	3
1_3	1_3	1_1	1_2	2_3	2_1	2_2	3
2_1	2_1	2_2	2_3	1_1+3	1_2+3	1_3+3	$2_1+2_2+2_3$
2_2	2_2	2_3	2_1	1_2+3	1_3+3	1_1+3	$2_1+2_2+2_3$
2_3	2_3	2_1	2_2	1_3+3	1_1+3	1_2+3	$2_1+2_2+2_3$
3	3	3	3	$2_1+2_2+2_3$	$2_1+2_2+2_3$	$2_1+2_2+2_3$	$1_1+1_2+1_3+3+3$

Particle Assignments

- LH leptons in Triplet RH leptons in Singlet

$$\left.\begin{matrix}\begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L\\ \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L\\ \begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L\end{matrix}\right\} L_L(3,+1)$$

$$\begin{matrix}\tau_R^- & (1_1,-1) & \text{and} & N_R^{(1)} & (1_1,+1)\\ \mu_R^- & (1_2,-1) & \text{and} & N_R^{(2)} & (1_2,+1)\\ e_R^- & (1_3,-1) & \text{and} & N_R^{(3)} & (1_3,+1)\end{matrix}$$

- Uses 2+1 for quarks allowing for top quark singlet

$$\begin{pmatrix}t\\ b\end{pmatrix}_{\rm L} \quad \mathcal{Q}_{\rm L} \quad (1_1,+1)$$

$$\left.\begin{matrix}\begin{pmatrix}c\\ s\end{pmatrix}_{\rm L}\\ \begin{pmatrix}u\\ d\end{pmatrix}_{\rm L}\end{matrix}\right\} Q_{\rm L} \quad (2_1,+1),$$

$$\begin{matrix}t_{\rm R} & & (1_1,+1)\\ b_{\rm R} & & (1_2,-1)\\ \left.\begin{matrix}c_{\rm R}\\ u_{\rm R}\end{matrix}\right\} & \mathcal{C}_{\rm R} & (2_3,-1)\\ \left.\begin{matrix}s_{\rm R}\\ d_{\rm R}\end{matrix}\right\} & \mathcal{S}_{\rm R} & (2_2,+1)\end{matrix}$$

Forming Lagrangian Terms

Leptons	L_L	τ_R	μ_R	e_R	$N_R^{(1)}$	$N_R^{(2)}$	$N_R^{(3)}$
$\mathbf{T}'$	3	1_1	1_2	1_3	1_1	1_2	1_3
$\mathbf{Z_2}$	$+$	$-$	$-$	$-$	$+$	$+$	$+$

	1_1	1_2	1_3	2_1	2_2	2_3	3
1_1	1_1	1_2	1_3	2_1	2_2	2_3	3
1_2	1_2	1_3	1_1	2_2	2_3	2_1	3
1_3	1_3	1_1	1_2	2_3	2_1	2_2	3
2_1	2_1	2_2	2_3	1_1+3	1_2+3	1_3+3	$2_1+2_2+2_3$
2_2	2_2	2_3	2_1	1_2+3	1_3+3	1_1+3	$2_1+2_2+2_3$
2_3	2_3	2_1	2_2	1_3+3	1_1+3	1_2+3	$2_1+2_2+2_3$
3	3	3	3	$2_1+2_2+2_3$	$2_1+2_2+2_3$	$2_1+2_2+2_3$	$1_1+1_2+1_3+3+3$

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Leptons	L_L	τ_R	μ_R	e_R	$N_\mathrm{R}^{(1)}$	$N_\mathrm{R}^{(2)}$	$N_\mathrm{R}^{(3)}$
$\mathbf{T}'$	3	1_1	1_2	1_3	1_1	1_2	1_3
$\mathbf{Z_2}$	$+$	$-$	$-$	$-$	$+$	$+$	$+$

$$L_L e_R H$$

	1_1	1_2	1_3	2_1	2_2	2_3	3
1_1	1_1	1_2	1_3	2_1	2_2	2_3	3
1_2	1_2	1_3	1_1	2_2	2_3	2_1	3
1_3	1_3	1_1	1_2	2_3	2_1	2_2	3
2_1	2_1	2_2	2_3	1_1+3	1_2+3	1_3+3	$2_1+2_2+2_3$
2_2	2_2	2_3	2_1	1_2+3	1_3+3	1_1+3	$2_1+2_2+2_3$
2_3	2_3	2_1	2_2	1_3+3	1_1+3	1_2+3	$2_1+2_2+2_3$
3	3	3	3	$2_1+2_2+2_3$	$2_1+2_2+2_3$	$2_1+2_2+2_3$	$1_1+1_2+1_3+3+3$

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Leptons	L_L	τ_R	μ_R	e_R	$N_\mathrm{R}^{(1)}$	$N_\mathrm{R}^{(2)}$	$N_\mathrm{R}^{(3)}$
$\mathbf{T}'$	3	1_1	1_2	1_3	1_1	1_2	1_3
$\mathbf{Z_2}$	$+$	$-$	$-$	$-$	$+$	$+$	$+$

$$L_L e_R H'_3$$

$$H'_3 \quad (3, -1)$$

	1_1	1_2	1_3	2_1	2_2	2_3	3
1_1	1_1	1_2	1_3	2_1	2_2	2_3	3
1_2	1_2	1_3	1_1	2_2	2_3	2_1	3
1_3	1_3	1_1	1_2	2_3	2_1	2_2	3
2_1	2_1	2_2	2_3	1_1+3	1_2+3	1_3+3	$2_1+2_2+2_3$
2_2	2_2	2_3	2_1	1_2+3	1_3+3	1_1+3	$2_1+2_2+2_3$
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Leptons	L_L	τ_R	μ_R	e_R	$N_\mathrm{R}^{(1)}$	$N_\mathrm{R}^{(2)}$	$N_\mathrm{R}^{(3)}$
$\mathbf{T}'$	3	1_1	1_2	1_3	1_1	1_2	1_3
$\mathbf{Z_2}$	$+$	$-$	$-$	$-$	$+$	$+$	$+$

$$\mathcal{Q}_L t_R H$$

Quarks	$\mathcal{Q}_\mathrm{L}$	Q_L	t_R	b_R	$\mathcal{C}_\mathrm{R}$	$\mathcal{S}_\mathrm{R}$
$\mathbf{T}'$	1_1	2_1	1_1	1_2	2_3	2_2
$\mathbf{Z_2}$	$+$	$+$	$+$	$-$	$-$	$+$

$$H_3' \quad (3, -1)$$

	1_1	1_2	1_3	2_1	2_2	2_3	3
1_1	1_1	1_2	1_3	2_1	2_2	2_3	3
1_2	1_2	1_3	1_1	2_2	2_3	2_1	3
1_3	1_3	1_1	1_2	2_3	2_1	2_2	3
2_1	2_1	2_2	2_3	$1_1 + 3$	$1_2 + 3$	$1_3 + 3$	$2_1 + 2_2 + 2_3$
2_2	2_2	2_3	2_1	$1_2 + 3$	$1_3 + 3$	$1_1 + 3$	$2_1 + 2_2 + 2_3$
2_3	2_3	2_1	2_2	$1_3 + 3$	$1_1 + 3$	$1_2 + 3$	$2_1 + 2_2 + 2_3$
3	3	3	3	$2_1 + 2_2 + 2_3$	$2_1 + 2_2 + 2_3$	$2_1 + 2_2 + 2_3$	$1_1 + 1_2 + 1_3 + 3 + 3$

Forming Lagrangian Terms

Leptons	L_{L}	τ_{R}	μ_{R}	e_{R}	$N_{\mathrm{R}}^{(1)}$	$N_{\mathrm{R}}^{(2)}$	$N_{\mathrm{R}}^{(3)}$
$\mathbf{T}'$	3	1_1	1_2	1_3	1_1	1_2	1_3
$\mathbf{Z_2}$	$+$	$-$	$-$	$-$	$+$	$+$	$+$

$$\mathcal{Q}_L t_R H_{1_1}$$

Quarks	$\mathcal{Q}_{\mathrm{L}}$	Q_{L}	t_{R}	b_{R}	$\mathcal{C}_{\mathrm{R}}$	$\mathcal{S}_{\mathrm{R}}$
$\mathbf{T}'$	1_1	2_1	1_1	1_2	2_3	2_2
$\mathbf{Z_2}$	$+$	$+$	$+$	$-$	$-$	$+$

$$H_3' \quad (3,-1)\; H_{1_1} \quad (1_1,+1)$$

	1_1	1_2	1_3	2_1	2_2	2_3	3
1_1	1_1	1_2	1_3	2_1	2_2	2_3	3
1_2	1_2	1_3	1_1	2_2	2_3	2_1	3
1_3	1_3	1_1	1_2	2_3	2_1	2_2	3
2_1	2_1	2_2	2_3	1_1+3	1_2+3	1_3+3	$2_1+2_2+2_3$
2_2	2_2	2_3	2_1	1_2+3	1_3+3	1_1+3	$2_1+2_2+2_3$
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Leptons	L_L	τ_R	μ_R	e_R	$N_\mathrm{R}^{(1)}$	$N_\mathrm{R}^{(2)}$	$N_\mathrm{R}^{(3)}$
$\mathbf{T}'$	$\mathbf{3}$	$\mathbf{1}_1$	$\mathbf{1}_2$	$\mathbf{1}_3$	$\mathbf{1}_1$	$\mathbf{1}_2$	$\mathbf{1}_3$
$\mathbf{Z_2}$	$+$	$-$	$-$	$-$	$+$	$+$	$+$

Quarks	$\mathcal{Q}_\mathrm{L}$	Q_L	t_R	b_R	$\mathcal{C}_\mathrm{R}$	$\mathcal{S}_\mathrm{R}$
$\mathbf{T}'$	$\mathbf{1}_1$	$\mathbf{2}_1$	$\mathbf{1}_1$	$\mathbf{1}_2$	$\mathbf{2}_3$	$\mathbf{2}_2$
$\mathbf{Z_2}$	$+$	$+$	$+$	$-$	$-$	$+$

$$H'_3 \quad (3,-1) \quad H_{1_1} \quad (1_1,+1)$$
$$H_3 \quad (3,+1) \quad H_{1_3} \quad (1_3,-1)$$

	1_1	1_2	1_3	2_1	2_2	2_3	3
1_1	1_1	1_2	1_3	2_1	2_2	2_3	3
1_2	1_2	1_3	1_1	2_2	2_3	2_1	3
1_3	1_3	1_1	1_2	2_3	2_1	2_2	3
2_1	2_1	2_2	2_3	1_1+3	1_2+3	1_3+3	$2_1+2_2+2_3$
2_2	2_2	2_3	2_1	1_2+3	1_3+3	1_1+3	$2_1+2_2+2_3$
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Leptons	L_{L}	τ_{R}	μ_{R}	e_{R}	$N_{\mathrm{R}}^{(1)}$	$N_{\mathrm{R}}^{(2)}$	$N_{\mathrm{R}}^{(3)}$
$\mathbf{T}'$	3	1_1	1_2	1_3	1_1	1_2	1_3
$\mathbf{Z_2}$	$+$	$-$	$-$	$-$	$+$	$+$	$+$

Quarks	$\mathcal{Q}_{\mathrm{L}}$	Q_{L}	t_{R}	b_{R}	$\mathcal{C}_{\mathrm{R}}$	$\mathcal{S}_{\mathrm{R}}$
$\mathbf{T}'$	1_1	2_1	1_1	1_2	2_3	2_2
$\mathbf{Z_2}$	$+$	$+$	$+$	$-$	$-$	$+$

Higgs	H_{1_1}	H_{1_3}	H_3	H_3'
$\mathbf{T}'$	1_1	1_3	3	3
$\mathbf{Z_2}$	$+$	$-$	$+$	$-$

Forming Lagrangian Terms

Leptons	L_{L}	τ_{R}	μ_{R}	e_{R}	$N_{\mathrm{R}}^{(1)}$	$N_{\mathrm{R}}^{(2)}$	$N_{\mathrm{R}}^{(3)}$
$\mathbf{T}'$	3	1_1	1_2	1_3	1_1	1_2	1_3
$\mathbf{Z_2}$	$+$	$-$	$-$	$-$	$+$	$+$	$+$

Quarks	$\mathcal{Q}_{\mathrm{L}}$	Q_{L}	t_{R}	b_{R}	$\mathcal{C}_{\mathrm{R}}$	$\mathcal{S}_{\mathrm{R}}$
$\mathbf{T}'$	1_1	2_1	1_1	1_2	2_3	2_2
$\mathbf{Z_2}$	$+$	$+$	$+$	$-$	$-$	$+$

Higgs	H_{1_1}	H_{1_3}	H_3	H_3'
$\mathbf{T}'$	1_1	1_3	3	3
$\mathbf{Z_2}$	$+$	$-$	$+$	$-$

$$
\begin{aligned}
\mathcal{L}_Y = M_1 N_R^{(1)} N_R^{(1)} + M_{23} N_R^{(2)} N_R^{(3)} + \\
Y_e L_L e_R H_3' + Y_\mu L_L \mu_R H_3' + Y_\tau L_L \tau_R H_3' + \\
Y_1 L_L N_R^{(1)} H_3 + Y_2 L_L N_R^{(2)} H_3 + Y_3 L_L N_R^{(3)} H_3 + \\
Y_t (\mathcal{Q}_L t_R H_{1_1}) + Y_b (\mathcal{Q}_L b_R H_{1_3}) + \\
Y_{\mathcal{C}} (Q_L \mathcal{C}_R H_3') + Y_{\mathcal{S}} (Q_L \mathcal{S}_R H_3) + h.c.
\end{aligned}
$$

Higgs VEVs

$$\mathcal{L}_Y = M_1 N_R^{(1)} N_R^{(1)} + M_{23} N_R^{(2)} N_R^{(3)} +$$
$$Y_e L_L e_R H_3^{'} + Y_\mu L_L \mu_R H_3^{'} + Y_\tau L_L \tau_R H_3^{'} +$$
$$Y_1 L_L N_R^{(1)} H_3 + Y_2 L_L N_R^{(2)} H_3 + Y_3 L_L N_R^{(3)} H_3 +$$
$$Y_t(\mathcal{Q}_L t_R H_{1_1}) + Y_b(\mathcal{Q}_L b_R H_{1_3}) +$$
$$Y_{\mathcal{C}}(Q_L \mathcal{C}_R H_3^{'}) + Y_{\mathcal{S}}(Q_L \mathcal{S}_R H_3) + h.c.$$

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$$< H_3^{'} > \; = \; (\frac{m_\tau}{Y_\tau}, \frac{m_\mu}{Y_\mu}, \frac{m_e}{Y_e})$$
$$< H_{1_1} >= (\frac{m_t}{Y_t}) \quad < H_{1_3} >= (\frac{m_b}{Y_b})$$

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$$Y_t(\mathcal{Q}_L t_R H_{1_1}) + Y_b(\mathcal{Q}_L b_R H_{1_3}) +$$
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$$< H_3^{'} > \;=\; \left(\frac{m_\tau}{Y_\tau}, \frac{m_\mu}{Y_\mu}, \frac{m_e}{Y_e}\right)$$

$$< H_{1_1} >= \left(\frac{m_t}{Y_t}\right) \quad < H_{1_3} >= \left(\frac{m_b}{Y_b}\right)$$

$$< H_3 >= (V, V, V) \qquad < H_3 >= (V, -2V, V)$$

Higgs VEVs

$$\mathcal{L}_Y = M_1 N_R^{(1)} N_R^{(1)} + M_{23} N_R^{(2)} N_R^{(3)} +$$
$$Y_e L_L e_R H_3^{'} + Y_\mu L_L \mu_R H_3^{'} + Y_\tau L_L \tau_R H_3^{'} +$$
$$Y_1 L_L N_R^{(1)} H_3 + Y_2 L_L N_R^{(2)} H_3 + Y_3 L_L N_R^{(3)} H_3 +$$
$$Y_t(\mathcal{Q}_L t_R H_{1_1}) + Y_b(\mathcal{Q}_L b_R H_{1_3}) +$$
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$$m_2 \gg m_1 = m_3 = 0 \qquad m_3 \gg m_1 = m_2$$

Higgs VEVs

$$
\begin{aligned}
\mathcal{L}_Y = {} & M_1 N_R^{(1)} N_R^{(1)} + M_{23} N_R^{(2)} N_R^{(3)} + \\
& Y_e L_L e_R H_3^{'} + Y_\mu L_L \mu_R H_3^{'} + Y_\tau L_L \tau_R H_3^{'} + \\
& Y_1 L_L N_R^{(1)} H_3 + Y_2 L_L N_R^{(2)} H_3 + Y_3 L_L N_R^{(3)} H_3 + \\
& Y_t (\mathcal{Q}_L t_R H_{1_1}) + Y_b (\mathcal{Q}_L b_R H_{1_3}) + \\
& Y_\mathcal{C} (Q_L \mathcal{C}_R H_3^{'}) + Y_\mathcal{S} (Q_L \mathcal{S}_R H_3) + h.c.
\end{aligned}
$$

$$
\begin{aligned}
< H_3^{'} > \; &= \; \left(\frac{m_\tau}{Y_\tau}, \frac{m_\mu}{Y_\mu}, \frac{m_e}{Y_e}\right) \\
< H_{1_1} > = \left(\frac{m_t}{Y_t}\right) \quad & < H_{1_3} > = \left(\frac{m_b}{Y_b}\right)
\end{aligned}
$$

$$\xcancel{< H_3 > = (V, V, V)} \qquad < H_3 > = (V, -2V, V)$$

$$m_2 \gg m_1 = m_3 = 0 \qquad m_3 \gg m_1 = m_2$$

Cabibbo Angle Prediction

- Minimal Renormalizable T´ Model (No Higgs T´ doublets)
- Shared Higgs allow connection between neutrino mixing and Cabibbo Matrix (not full CKM)
- Method for Quark Mixing Prediction:
  - Assume up-type quarks and charged leptons are mass eigenstates
  - Complex Clebsch-Gordan coefficients from symmetry
  - Diagonalize nontrivial 2x2 quark matrices

$$\tan 2\Theta_{12} = \frac{\sqrt{2}}{3}$$

$$\Theta_{12,\mathrm{predicted}} = 12.6^\circ$$

$$\Theta_{12,\mathrm{experimental}} = 13.0^\circ$$

Perturbations

- Historical Development vs. Optimal Input
- What neutrino mixing does Cabibbo Angle demand?
- Perturbations in Higgs VEVs and Mixing Angles

$$\langle H_3 \rangle = V'(1, -2+b, 1+a)$$

$$\theta_{ij} = (\theta_{ij})_{TBM} + \epsilon_k$$

$$\begin{aligned}
\delta(M_\nu)_{\text{diag}} &= \begin{pmatrix} \delta m_1 & 0 & 0 \\ 0 & \delta m_2 & 0 \\ 0 & 0 & \delta m_3 \end{pmatrix} \\
&= \delta U (M_\nu)_{\text{TBM}} U^T_{\text{TBM}} \\
&+ U_{\text{TBM}} \delta M_\nu U^T_{\text{TBM}} \\
&+ U_{\text{TBM}} (M_\nu)_{\text{TBM}} \delta U^T
\end{aligned}$$

Predictions

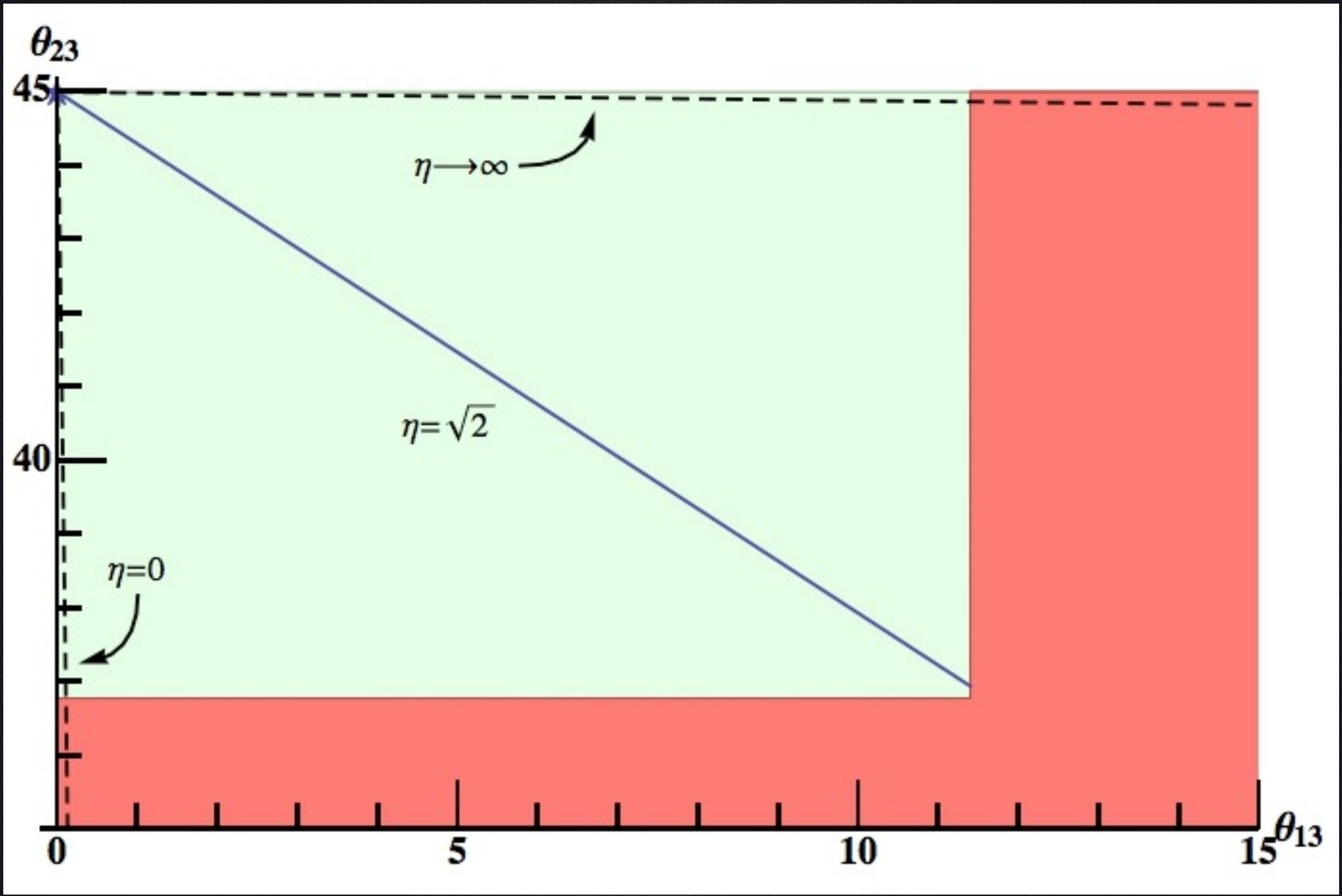
- Yields correlation between Atmospheric and Reactor Mixing Angles
- While noting the trivial case restores TBM values, use of Cabibbo Angle input forces symmetry breaking

Predictions

$$\theta_{13} = \sqrt{2}(\frac{\pi}{4} - \theta_{23})$$

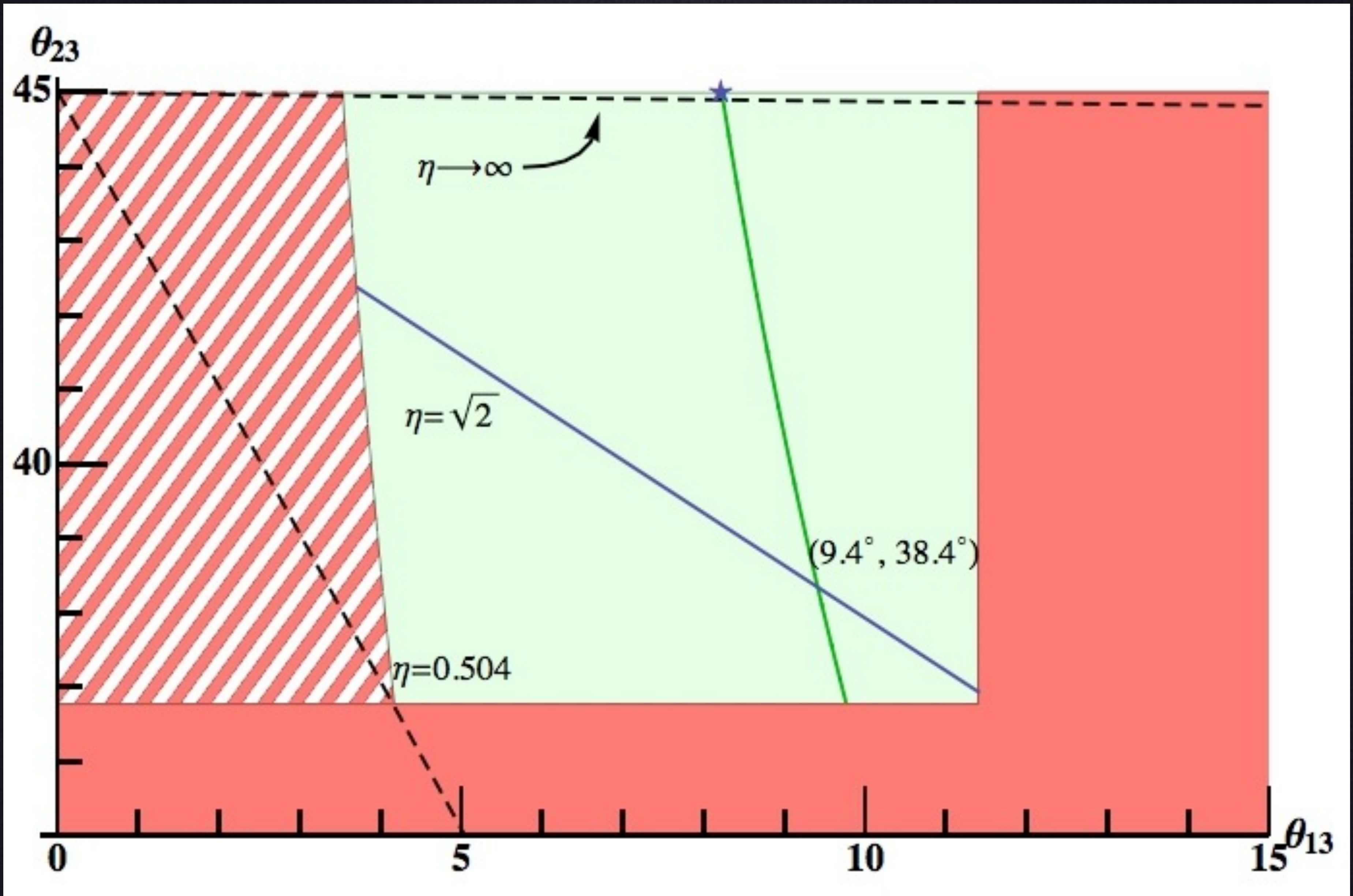
- Yields correlation between Atmospheric and Reactor Mixing Angles
- While noting the trivial case restores TBM values, use of Cabibbo Angle input forces symmetry breaking

$$\theta_{23} = -\frac{1}{\eta}\theta_{13} + \frac{\pi}{4}$$



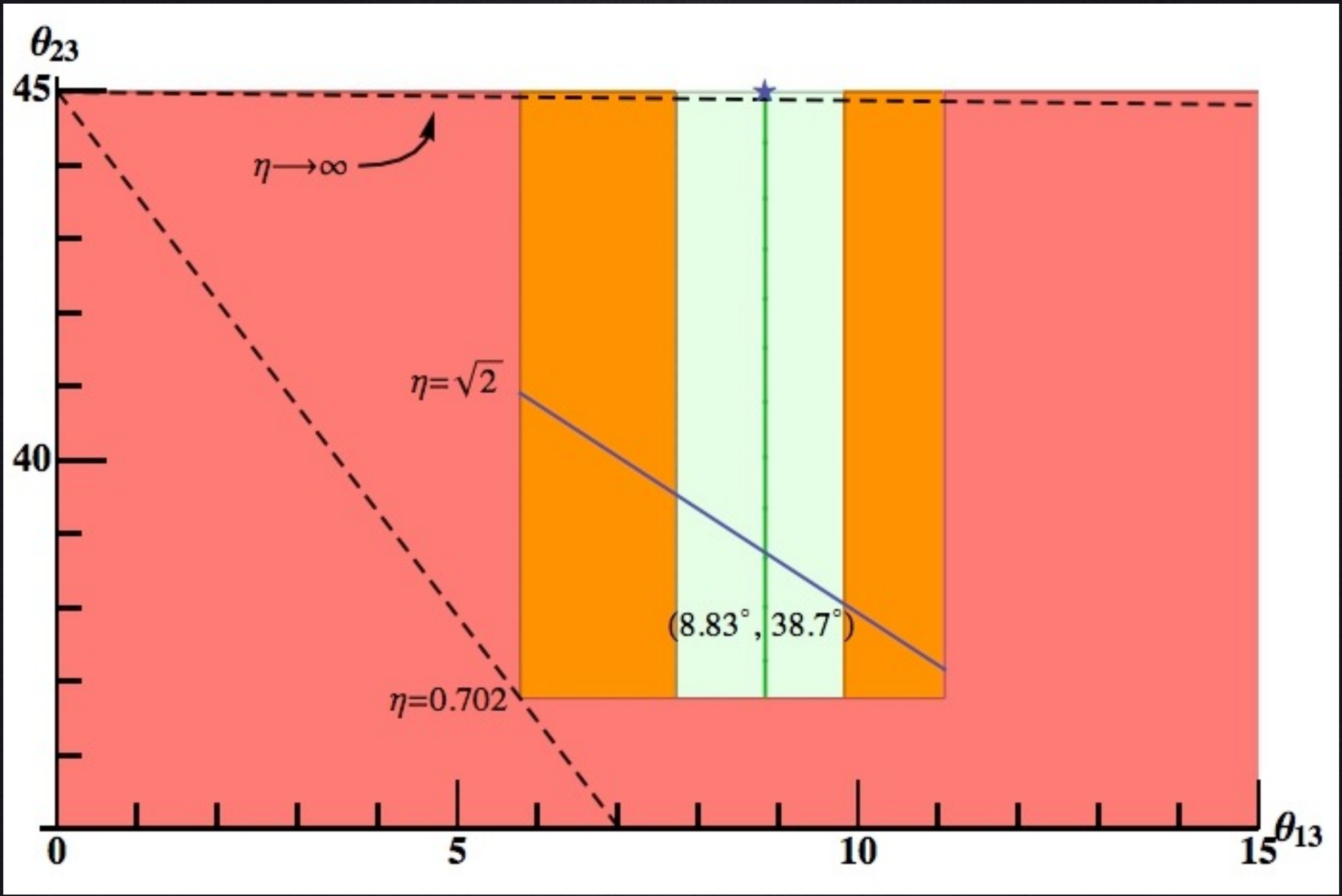
Particle Data Group 2010 Review

$$\theta_{23} = -\frac{1}{\eta}\theta_{13} + \frac{\pi}{4}$$



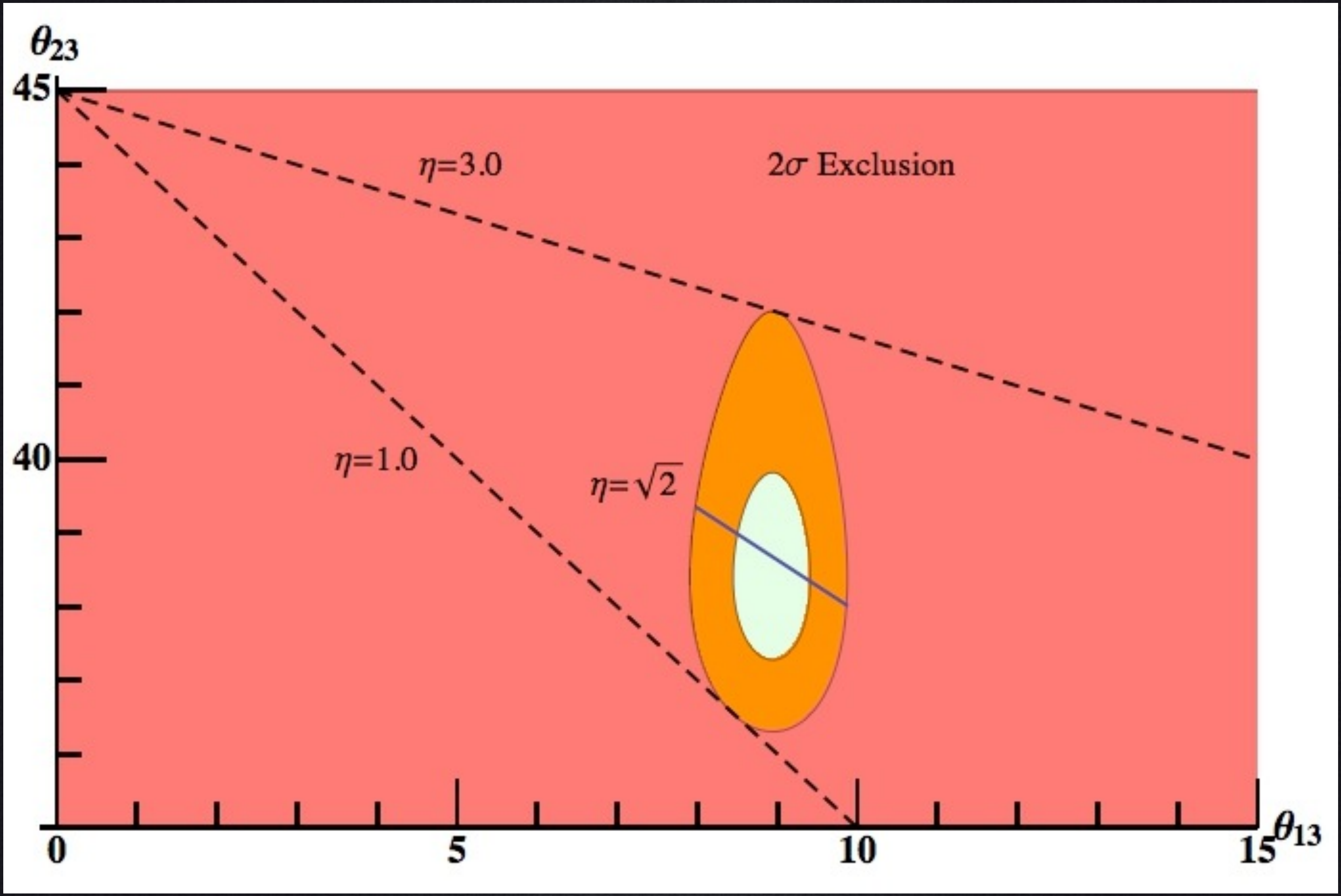
$$2\sin^2\theta_{23}\sin^2 2\theta_{13} = 0.080 \text{ (DC, T2K, MINOS)}$$

$$\theta_{23} = -\frac{1}{\eta}\theta_{13} + \frac{\pi}{4}$$



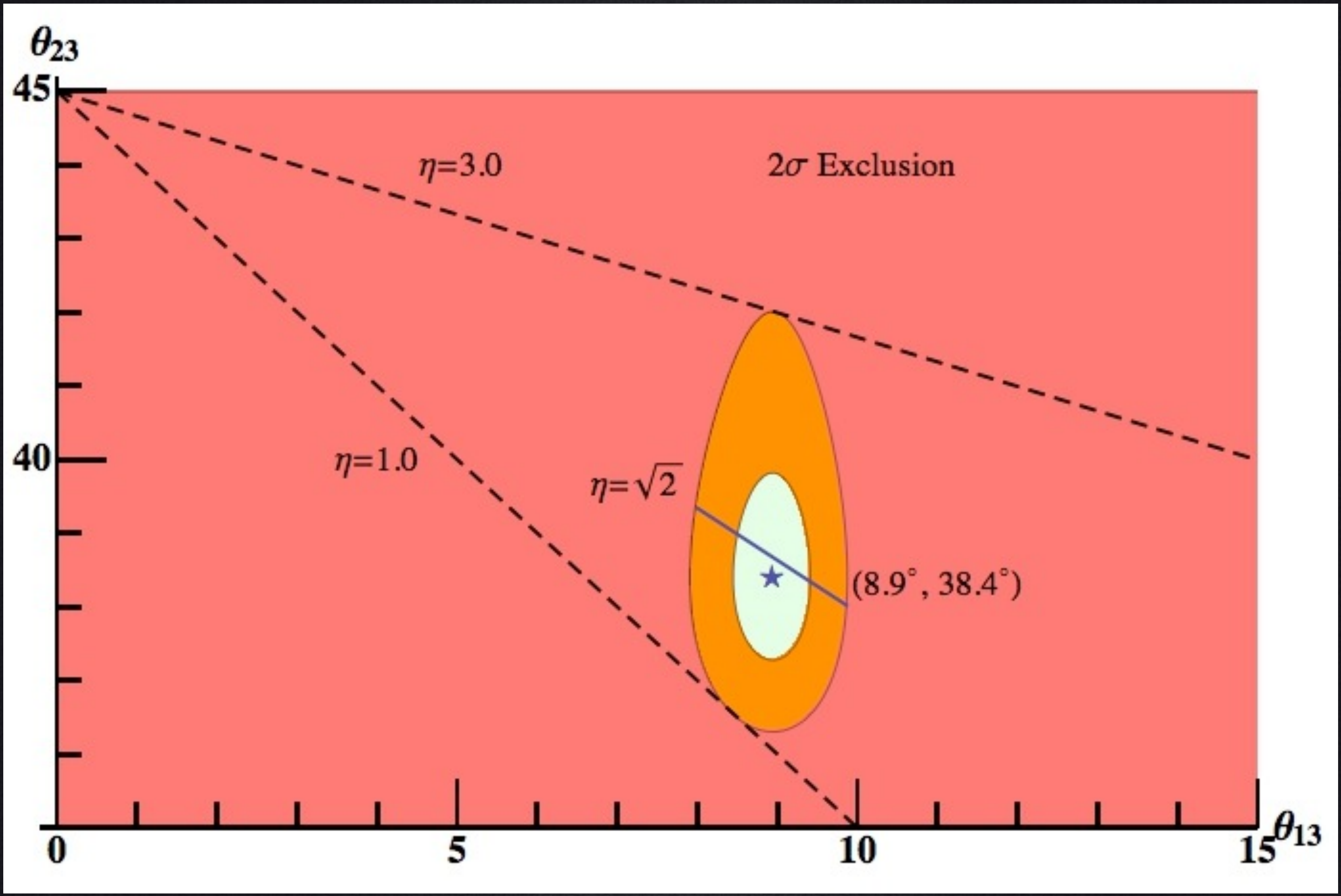
Daya Bay Early Results

$$\theta_{23} = -\frac{1}{\eta}\theta_{13} + \frac{\pi}{4}$$



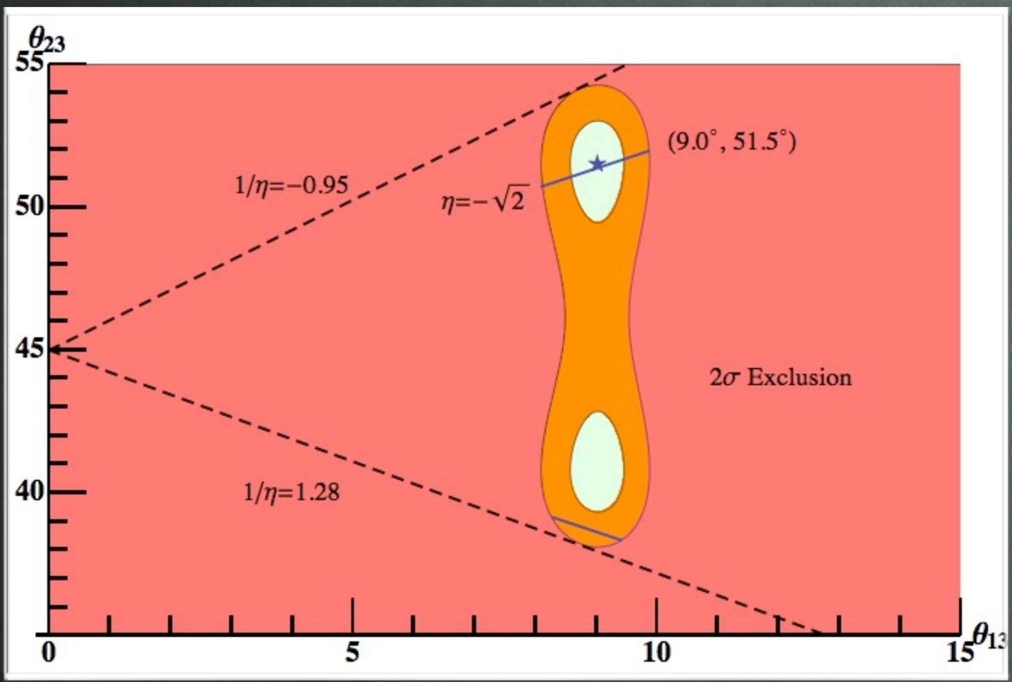
Fogli Global Results

$$\theta_{23} = -\frac{1}{\eta}\theta_{13} + \frac{\pi}{4}$$



Fogli Global Results (w/ Best Fit)

T´ is blind to Octant Degeneracy



$$\theta_{23} = -|\frac{1}{\eta}|\theta_{13} + \frac{\pi}{4}$$

- Different Global Analysis by Forero et al.
- Due to redefinition of angles, model prediction is only for correlation magnitude
- Though this analysis indicates lower angle precision, best fit value agrees within 2.5%

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Choices, Choices

- Need a Higgs doublet to add third family quark mixing
- Several options for the NMRT´M
- Many new variables limit new predictions
- Added complexity aside, this remains an intriguing avenue of investigation

A	$H_{2_1}(2_1, +1)$	$Y_{Qt} Q_{\mathrm{L}} t_{\mathrm{R}} H_{2_1}$
B	$H'_{2_3}(2_3, -1)$	$Y_{Qb} Q_{\mathrm{L}} b_{\mathrm{R}} H'_{2_3}$
C	$H'_{2_2}(2_2, -1)$	$Y_{\mathcal{QC}} \mathcal{Q}_{\mathrm{L}} \mathcal{C}_{\mathrm{R}} H'_{2_2}$
D	$H_{2_3}(2_3, +1)$	$Y_{\mathcal{QS}} \mathcal{Q}_{\mathrm{L}} \mathcal{S}_{\mathrm{R}} H_{2_3}$

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$$\begin{array}{lll}
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\mathbf{B} & H'_{2_3}(2_3,-1) & Y_{Qb}Q_{\mathrm{L}}b_{\mathrm{R}}H'_{2_3} \\
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\end{array}$$

$$\mathcal{D} = \begin{pmatrix} 3 & -\frac{\sqrt{2}}{3} \\ -\frac{\sqrt{2}}{3} & 1 \end{pmatrix}$$

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\end{array}
$$

$$
\mathcal{D} = \begin{pmatrix} 3 & -\frac{\sqrt{2}}{3} \\ -\frac{\sqrt{2}}{3} & 1 \end{pmatrix}
$$

$$
\mathcal{D} = \begin{pmatrix}
(Y'_b V'_{1_3})^2 + (Y'_{\mathcal{QS}}V'_{2_3})^2 & \frac{1}{\sqrt{6}}Y'_{\mathcal{QS}}V'_{2_3}(1-2\sqrt{2}\omega) & \frac{1}{\sqrt{6}}Y'_{\mathcal{QS}}V'_{2_3}(\omega+\sqrt{2}) \\
\frac{1}{\sqrt{6}}Y'_{\mathcal{QS}}V'_{2_3}(1-2\sqrt{2}\omega^2) & 3 & -\frac{\sqrt{2}}{3} \\
\frac{1}{\sqrt{6}}Y'_{\mathcal{QS}}V'_{2_3}(\omega^2+\sqrt{2}) & -\frac{\sqrt{2}}{3} & 1
\end{pmatrix}
$$

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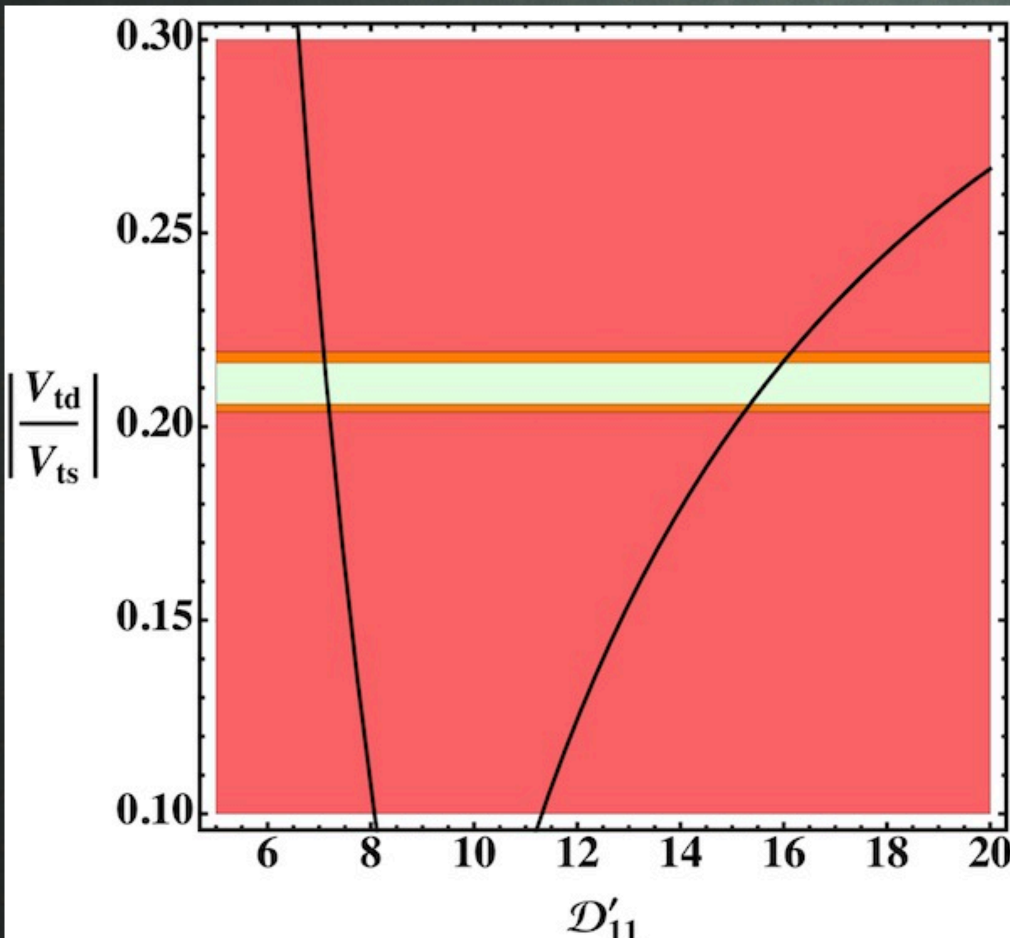
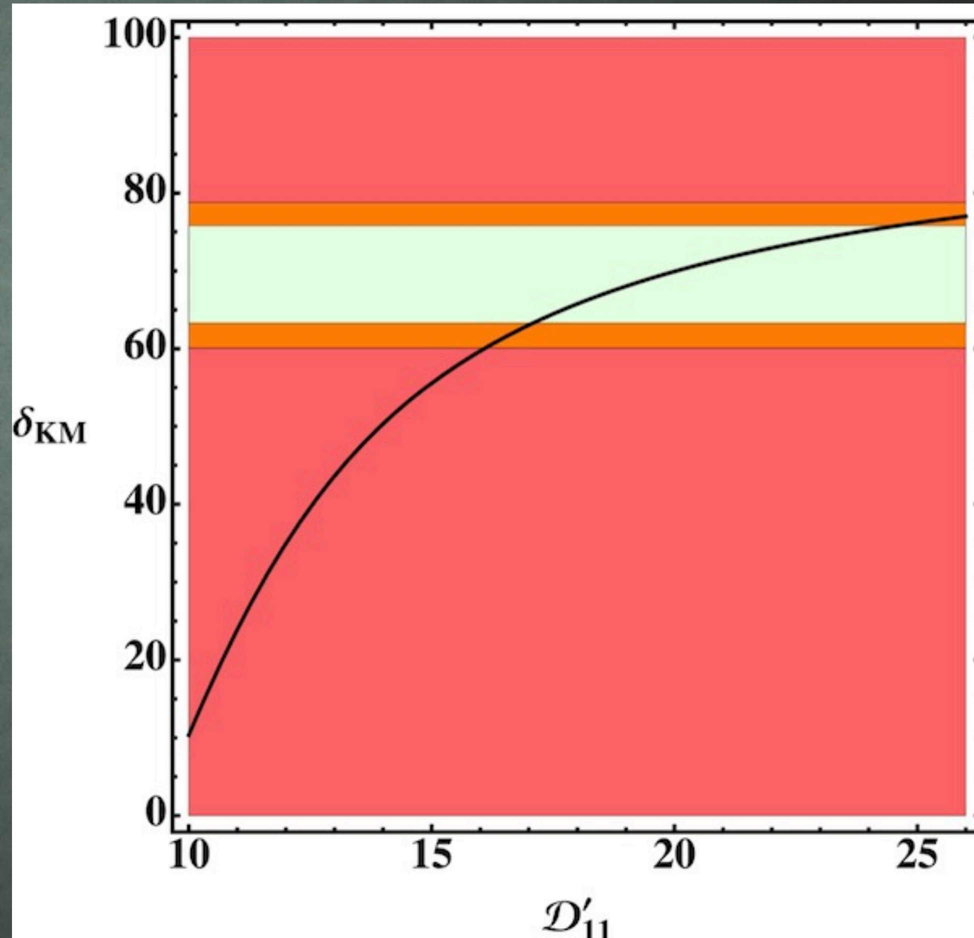
$$\mathcal{D} = \begin{pmatrix} 3 & -\frac{\sqrt{2}}{3} \\ -\frac{\sqrt{2}}{3} & 1 \end{pmatrix}$$

$$\mathcal{D} = \begin{pmatrix} (Y_b'V_{1_3}')^2 + (Y_{\mathcal{QS}}'V_{2_3}')^2 & \frac{1}{\sqrt{6}}Y_{\mathcal{QS}}'V_{2_3}'(1-2\sqrt{2}\omega) & \frac{1}{\sqrt{6}}Y_{\mathcal{QS}}'V_{2_3}'(\omega+\sqrt{2}) \\ \frac{1}{\sqrt{6}}Y_{\mathcal{QS}}'V_{2_3}'(1-2\sqrt{2}\omega^2) & 3 & -\frac{\sqrt{2}}{3} \\ \frac{1}{\sqrt{6}}Y_{\mathcal{QS}}'V_{2_3}'(\omega^2+\sqrt{2}) & -\frac{\sqrt{2}}{3} & 1 \end{pmatrix}$$

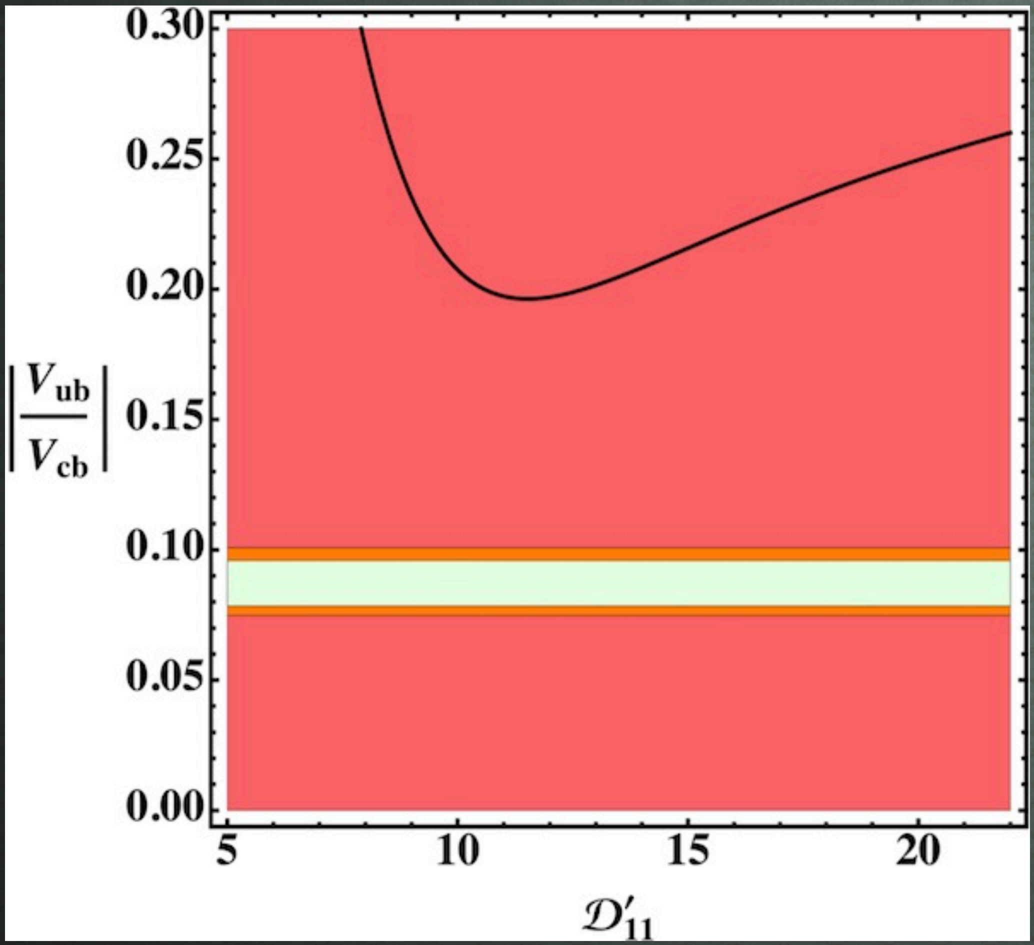
CKM Fits I

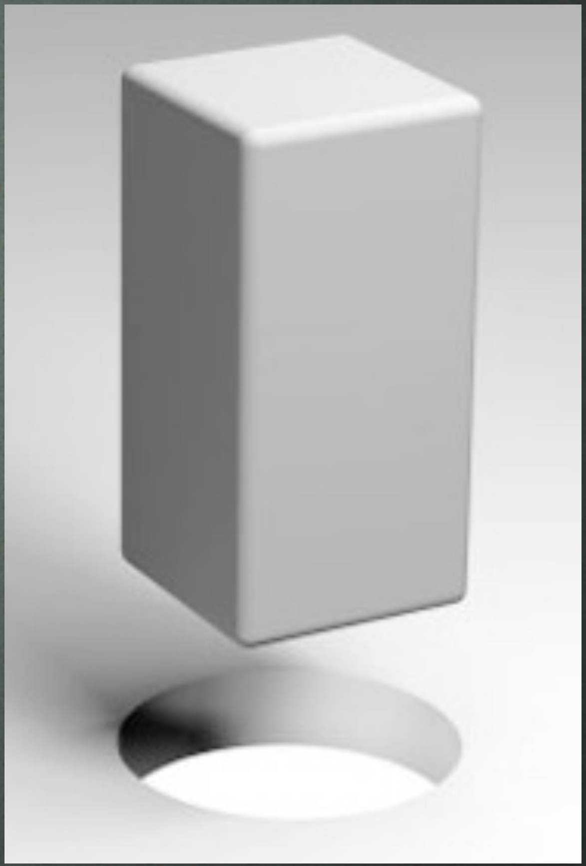




$$\mathcal{D}_{11}^{'} = 3[(Y_b V_{1_3})^2 + (Y_{Q\mathcal{S}} V_{2_3})^2]/(Y_{\mathcal{S}} V_3)^2$$

CKM Fits II





$$\mathcal{D}_{11}^{'} = 3[(Y_b V_{1_3})^2 + (Y_{\mathcal{QS}} V_{2_3})^2]/(Y_{\mathcal{S}} V_3)^2$$

Quartification

- Toy Quiver Model
- Combines T´ and SM groups
- A non-specific test of compatibility
- Demands an additional sub-quiver representation

$$\mathbf{SU(3)}_{\mathrm{C}} \times \mathbf{SU(3)}_{\mathrm{L}} \times \mathbf{SU(3)}_{\ell} \times \mathbf{SU(3)}_{\mathrm{R}}$$

$$(3\bar{3}11)_3 \supset \begin{pmatrix} t \\ b \end{pmatrix}_{\mathrm{L}} \quad \mathcal{Q}_{\mathrm{L}} \qquad (\mathbf{1_1}, +1)$$

$$\left.\begin{aligned} (3\bar{3}11)_2 &\supset \begin{pmatrix} c \\ s \end{pmatrix}_{\mathrm{L}} \\ (3\bar{3}11)_1 &\supset \begin{pmatrix} u \\ d \end{pmatrix}_{\mathrm{L}} \end{aligned}\right\} Q_{\mathrm{L}} \qquad (\mathbf{2_1}, +1)$$

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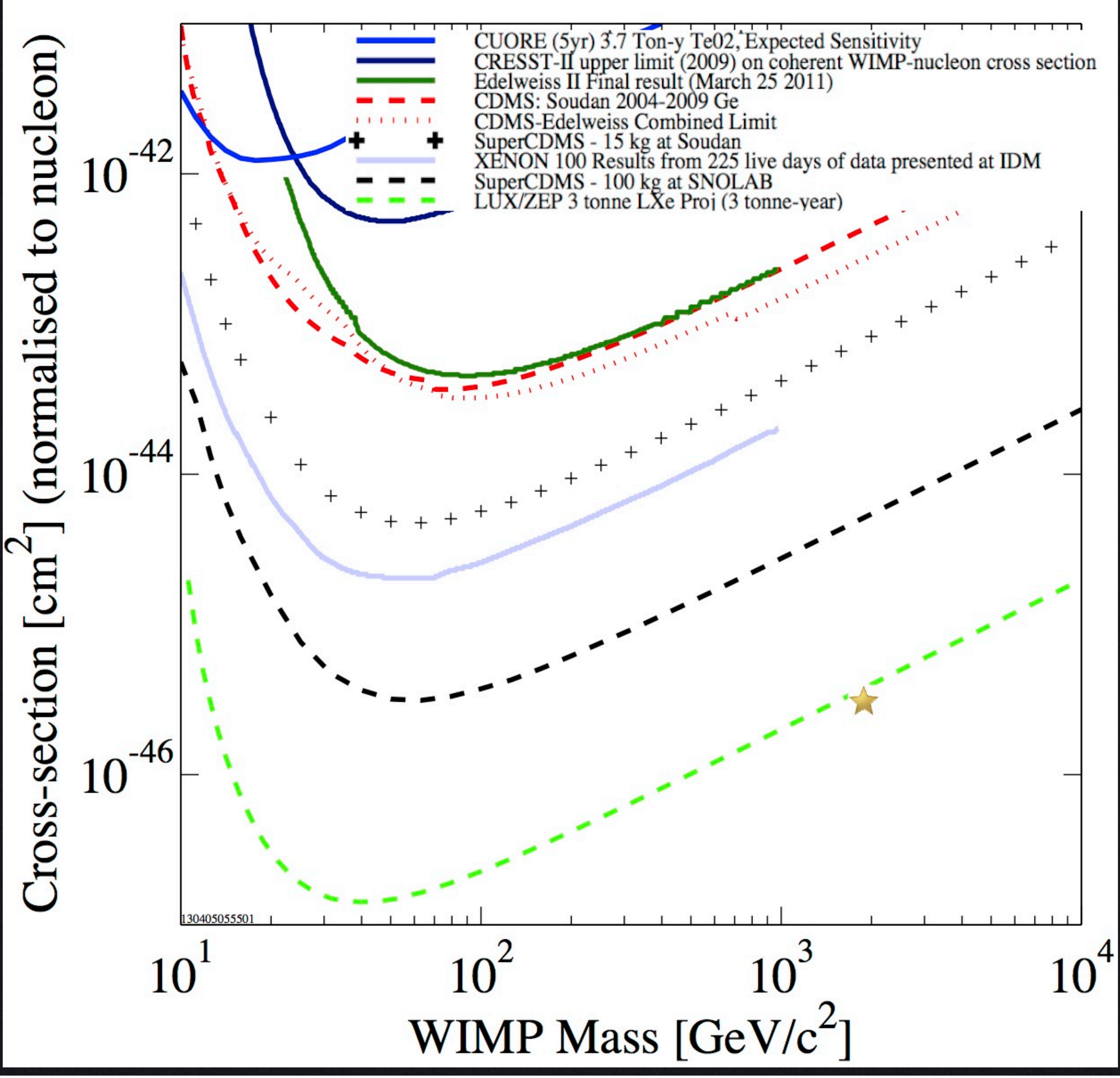
DM & Leptogenesis

- Meanwhile in Valencia...
- New Symmetry, New RH Neutrinos, New Higgs, New Model
- Dark Matter generated from the neutral real scalar parts of Higgs triplet
- New Lagrangian Terms
- If Y_4 and Y_5 are complex, they can yield Leptogenesis
- Relic Density leads to approximate WIMP mass of ≈1.62 TeV

$$\begin{aligned}\mathcal{L}_Y = M_0 N_T N_T + M_1 N_R^{(1)} N_R^{(1)} + M_{23} N_R^{(2)} N_R^{(3)} + \\ Y_e L_L e_R H_3^{'} + Y_\mu L_L \mu_R H_3^{'} + Y_\tau L_L \tau_R H_3^{'} + \\ Y_1 L_L N_R^{(1)} H_3 + Y_2 L_L N_R^{(2)} H_3 + Y_3 L_L N_R^{(3)} H_3 + \\ Y_4 L_L (N_T H_3^{''})_3 + Y_5 L_L (N_T H_3^{''})_{3'} + \\ Y_t (Q_L t_R H_{1_1}) + Y_b (Q_L b_R H_{1_3}) + \\ Y_C (Q_L C_R H_3^{'}) + Y_S (Q_L S_R H_3) + h.c.\end{aligned}$$


CUORE (5yr) 3.7 Ton-y Te02, Expected Sensitivity
CRESST-II upper limit (2009) on coherent WIMP-nucleon cross section
Edelweiss II Final result (March 25 2011)
CDMS: Soudan 2004-2009 Ge
CDMS-Edelweiss Combined Limit
SuperCDMS - 15 kg at Soudan
XENON 100 Results from 225 live days of data presented at IDM
SuperCDMS - 100 kg at SNOLAB
LUX/ZEP 3 tonne LXe Proj (3 tonne-year)
Cross-section [cm^2] (normalised to nucleon)
10^{-42}
10^{-44}
10^{-46}
130405055501
10^1
10^2
10^3
10^4
WIMP Mass [GeV/c^2]

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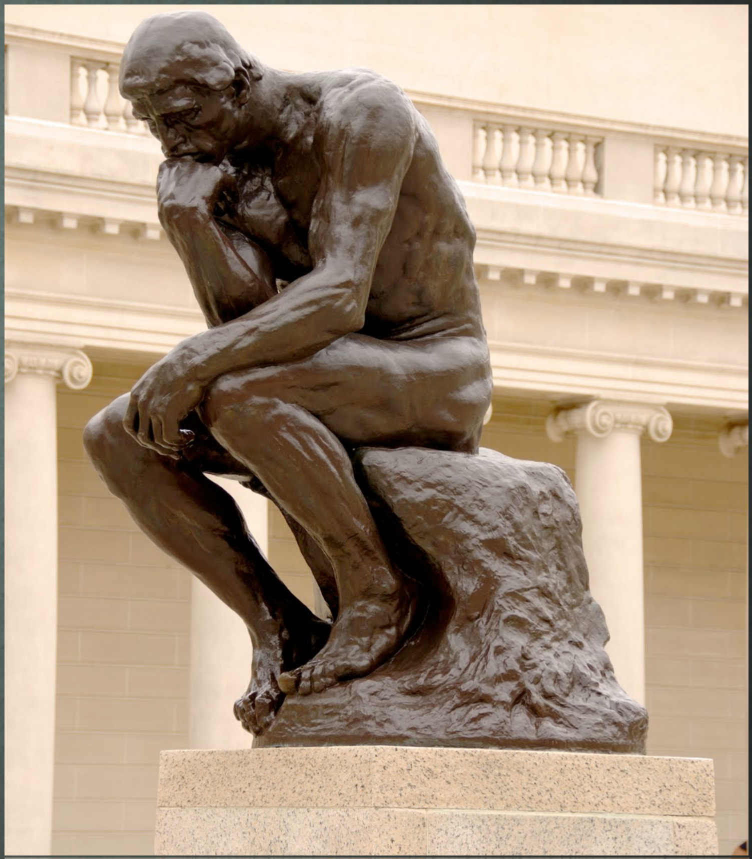
Limitations and Unanswered Questions

- Hopes for Future Work:
  - Higher-Order Calc. w/o Fine-Tuning
  - Combining with SUSY or other GUTs
- Leptogenesis:
  - CP-Violating Phase - Practical Limitation
  - Evaluating potential in T´ WIMP Model
- Structural Limitations:
  - Solar Mass Split - Symmetry Limitation
  - NMRT´M with all CKM Angles



Conclusions

- We unify TBM breaking with precise CKM angles
- Successful Predictions:
  - TBM Symmetry is broken
  - Global fits indicate η lies within 5% of our expectation
- Intriguing Dark Matter Candidate with interesting behavior
- We need more data to understand neutrinos (don't we always?)
- Between new detectors , new results, and new theories this remains an exciting time in neutrino physics

Thank you for coming!

Questions?