The Neutrino Flavour Puzzle in the Light of “Large” θ_{13}^{PMNS}

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The last year has been an exciting time for models of neutrino masses and mixings …

$$\theta_{13}^{PMNS} \approx 9° \pm 1°$$

Daya Bay Collaboration, arXiv:1203.1669

T2K, Minos, Double CHOOZ, Daya Bay, RENO

Finally, out of the many models …

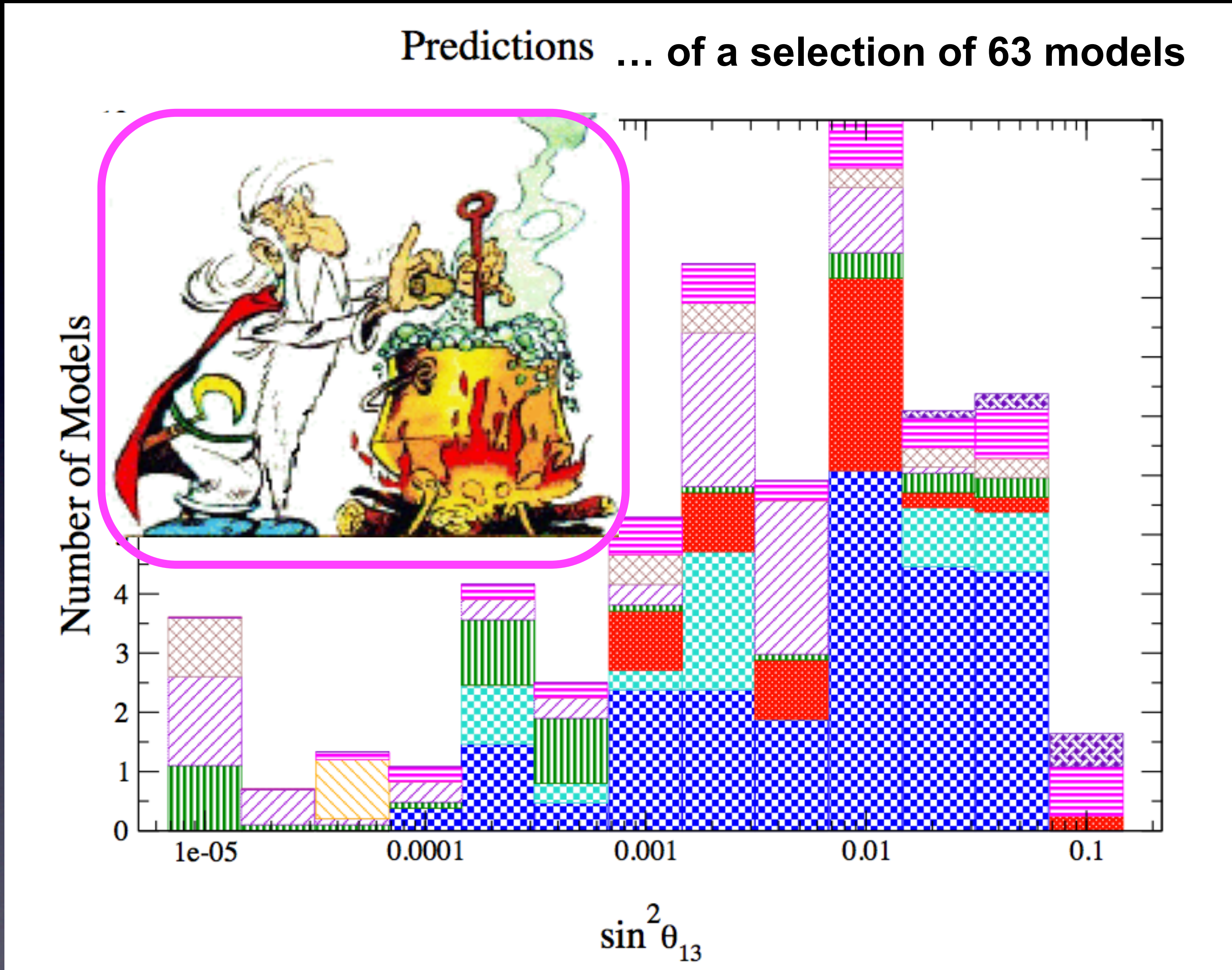


Figure shows only a small subset
of the existing models … !

based on figure from Albright, Mu-Chun Chen ('06)

… a large fraction has been excluded!

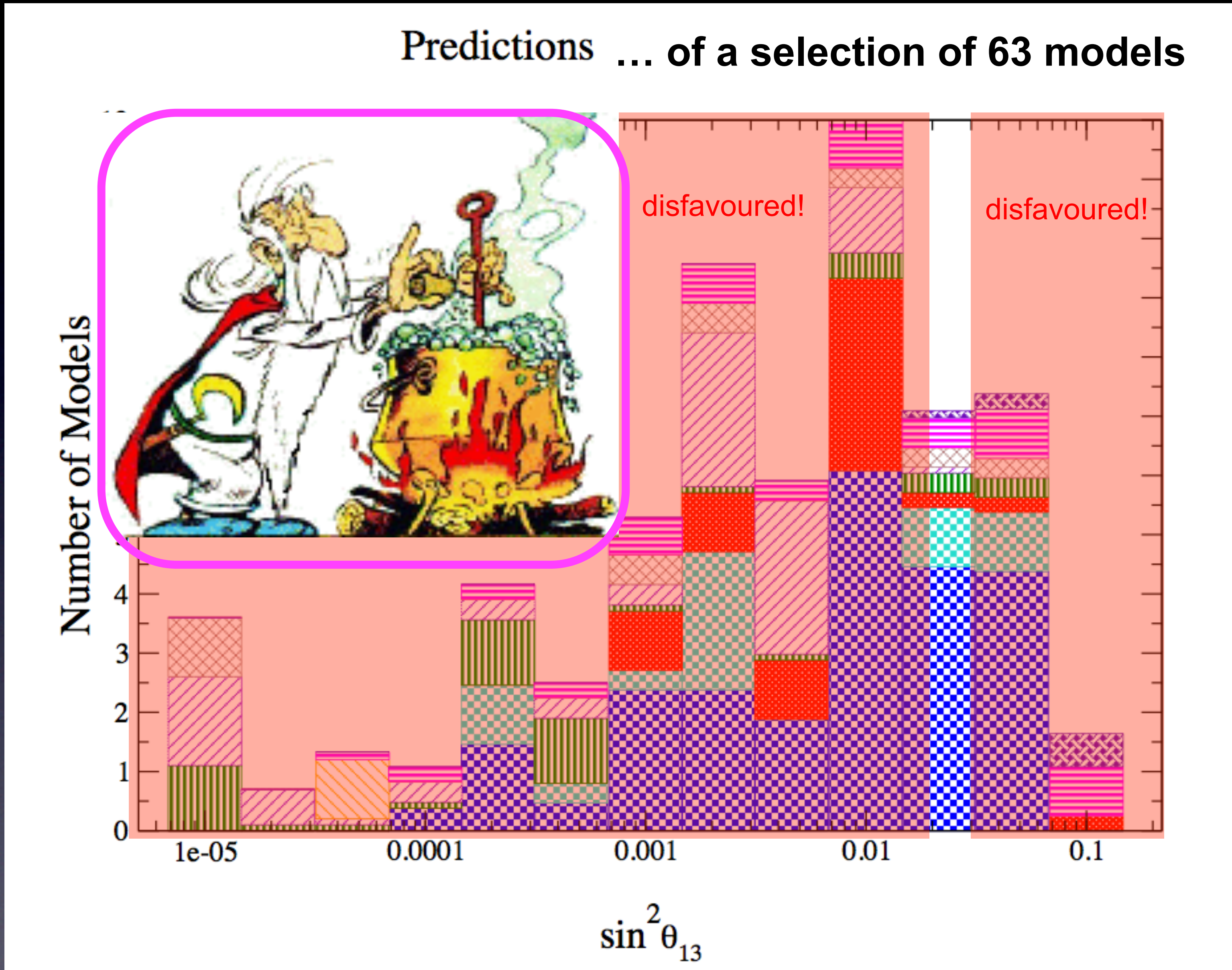


Figure shows only a small subset of the existing models … !

based on figure from Albright, Mu-Chun Chen ('06)

Many new ideas and studies were inspired by the recent θ_{13}-measurements …

Many works by various authors, e.g.:

A. Adulpravitchai, Y. H. Ahn, C. H. Albright, G. Altarelli, A. Aranda, T. Araki, F. Bazzocchi, W. Buchmuller, P. S. Bhupal Dev, G. C. Branco, Q.-H. Cao, H.-Y. Cheng, I. K. Cooper, S. Dev, G. Blankenburg, C. Bonilla, F. Gonzalez Canales, W. Chao, J.-M. Chen, M.-C. Chen, X. Chu, A. Datta, K. N. Deepthi, M. Dhen, D. A. Dicus, G.-J. Ding, P. V. Dong, V. Domcke, L. Dorame, B. Dutta, D. A. Eby, L. Everett, R. P. Feger, F. Feruglio, P. Ferreira, P. H. Frampton, M. Fukugita, R. R. Gautam, S. -F. Ge, D. K. Ghosh, R. Gonzalez Felipe, S. Gollu, S. Gupta, W. Grimus,C. Gross, N. Haba, C. Hagedorn, T. Hambye, J. E. Kim, Y. Koide, K. Hashimoto, K. Harigaya, H. -J. He, X. -G. He, J. Heek, D. Hernandez, M. Holthausen, R. S. Hundi, M. Ibe, H. Ishimori, F. R. Joaquim, A. S. Joshipura, S. K. Kang, T. W. Kephart, S. Khalil, S. F. King, T. Kobayashi, S. Kumar, L. Lavoura, X.-Q. Li, H. N. Long, P. O. Ludl, C. Luhn, B. Q. Ma, E. Ma, S. K. Majee, K.T. Mahanthappa, D. Marzocca, V. Maurer, D. Meloni, A. Merle, A. Meroni, R. Mohanta, R. N. Mohapatra, E. Molinaro, A. Mondragon, M. Mondragon, S. Morisi, C. H. Nam, H. Nishiura, S. Oh, H. Okada, K. M. Patel, K. M. Parattu, E. Peinado, S. T. Petcov, N. Qin, A. Rashed, W. W. Repko, A. D. Rojas, W. Rodejohann, A. Romanino, G. G. Ross, S. Rigolin, M. A. Schmidt, K. Schmitz, M. Severson, M.-S. Seo, H. Serodio, Y. Shimizu, J. I. Silva-Marcos, L. Singh, K. Siyeon, C. Sluka, A. Yu. Smirnov, M. Spinrath, E. Stamou, A. J. Stuart, R. Takahashi, M. Tanimoto, R. d. A. Toorop, J. W. F. Valle, I. d. M. Varzielas, V. V. Vien, B. Wang, Q. Wang, A. Watanabe, D. Wegman, A. Wingerter, Yue-Liang Wu, Z. -Z. Xing, T. T. Yanagida, W.-M. Yang, B. Zaldívar, F. -R. Yin, A. Zee, H. Zhang, Y. -j. Zheng, J.-J. Zhong, S. Zhou, R. Zwicky, …

sorry for incompleteness!

Many unknowns remain ...

- What are the values of the Dirac CP phase δ^{PMNS}
- Is the mass scheme “normal” or “inverse”, i.e., what is $sgn(\Delta m_{31}^2)$?
- What is the deviation of θ_{23}^{PMNS} from maximal (i.e. from 45°)
- What is the absolute neutrino mass scale?
- Are neutrino masses of Dirac- or Majorana-type?
- If they are Majorana-type, what are the values of the Majorana phases?

Great for theorists! It means we can still make predictions ... !

Two main "neutrino puzzles"

Neutrino masses:
Why so small?
How to extend the SM?

Lepton mixing:
Why so large (compared to the quark mixings)?

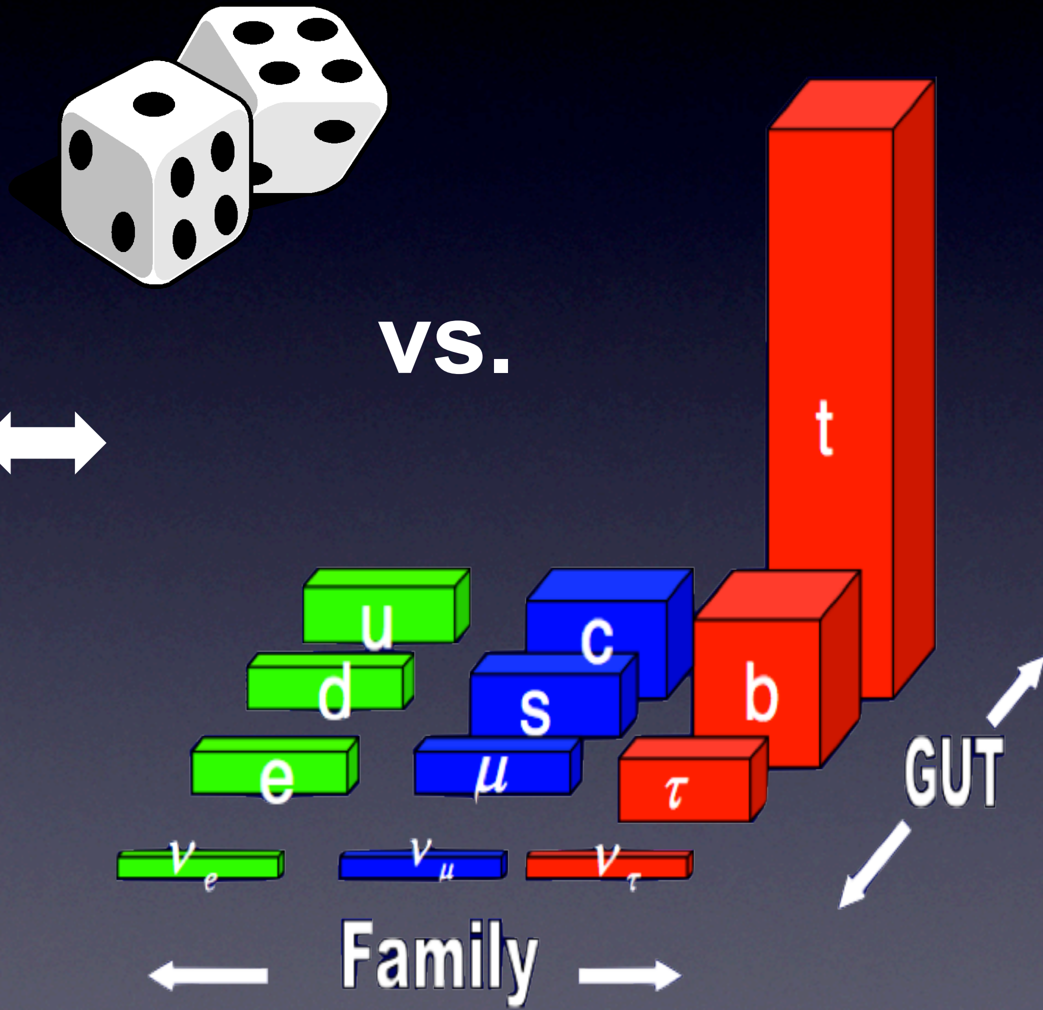
Main question for this talk:

What can we learn from the experimental results about the about the origin of the flavour structure?

Ideas and approaches ...

Various top-down possibilities:

- Random - Anarchical?
  Hall, Murayama, Weiner ('99), …
- Family symmetries?
  Froggatt, Nielsen ('79); … Ma, Rajasekaran, Babu, Valle, King, Ross, Altarelli, Feruglio, …
- Grand Unified Theories (GUTs)?
  Georgi, Glashow ('74), Fritzsch, Minkowski ('75), … Mohapatra, Senjanovic, Pati, Salam, Raby, Bajc, Aulakh, Vissani, …
- Extra dimensions, string theory, …
  Arkani-Hamed, Dimopoulos, Dvali ('98), Dienes, Dudas, Ghergetta, March-Russel, Volkas, …



Bottom-up suggestions ...

Tri-Bimaximal mixing:

$$\theta_{12}^{\rm PMNS} = \arcsin\left(\frac{1}{\sqrt{3}}\right) \approx 35.3^\circ$$

$$\theta_{13}^{\rm PMNS} = 0$$

$$\theta_{23}^{\rm PMNS} = 45^\circ$$

Bimaximal mixing:

$$\theta_{12}^{\rm PMNS} = 45^\circ$$

$$\theta_{13}^{\rm PMNS} = 0$$

$$\theta_{23}^{\rm PMNS} = 45^\circ$$

… but may be useful as leading order structures!?

Observations and suggestions:

- Tri-bimaximal (TB) mixing?
  Harrison, Perkins, Scott ('02)
- Bimaximal mixing? Vissani ('97)
  Barger, Pakvasa, Weiler, Whisnant ('98)
- Quark lepton complementarity (QLC): $\theta_{12}^{\rm PMNS} + \theta_C = 45°$?
  Smirnov ('04); Raidal ('04), Minakata, Smirnov ('04)
- $\theta_{13}^{\rm PMNS} = \theta_C / \sqrt{2}$?
- ...

Top-down vs. bottom-up …

Various top-down possibilities:

- Random - Anarchical?
- Family symmetries?
- Grand Unified Theories (GUTs)?
- Extra dimensions
- String theory, …
- …

⟺

Observations and suggestions:

- Tri-bimaximal (TB) mixing?
- Bimaximal mixing?
- Quark lepton complementarity (QLC): $\theta_{12}^{PMNS} + \theta_C = 45°$?
- $\theta_{13}^{PMNS} = \theta_C / \sqrt{2}$?
- ...

Various ideas and new developments have emerged … and I can only discuss a small selection of them in my talk …

One aspect which got a lot of attention:

Neutrino mixing patterns ↔ Family symmetries …

Most prominent example: Tri-bimaximal mixing ↔ A_4, S_4, …

Tri-bimaximal mixing

Harrison, Perkins, Scott ('02)

$\theta_{13} = 0°$

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

$\theta_{12} = 35.3°$

$\theta_{23} = 45°$

- Remark: No conserved symmetry can enforce TB mixing!

Simple argument: Large mixing is **no** fixed point of the RG evolution

RGEs for the leptonic mixing angles (in LO in θ_{13}; in the MSSM):

$$\dot\theta_{12} \approx -\frac{y_\tau^2}{32\pi^2}\sin 2\theta_{12}\, s_{23}^2 \frac{|m_1\, e^{i\varphi_1} + m_2\, e^{i\varphi_2}|^2}{\Delta m^2_{\mathrm{sol}}} + \mathscr{O}(\theta_{13})$$

$$\dot\theta_{13} \approx \frac{y_\tau^2}{32\pi^2}\sin 2\theta_{12}\sin 2\theta_{23}\frac{m_3}{\Delta m^2_{\mathrm{atm}}}\left[m_1\cos(\varphi_1-\delta) - m_2\cos(\varphi_2-\delta)\right] + \mathscr{O}(\theta_{13})$$

$$\dot\theta_{23} \approx -\frac{y_\tau^2}{32\pi^2}\sin 2\theta_{23}\frac{1}{\Delta m^2_{\mathrm{atm}}}\left[c_{12}^2\,|m_2\, e^{i\varphi_2} + m_3|^2 + s_{12}^2\,|m_1\, e^{i\varphi_1} + m_3|^2\right] + \mathscr{O}(\theta_{13})$$

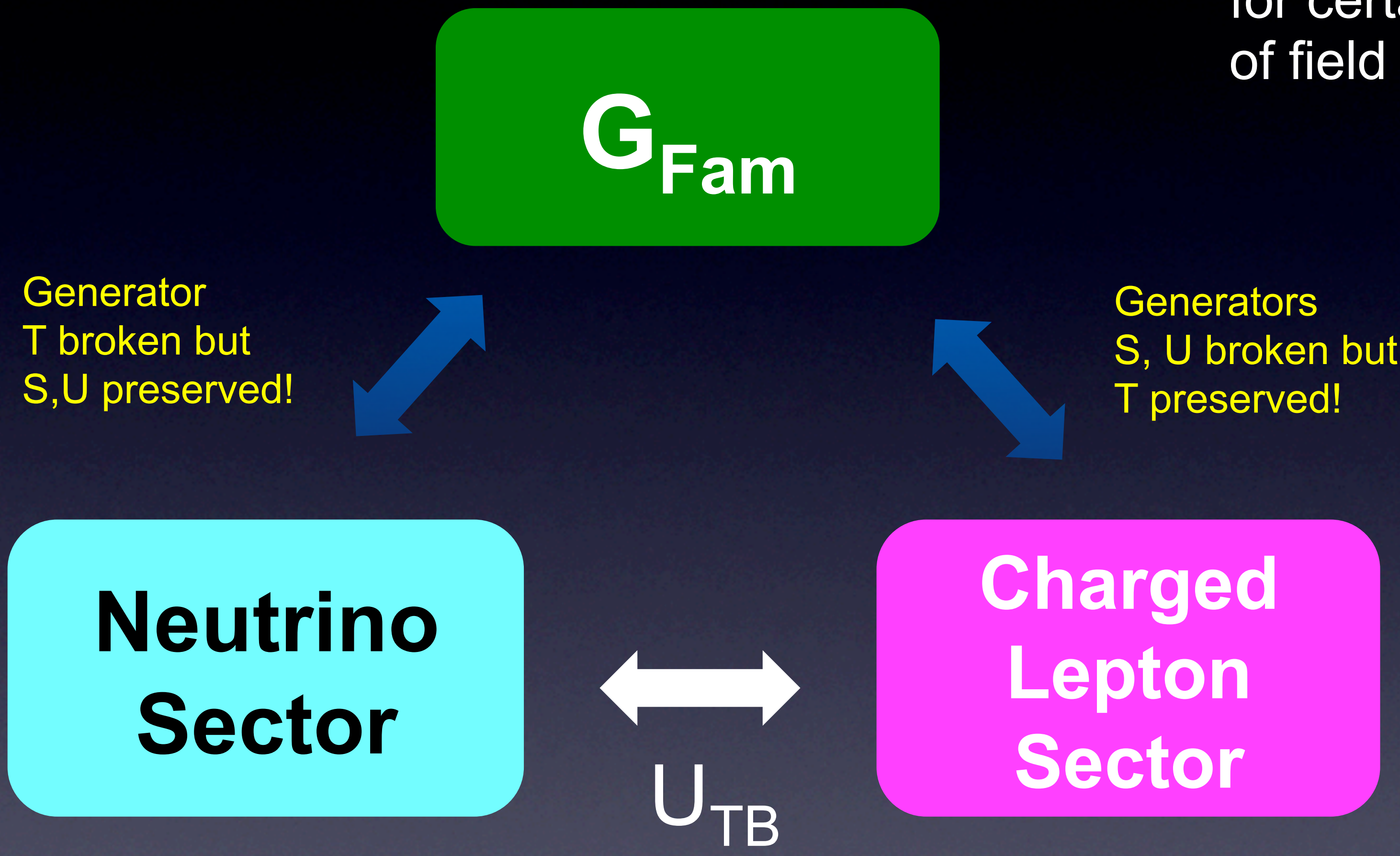
See e.g.: S.A., Kersten, Lindner, Ratz ('03)

(RGEs in the SM: above equations times -3/2)

I) “Direct” models:

Identify remnant symmetries!
G_{Fam} generated by S,T and U
$\rightarrow S_4$ family symmetry

A_4 possible as well for certain selection of field reps



Altarelli, Feruglio, Ma, Hagedorn, Merlo, Luhn ...

S_4 preferred: Lam

‘Direct’ vs. ‘indirect’ models:
King, Luhn (‘09)

II) “Indirect” models:

Dynamical fields = Flavons
~ A, B, C in 3 of G_{Fam} generate the flavour structure in the neutrino sector

$$C \sim \begin{pmatrix} 2 \\ -1 \\ 1 \end{pmatrix} \quad B \sim \begin{pmatrix} 1 \\ 1 \\ -1 \end{pmatrix} \quad A \sim \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix}$$

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

In seesaw:
Form Dominance
King, Chen (’09)

In string theory context:
S.A., Ibanez, Macri (‘07)

G_{Fam} typically broken completely in m_ν
$\longrightarrow$ flavour breaking directions are crucial!

King, Ross, de Medeiros Varzielas, Malinsky, Chen, Mahanthappa ...

Both approaches point to non-Abelian (discrete) family symmetries G_{Fam}!

Various models have been constructed by many authors …

TB mixing confronted with $\theta_{13}^{PMNS} = 9° \pm 1°$

- As already stated: The exact TB mixing pattern is ruled out by data. Two possible reactions are …

- Look for alternatives … such as for example
  - New flavour breaking directions (in "indirect" models), e.g. CSD2 S.A., King, Luhn, Spinrath ('11)
  - New discrete symmetries (leading to new "direct" models)

  See e.g.: de Adelhart Toorop, Feruglio, Hagedorn ('11)

- View TB mixing as LO pattern only. Consider subleading effects, e.g. ...
  - Small correction to flavour breaking directions ($A \propto (0,1,1) \rightarrow (\varepsilon,1,1)$) King, Luhn ('11)
  - Include charged lepton mixing effects (with TB mixing in the neutrino sector)

  See e.g.: King ('02), Frampton, Petcov, Rodejohann ('04), Altarelli, Feruglio, Masina ('04), S.A., King ('04), Ferrandis, Pakvasa ('04), Feruglio ('05), Datta, Everett, Ramond ('05), Mohapatra, Rodejohann ('05), S.A., King ('05), …

The latter of these possibilities receives some motivation from the perspective of GUT models, because:

In GUT models, non-zero θ_{13}^{PMNS} is generically expected via charged lepton mixing contributions ...

Let us therefore discuss this connection in a bit more detail:

θ_{13}^{PMNS} from charged lepton mixing effects ↔ Grand Unified Theories

M_u ⟷ M_d

$U_{CKM} = U^{u\dagger} U^d$

Let us consider ...

Specific mixing pattern in m_ν, e.g.:

m_ν ⟷ M_e

$U_{PMNS} = U^{e\dagger} U^\nu$

- Tri-bimaximal mixing: $U^\nu = U_{TB}$
- Bimaximal mixing: $U^\nu = U_{Bimax}$

} with $\theta_{13}^\nu \approx 0$

Hierarchical masses in M_u and M_d $\Rightarrow$ $\theta_{ij}^u << \theta_{ij}^d$ $\Rightarrow$ typically $\boldsymbol{\theta_{12}^d \cong \theta_C}$

and $\theta_{13}^d, \theta_{23}^d << \theta_C$

$M_u \longleftrightarrow M_d$

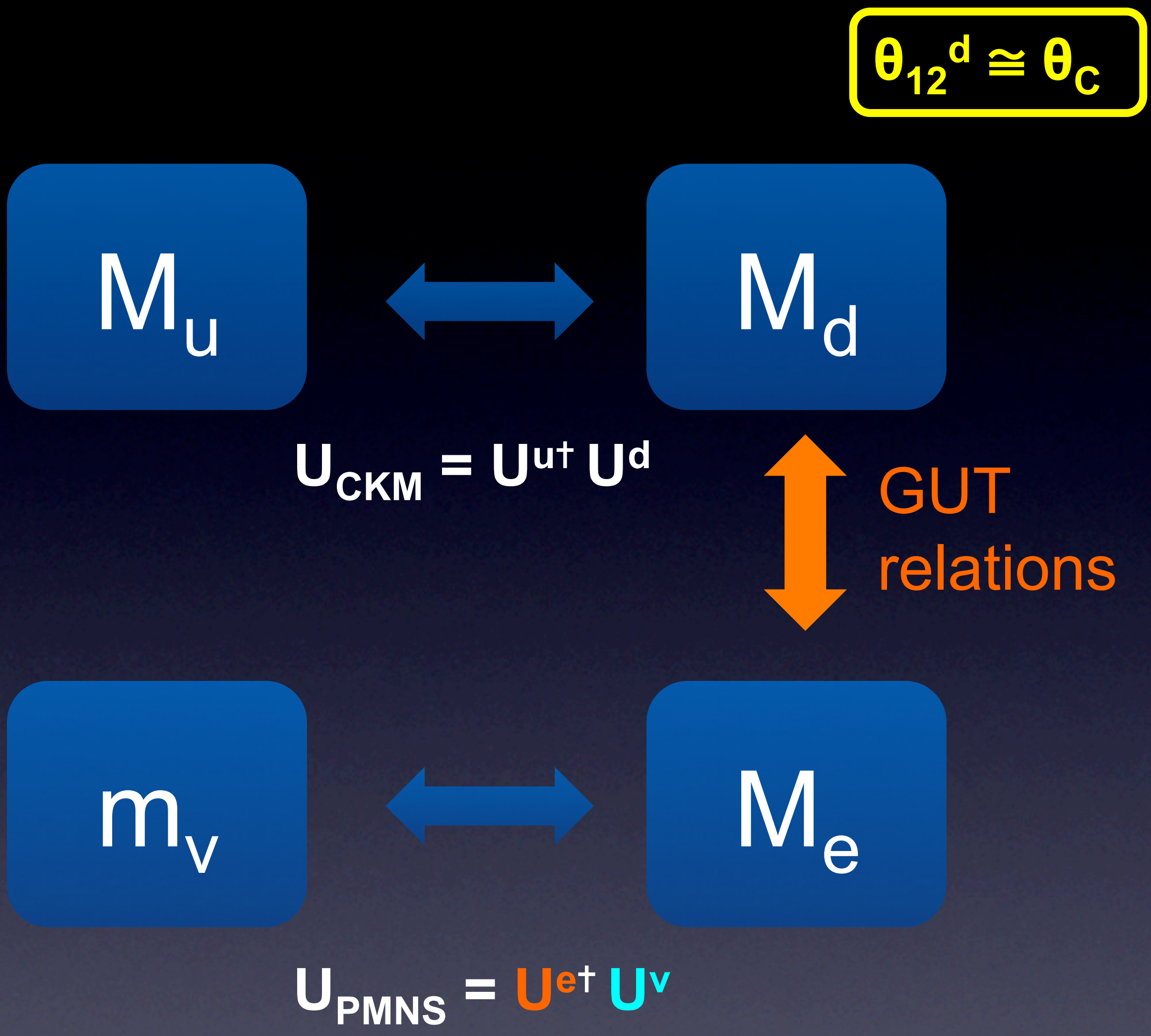
$U_{CKM} = U^{u\dagger} U^d$

Let us consider
U^ν with:

$\theta_{13}^\nu \approx 0$

$m_\nu \longleftrightarrow M_e$

$U_{PMNS} = U^{e\dagger} U^\nu$



Let us consider U^{ν} with:

$\theta_{13}^{\nu} \approx 0$

$\theta_{12}^d \cong \theta_C$

M_u ⟷ M_d

$U_{CKM} = U^{u\dagger} U^d$

Mass relations @ M_{GUT}, e.g.:

$$\frac{m_\tau}{m_b} = c_{33} = 1, \frac{3}{2}$$

GUT relations

$$\frac{m_\mu}{m_s} = c_{22} = 3, \frac{9}{2}, 6$$

Let us consider U^ν with:

$\theta_{13}^\nu \approx 0$

m_ν ⟷ M_e

(c_{ij}: group theory Clebsch factors)

$U_{PMNS} = U^{e\dagger} U^\nu$

Clebsch factors ∈ {1,3} in GUTs: Georgi, Jarlskog ('79)
New possible Clebsch factors ∈ {3/2,3,9/2,6,...}: S.A., Spinrath ('09)

$\theta_{12}^{d} \cong \theta_C$

M_u ⟷ M_d

$U_{CKM} = U^{u\dagger} U^{d}$

But also mixing angle relations @ M_{GUT}, e.g.:

GUT relations

m_ν ⟷ M_e

$$\theta_{12}^{e} = \frac{c_{12}}{c_{22}}\,\theta_{12}^{d} = \frac{c_{12}}{c_{22}}\,\theta_C$$

Let us consider U^{ν} with:

$\theta_{13}^{\nu} \approx 0$

$U_{PMNS} = U^{e\dagger} U^{\nu}$

Possible new combinations of Clebsches leading to large θ_{13}^{PMNS}: S.A., Maurer ('11) Mazocca, Petcov, Romanino, Spinrath ('11)

$\theta_{12}^d \cong \theta_C$

M_u ⟷ M_d

$U_{CKM} = U^{u\dagger} U^d$

M_d ⟷ M_e: GUT relations

Let us consider U^ν with:

$\theta_{13}^\nu \approx 0$

m_ν ⟷ M_e

$$\theta_{12}^e = \frac{c_{12}}{c_{22}} \theta_C$$

and θ_{13}^e, $\theta_{23}^e << \theta_C$

$U_{PMNS} = U^{e\dagger} U^\nu$

The PMNS mixing parameters result from U^ν <u>and</u> charged lepton mixing effects ($U^{e\dagger}$)

⇒ Two main effects

θ_C enters via GUT relations

1) Prediction for θ_{13}^{PMNS}:

$$\theta_{13}^{\mathrm{PMNS}} = \frac{\theta_{12}^{\mathrm{e}}}{\sqrt{2}} = \frac{\theta_{\mathrm{C}}}{\sqrt{2}} \frac{c_{12}}{c_{22}}$$

S.A., Maurer ('11)
Mazocca, Petcov, Romanino, Spinrath ('11)

⇒ Simple conditions (including $c_{12} = c_{22}$) in GUTs can lead to:

$$\theta_{13}^{\mathrm{PMNS}} = \frac{\theta_{\mathrm{C}}}{\sqrt{2}}$$

S.A., Gross, Maurer, Sluka ('12); See also: King ('12); Meroni, Petcov, Spinrath ('12);

With conventional Clebsch factors (c_{12} = 1, c_{22} = 3) many models predicted non-zero but smaller value $\theta_{13}^{PMNS} = \theta_C/(3\sqrt{2}) \approx 3°$ (... and are now ruled out by data): works by many authors ...

Relation $\theta_{13}^{PMNS} = \theta_C/\sqrt{2}$ also appears in a special variant of "Quark Lepton Complementarity" … : Minakata, Smirnov ('04); see also: Patel ('11)

1) Prediction for θ_{13}^{PMNS}:

$$\theta_{13}^{\rm PMNS} = \frac{\theta_{12}^{\rm e}}{\sqrt{2}} = \frac{\theta_{\rm C}}{\sqrt{2}}\frac{c_{12}}{c_{22}}$$

S.A., Maurer ('11)
Mazocca, Petcov, Romanino, Spinrath ('11)

⇒ Simple conditions (including $c_{12} = c_{22}$) in GUTs can lead to:

$$\theta_{13}^{\rm PMNS} = \frac{\theta_{\rm C}}{\sqrt{2}}$$

S.A., Gross, Maurer, Sluka ('12); See also: King ('12); Meroni, Petcov, Spinrath ('12);

2) The "Lepton Mixing Sum Rule":

$$\left.\begin{aligned}\theta_{13}^{\rm PMNS} &= \frac{\theta_{12}^{\rm e}}{\sqrt{2}} \\ \theta_{12}^{\rm PMNS} &= \theta_{12}^{\nu} + \frac{\theta_{12}^{\rm e}}{\sqrt{2}}\cos(\delta^{\rm PMNS})\end{aligned}\right\}\quad \theta_{12}^{\rm PMNS} = \theta_{12}^{\nu} + \theta_{13}^{\rm PMNS}\cos(\delta^{\rm PMNS})$$

King ('05); Masina ('05); S.A., King ('05)

characterizes a possible LO neutrino mixing pattern (TB: $\theta_{12}^{\nu} \approx 35.3°$; Bimax: $\theta_{12}^{\nu} = 45°$)

Reconstructing θ_{12}^{ν} using the lepton mixing sum rule

$$\theta_{12}^{\mathrm{PMNS}} = \theta_{12}^{\nu} + \theta_{13}^{\mathrm{PMNS}} \cos(\delta^{\mathrm{PMNS}})$$

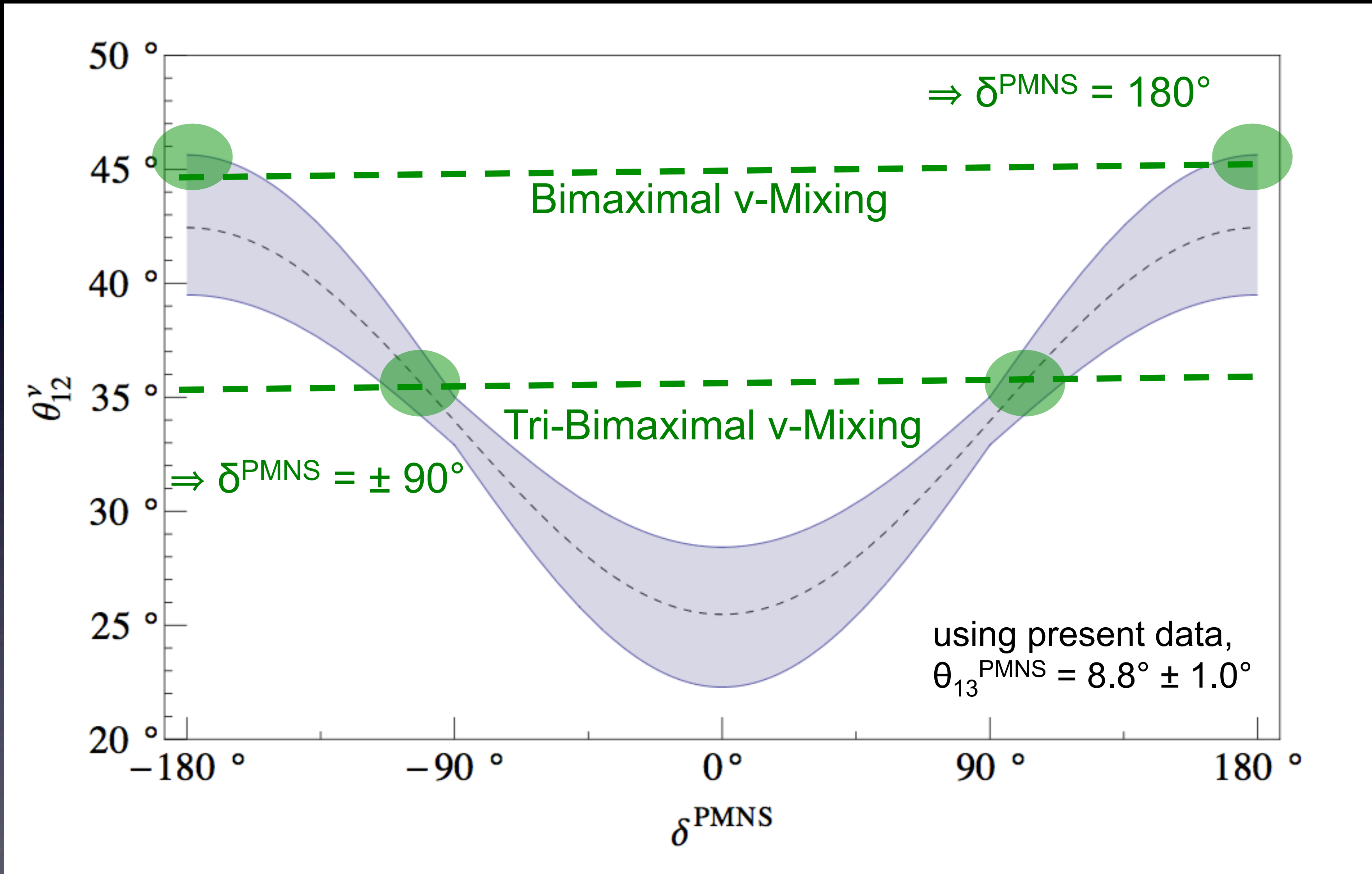


figure from S.A., Gross, Maurer, Sluka ('12)

Summary and conclusions

- Recent measurement of $\theta_{13}^{PMNS} \approx 9° \pm 1°$ → Exciting time for neutrino mass and mixing models!
- While exact mixing patterns with $\theta_{13}^{PMNS} = 0$ (e.g. exact TB mixing of U_{PMNS}) are ruled out by data … they may still provide viable LO structures, e.g.:
  - ✓ TB neutrino mixing + charged lepton contribution θ_{12}^{e}. Predicts $\delta^{PMNS} \approx \pm 90°$
  - ✓ Bimaximal neutrino mixing + charged lepton contribution θ_{12}^{e}. Predicts $\delta^{PMNS} \approx 180°$
- Independent of neutrino mixing pattern: $\theta_{13}^{PMNS} = \theta_C / \sqrt{2}$ can emerge in GUT flavour models under simple conditions …
- Expected future (and already present) high experimental precision for the leptonic mixing parameters: Accurate model analysis required … !