New developments in leptonic flavor

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ICTP

Normal physicists worried about strings and other regular stuff

Physicist that thought too much about the Flavour Puzzle

Hints or handles to leptonic flavor

- U_{CKM} vs U_{PMNS}. Small vs Large angles
- Neutrinos may be Majorana
- Lack of horizontal (flavor) symmetry

Related??

maybe continuous or discrete

Flavor symmetries

……the discrete path…

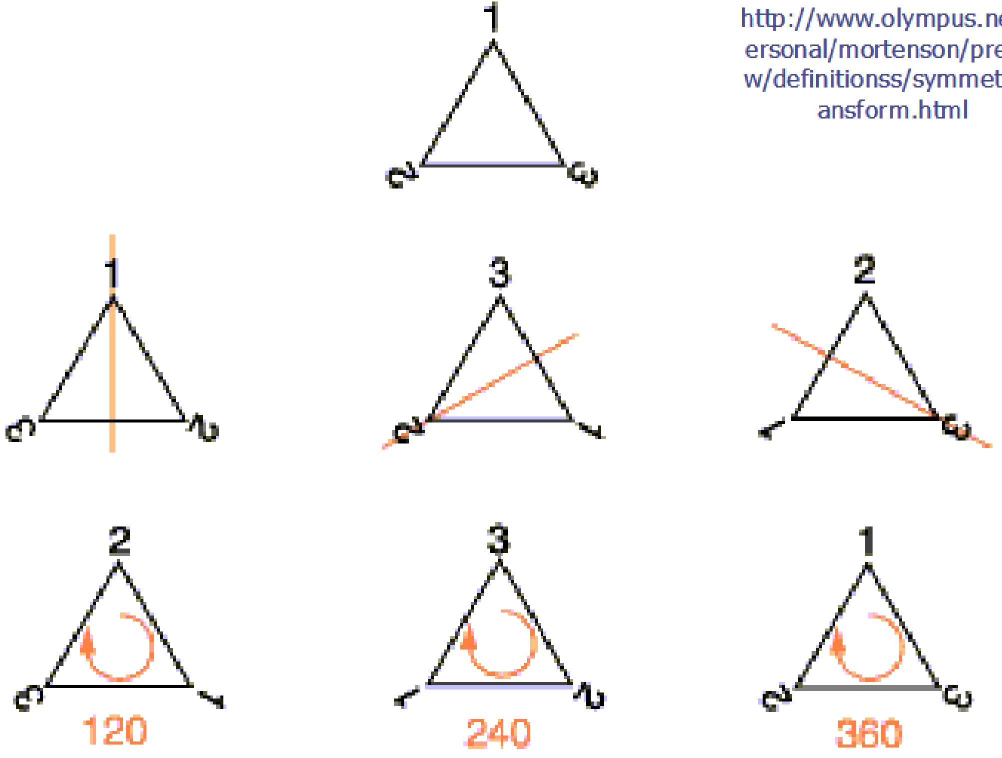
D. H. and A. Yu. Smirnov, ;
arXiv:1204.0445, **arXiv:1212.2149**,
arXiv:1304.7778

What are (nonabelian) discrete symmetries?

Generators

Reflections(P) →

120º Rotations(O) →



* Images taken from http://www.olympus.net/personal/mortenson/preview/definitionss/symmetrytransform.html

Do not commute.

$$PO \neq OP$$

Raised to some power, equal the identity

FOR INSTANCE $P^2 = O^3 = 1$

A4: symmetry group of the tetrahedron

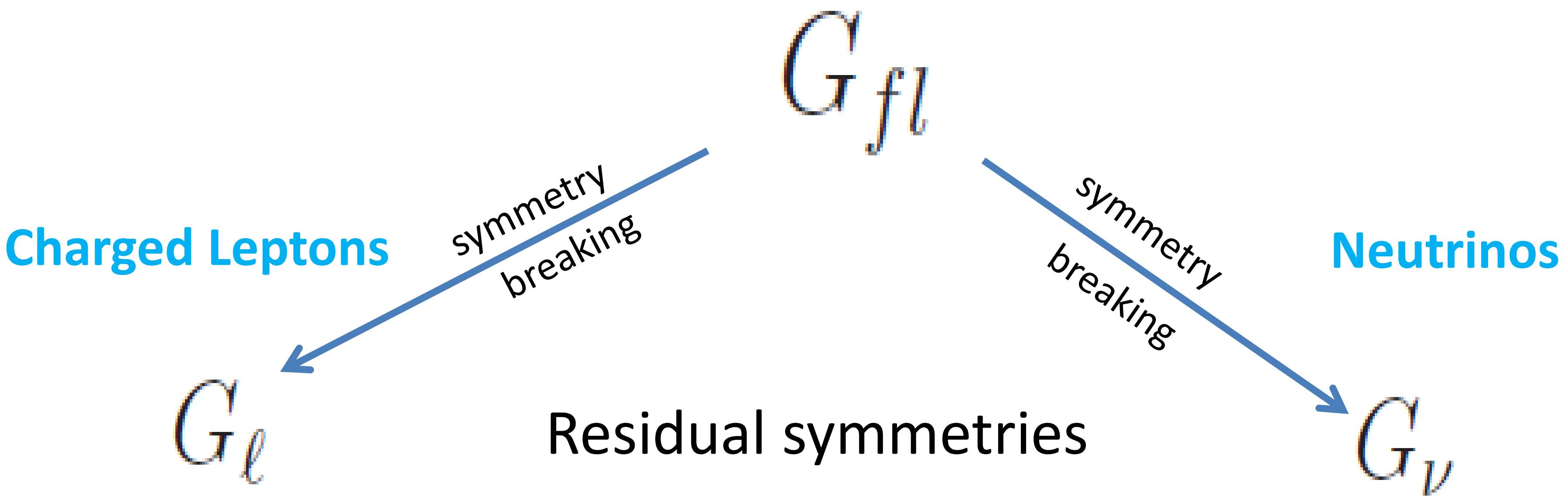
S4: symmetry group of the cube

A5: symmetry group of the icosahedron

……………………………………………………….

Important fact: These symmetries have 3-dimensional representations that account for the presence of 3 families

Flavor Symmetry



G_{fl}

Charged Leptons

symmetry breaking

G_ℓ

Residual symmetries

symmetry breaking

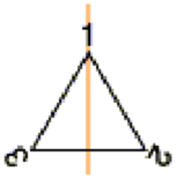
Neutrinos

G_ν

Example: G_{fl} **the symmetry of the equilateral triangle**

$G_\ell \equiv O$

$G_\nu \equiv P$



WHAT ARE THE CONSTRAINTS DISCRETE SYMMETRIES IMPOSE IN **LEPTON MIXING**?

ARE THEY **MODEL INDEPENDENT**?

CAN **MASSES** BE INCLUDED IN THE GAME?

$$\mathscr{L} = \frac{g}{\sqrt{2}}\bar{\ell}_L\gamma^\mu\nu_L W^+_\mu + \bar{E}_R M_\ell \ell_L + \frac{1}{2}\bar{\nu^c}_L M_\nu \nu_L + \cdots + \text{h.c.}$$

The mixing matrix is the mismatch between the directions, in flavor space, defined by the mass matrices

$$M_\nu = U_\nu^T M_{\nu D} U_\nu$$

$$M_\ell = V_E^\dagger M_{\ell D} V_\ell$$

$$U_{PMNS} = V_\ell U_\nu^\dagger$$

S : symmetry preserved by the neutrino mass matrix

T : symmetry preserved by the charged lepton mass matrix

For neutrinos $SM_\nu S^T = M_\nu$

For charged leptons $TM_\ell T^\dagger = M_\ell$

BUILDING THE DISCRETE GROUP

$$S^n = \mathbb{I}$$

$$T^m = \mathbb{I}$$

U_{PMNS} is also the mismatch between ***S*** and ***T*** !

$$(ST)^p = (U_{PMNS} S_D U^\dagger_{PMNS} T_D)^p = \mathbb{I}$$

$${S_D}^n = {T_D}^m = \mathbb{I}$$

symmetry in the mass basis

Constraints on the mixing matrix

$$(ST)^p = (U_{PMNS} S_D U^{\dagger}_{PMNS} T_D)^p = \mathbb{I}$$

$$\mathrm{Det}[ST - \lambda \mathbb{I}] = 0$$ **cubic equation with** $\lambda_i^p = 1$

$$\lambda^3 + a\lambda^2 - a^* \lambda - 1 = 0$$ with $a = -\mathrm{Tr}[U_{PMNS} S_D U^{\dagger}_{PMNS} T_D]$

Two equations, one for the real and one for the imaginary part of a

TWO CONSTRAINTS ON THE MIXING MATRIX

THUS, IN GENERAL, DISCRETE SYMMETRIES IMPOSE TWO CONDITIONS ON THE PARAMETERS OF THE MIXING MATRIX

$$a = -\mathrm{Tr}[U_{PMNS} S_D U^\dagger_{PMNS} T_D]$$

So, the constraints on the entries of the mixing matrix depend on:

$$a = -\mathrm{Tr}[ST]$$

$$T_D = \begin{pmatrix} e^{2\pi i \frac{k_1}{m}} & & \\ & e^{2\pi i \frac{k_2}{m}} & \\ & & e^{-2\pi i \frac{k_1+k_2}{m}} \end{pmatrix}$$

$$\boxed{{S_D}^n = {T_D}^m = \mathbb{I}}$$

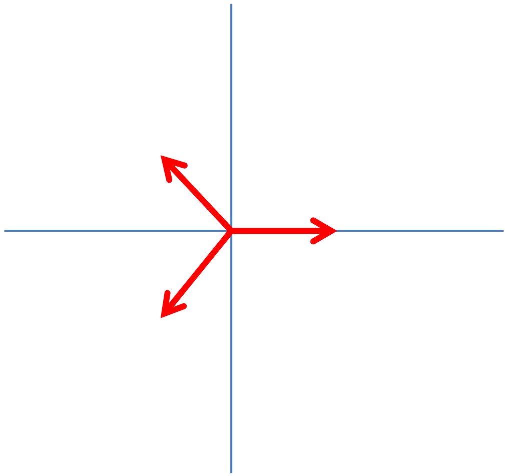
and define S_{Di} with $n=2$ so that $S_{Di}^2 = I$

$$S_{D1} = \begin{pmatrix} 1 & & \\ & -1 & \\ & & -1 \end{pmatrix}, \quad S_{D2} = \begin{pmatrix} -1 & & \\ & 1 & \\ & & -1 \end{pmatrix}, \quad S_{D3} = \begin{pmatrix} -1 & & \\ & -1 & \\ & & 1 \end{pmatrix}$$

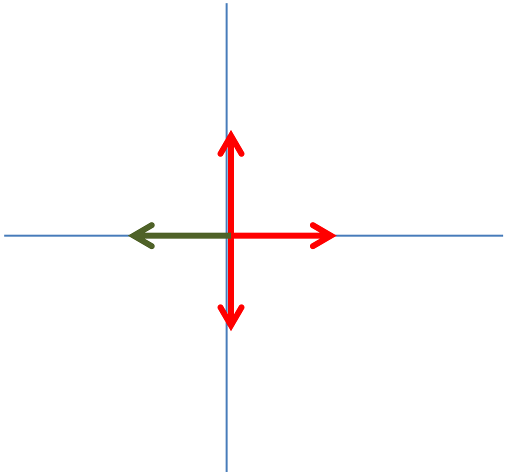
Constraints on the mixing matrix

$$a = -\mathrm{Tr}[ST]$$

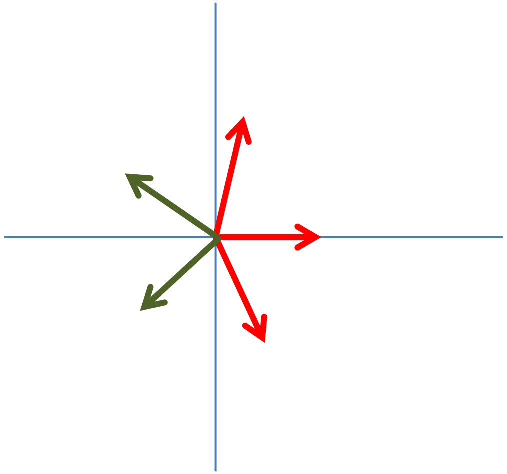
p=3



p=4



p=5



For instance, for $p = 3 \longrightarrow (\lambda - 1)(\lambda - \omega)(\lambda - \omega^2) = \lambda^3 - 1 \longrightarrow a = 0$

or $p = 4 \longrightarrow (\lambda - 1)(\lambda + i)(\lambda - i) = \lambda^3 - \lambda^2 + \lambda - 1 \longrightarrow a = -1$

The absolute values squared of one column are determined (two constraints plus unitarity)

$$|U_{l\nu}|^2 = \begin{array}{c} \\ \\ \\ \\ \end{array}\!\!\begin{array}{ccc} S_1 & S_2 & S_3 \\ \left(\begin{matrix} |U_{e1}|^2 \\ |U_{\mu 1}|^2 \\ |U_{\tau 1}|^2 \end{matrix}\right. & \begin{matrix} |U_{e2}|^2 \\ |U_{\mu 2}|^2 \\ |U_{\tau 3}|^2 \end{matrix} & \left.\begin{matrix} |U_{e3}|^2 \\ |U_{\mu 3}|^2 \\ |U_{\tau 3}|^2 \end{matrix}\right) \end{array}$$

$$\begin{aligned} R_i &= \mathrm{Re}[a_i + \mathrm{Tr}[T]] \\ I_i &= \mathrm{Im}[a_i + \mathrm{Tr}[T]] \end{aligned}$$

$$|U_{ei}|^2 = -\frac{R_i \cos\left(\pi \frac{k_1}{m}\right) - 2\cos\left(\pi \frac{k_1+2k_2}{m}\right) - I_i \sin\left(\pi \frac{k_1}{m}\right)}{4\sin\left(\pi \frac{k_1-k_2}{m}\right) \sin\left(\pi \frac{2k_1+k_2}{m}\right)}$$

$$|U_{\mu i}|^2 = \frac{R_i \cos\left(\pi \frac{k_2}{m}\right) - 2\cos\left(\pi \frac{2k_1+k_2}{m}\right) - I_i \sin\left(\pi \frac{k_2}{m}\right)}{4\sin\left(\pi \frac{k_1-k_2}{m}\right) \sin\left(\pi \frac{k_1+2k_2}{m}\right)}$$

$$|U_{\tau i}|^2 = -\frac{R_i \cos\left(\pi \frac{k_1+k_2}{m}\right) - 2\cos\left(\pi \frac{k_1-k_2}{m}\right) + I_i \sin\left(\pi \frac{k_1+k_2}{m}\right)}{4\sin\left(\pi \frac{2k_1+k_2}{m}\right) \sin\left(\pi \frac{k_1+2k_2}{m}\right)}$$

Recapitulating: What I have shown (under some - mostly harmless - assumptions)

After a number of choices have been made

1. The **T-charge** of the charged leptons (k_1 and k_2 value)
2. The **order of T** (m value)
3. The **S-charges** of the neutrinos
4. The **eigenvalues of ST** (a value)

A two-dimensional surface is cut in the parameter space of the mixing matrix.

THIS IS ALL DISCRETE SYMMETRIES CAN TELL YOU FOR SURE ABOUT MIXING!

Choose $\alpha = e$ in the ‘lazy’ case

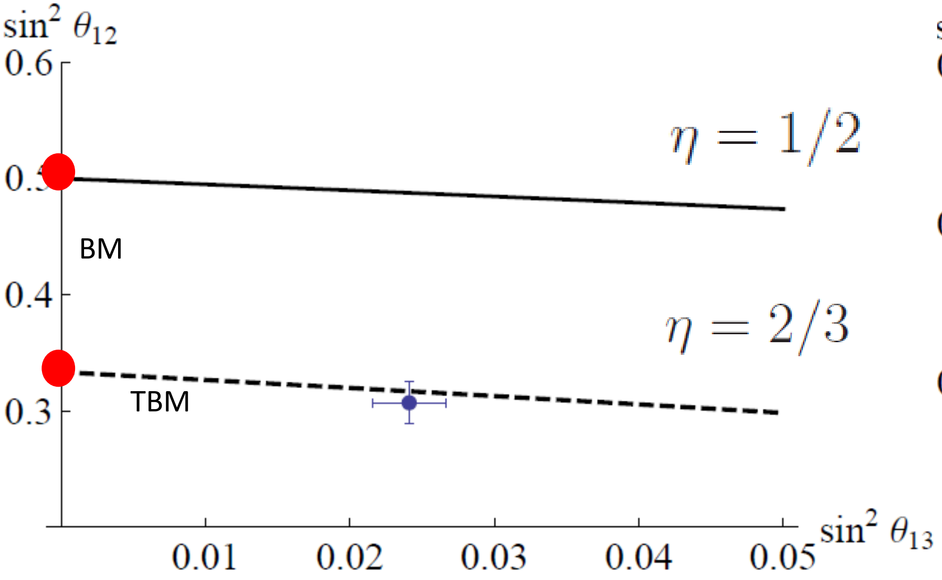
$$S_{iU}^n = T^m = (S_{iU}T)^p = \mathbb{I}$$

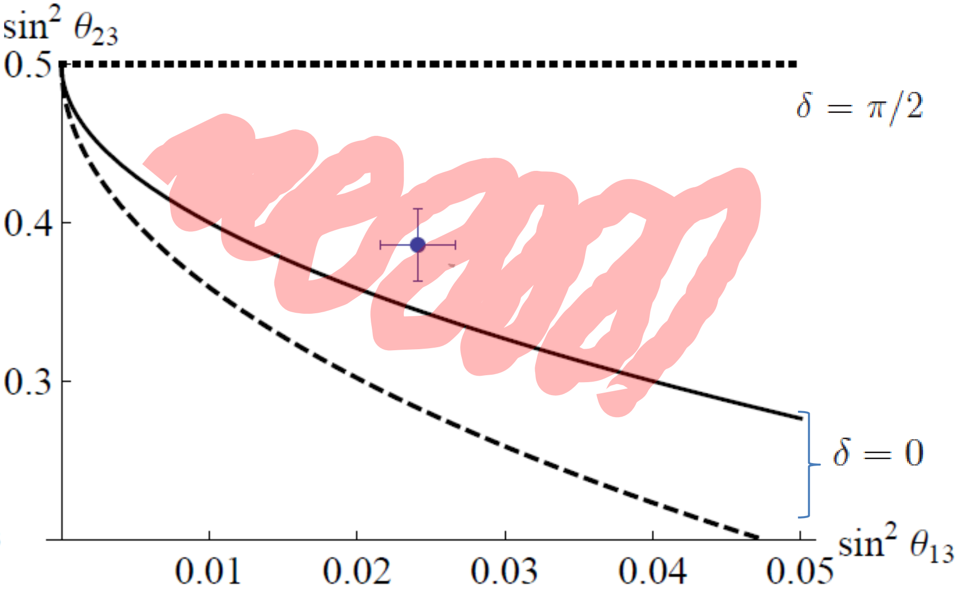
$$\lambda^3 + a\lambda^2 - a^*\lambda - 1 = 0$$

$$\eta \equiv \frac{1-a}{4\sin^2\left(\frac{\pi k}{m}\right)}$$

Taking $i = 1$

- Solid: *m = 4, p = 3. k=1* and from $(\lambda - 1)(\lambda - \omega)(\lambda - \omega^2) = \lambda^3 - 1$, *a=0* . Group is **S**$_4$
- Dashed: *m = 3, p = 4. k=1, a=-1.* Group is **S**$_4$





THIS KIND OF PLOTS CODIFY **THE MOST GENERAL PREDICTION** THAT DISCRETE SYMMETRIES CAN MAKE ABOUT THE MIXING PARAMETERS

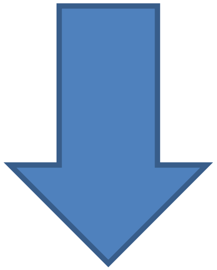
NO DEPENDENCE ON MODEL SPECIFICS, JUST GO AND CHOOSE YOUR FAVORITE DISCRETE GROUP AND FIND OUT WHAT MIXINGS YOU MAY GET

WHAT ABOUT THE MASSES?

IN DETAIL

For Majorana neutrinos, ***S_D*** is an orthogonal matrix

$$S^n = \mathbb{I}$$



$$n \geq 3$$

Neutrinos must be degenerate!

$$S^n = T^m = \mathbb{I}$$

$$S_D = \begin{pmatrix} \cos\phi & -\sin\phi & 0 \\ \sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\phi = \frac{2\pi}{n}$$

$$m_\nu = S_D m_\nu S_D^T$$

Only for approximately degenerate m_1 AND m_2

$$M_{\nu D} \simeq \begin{pmatrix} m & & \\ & m & \\ & & m' \end{pmatrix}$$

So that the group is finite

$$(ST)^2 = (U_{PMNS} S_D U^\dagger_{PMNS} T_D)^2 = 1$$

$$\Big\Downarrow$$

Again, there seem to be 2 constraints on mixing

$$(|U_{\alpha 3}|^2 \mp x)^2 - 2x \cdot \mathrm{Im}[U_{\beta 1} U^*_{\beta 2} - U_{\gamma 1} U^*_{\gamma 2} \mp 1] = 0$$

$$2\mathrm{Im}[U_{\alpha 1} U^*_{\alpha 2}] + y \cdot (|U_{\gamma 3}|^2 - |U_{\beta 3}|^2) = 0$$

$\beta, \gamma \neq \alpha$

x and y fixed by T_D, for instance $x = \cot\left(\frac{\pi k_n}{n}\right) \cot\left(\frac{\pi k_n}{m}\right)$

$$x = \cot\left(\frac{\pi k_n}{n}\right)\cot\left(\frac{\pi k_n}{m}\right)$$

Actually, we get 4 constraints!

$$|U_{\alpha i}|^2 = x$$

$$\mathrm{Im}[U_{\alpha j}U^*_{\alpha k}] = 0\,, \quad j,k \neq i$$

$$|U_{\beta i}|^2 = |U_{\gamma i}|^2$$

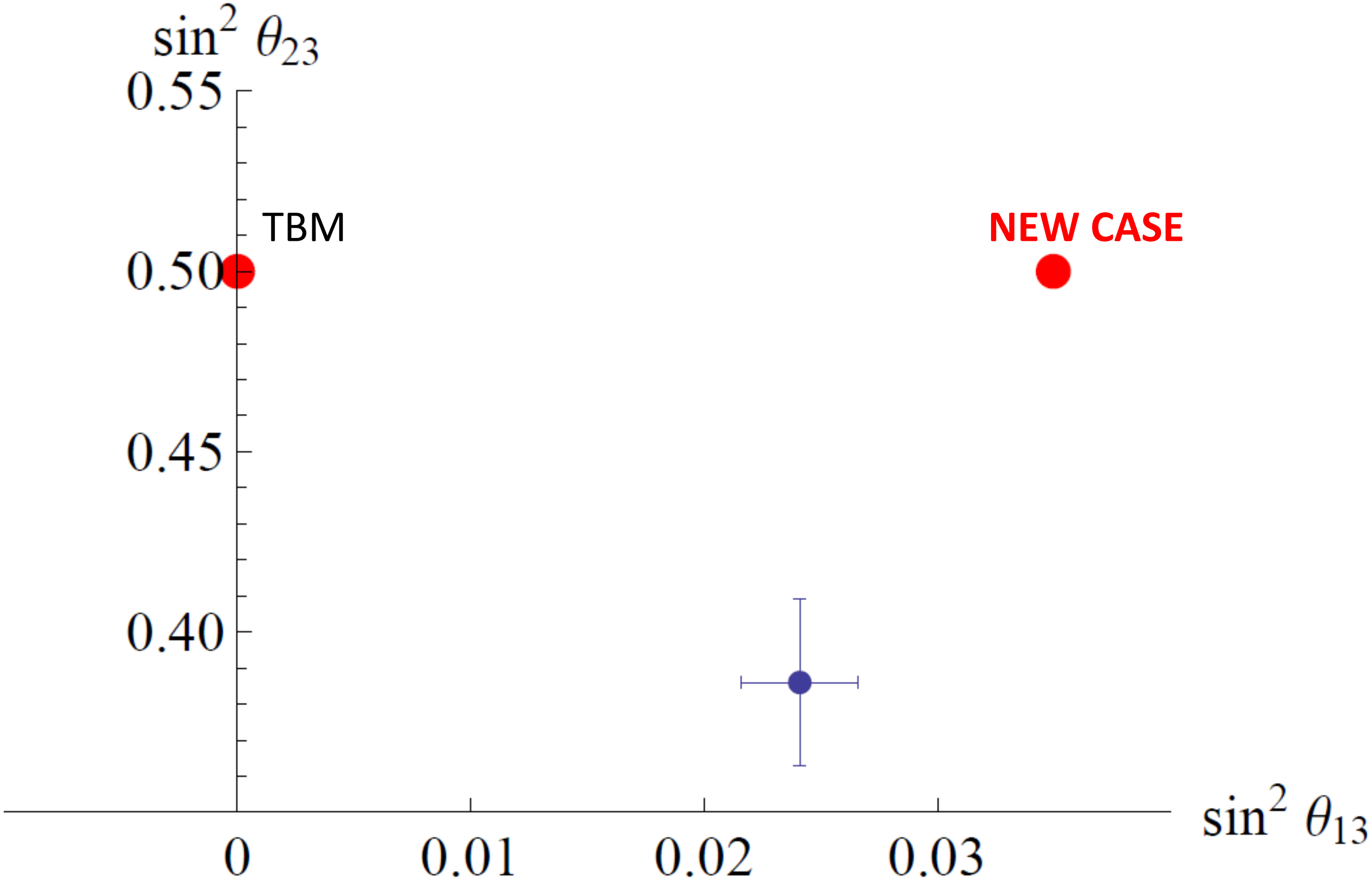
$$\mathrm{Im}[U_{\beta j}U^*_{\beta k} - U_{\gamma j}U^*_{\gamma k}] = \pm 1$$

$\alpha = e$

$$\sin\theta_{13} = \pm\cot\frac{\pi k_n}{n}\cot\frac{\pi k_m}{m}\,, \qquad \theta_{23} = \frac{\pi}{4}\,, \quad \delta = \frac{\pi}{2}\,, \quad \kappa = 0$$

$$m = 3, \quad k_m = 1\,; \qquad n = 5\,, \quad k_n = 2$$

$$\sin\theta_{13} = \cot\frac{\pi}{3}\cot\frac{2\pi}{5} = \sqrt{\frac{1}{3}\left(1 - \frac{2}{\sqrt{5}}\right)} \simeq 0.187$$


$\sin^2\theta_{23}$
0.55
0.50
0.45
0.40
TBM
NEW CASE
$\sin^2\theta_{13}$
0
0.01
0.02
0.03

Conclusions

- Constraints on mixing from discrete symmetries are model independent…
- … and can be obtained in a systematic, rather simple way
- Theta13 is not forced to be zero. In general, two parameters are defined out of 4 in the mixing matrix.
- Many results can be obtained: TBM, BM and analysis of less known groups made easy.

Conclusions

- IF a larger residual symmetry is imposed in the neutrino sector, up to 4 constraints in the mixing matrix.

- In this case, there's still compatibility with measured mixings. Masses predicted degenerate. Corrections expected to account for both the 12 mass difference and the exact values for the mixing

$$\begin{tikzcd} & G_{fl} \arrow[dl] \arrow[dr] & \\ G_{\ell} & & G_{\nu} \end{tikzcd}$$

BOTTOM UP

1. Find accidental symmetries of the charged lepton and neutrino mass terms

2. Choose discrete subgroups in both cases

3. Combine them to define G_{fl}

IN DETAIL

1.- Identifying the accidental symmetries

$$\mathscr{L} = \frac{g}{\sqrt{2}}\bar{\ell}_L U_{PMNS}\gamma^\mu \nu_L W^+_\mu + \bar{E}_R m_\ell \ell_L + \frac{1}{2}\bar{\nu^c}_L m_\nu \nu_L + \ldots + \text{h.c.}$$

Charged Leptons

$\bar{E}_R m_\ell \ell_L$ is invariant under $U(1)^3$ **accidental**

$$E_R \to T E_R\,, \quad \ell_L \to T\ell_L \qquad\qquad T = \text{diag}\{e^{i\alpha}, e^{i\beta}, e^{i\gamma}\}$$

IN DETAIL

1.- Identifying the accidental symmetries

$$\mathscr{L} = \frac{g}{\sqrt{2}}\bar{\ell}_L U_{PMNS}\gamma^{\mu}\nu_L W_{\mu}^{+} + \bar{E}_R m_{\ell}\ell_L + \frac{1}{2}\bar{\nu^c}_L m_{\nu}\nu_L + \ldots + \text{h.c.}$$

Neutrinos

$\frac{1}{2}\bar{\nu^c}_L m_{\nu}\nu_L$ invariant under $Z_2 \otimes Z_2$ accidental

$$S_1 = \begin{pmatrix} 1 & & \\ & -1 & \\ & & -1 \end{pmatrix}, \quad S_2 = \begin{pmatrix} -1 & & \\ & 1 & \\ & & -1 \end{pmatrix}, \quad S_3 = S_1 S_2 = \begin{pmatrix} -1 & & \\ & -1 & \\ & & 1 \end{pmatrix}$$

1.- Enter mixing matrix

$$\mathscr{L} = \frac{g}{\sqrt{2}}\bar{\ell}_L U_{PMNS}\gamma^\mu \nu_L W_\mu^+ + \bar{E}_R m_\ell \ell_L + \frac{1}{2}\bar{\nu^c}_L m_\nu \nu_L + \ldots + \text{h.c.}$$

Change of basis

$$\mathscr{L} = \frac{g}{\sqrt{2}}\bar{\ell}_L \gamma^\mu \nu_L W_\mu^+ + \bar{E}_R M_\ell \ell_L + \frac{1}{2}\bar{\nu^c}_L M_\nu \nu_L + \cdots + \text{h.c.}$$

$$M_\nu = U^* m_\nu U^\dagger$$

$$M_\ell = m_\ell V$$

$$U_{PMNS} = VU$$

Take $U \equiv U_{PMNS} \quad V \equiv 1$

Invariance of M_ν

under $Z_2 \otimes Z_2$

accidental

$\Rightarrow$ $S_{iU}^\dagger M_\nu S_{iU} = M_\nu$ with $S_{iU} = U S_i U^\dagger$

Still $S_{iU}^2 = 1$

2.- Choosing the flavor subgroups

For the neutrinos

Simply choose at least one of the S_{iU}

2.- Choosing the flavor subgroups

For charged leptons, use a **finite abelian** subgroup of $U(1)^3$ as the group of flavor

Impose $T^m = 1$, T unitary

$$T = \begin{pmatrix} e^{2\pi i k_1/m} & & \\ & e^{2\pi i k_2/m} & \\ & & e^{-2\pi i (k_1+k_2)/m} \end{pmatrix}$$

3.- Defining the flavor group

- Define a relation between S_{iU} and T

We had $T^m = 1$, $S_{iU}^2 = 1$

Add $(S_{iU}T)^p = (US_iU^\dagger T)^p = \mathbb{I}$

Constraints on the mixing matrix

$$W_i = S_{iU} T = U S_i U^\dagger T \,, \quad W_i^p = 1$$

$\mathrm{Det}[W_i - \lambda \mathbb{I}] = 0$ **cubic equation with** $\lambda_i^p = 1$

$\lambda^3 + a\lambda^2 - a^*\lambda - 1 = 0$ with $a = -\mathrm{Tr}[W_i]$

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TWO CONSTRAINTS ON THE MIXING MATRIX

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So, the constraints on the entries of the mixing matrix depend on

$$a = -\mathrm{Tr}[W_i]$$

$$T = \begin{pmatrix} e^{2\pi i k_1/m} & & \\ & e^{2\pi i k_2/m} & \\ & & e^{-2\pi i(k_1+k_2)/m} \end{pmatrix}$$

and which S_i is chosen

$$S_1 = \begin{pmatrix} 1 & & \\ & -1 & \\ & & -1 \end{pmatrix} \quad S_2 = \begin{pmatrix} -1 & & \\ & 1 & \\ & & -1 \end{pmatrix} \quad S_3 = S_1 S_2 = \begin{pmatrix} -1 & & \\ & -1 & \\ & & 1 \end{pmatrix}$$

$$W_i = S_{iU} T = U S_i U^\dagger T\,, \quad W_i^p = 1$$

Constraints on the mixing matrix

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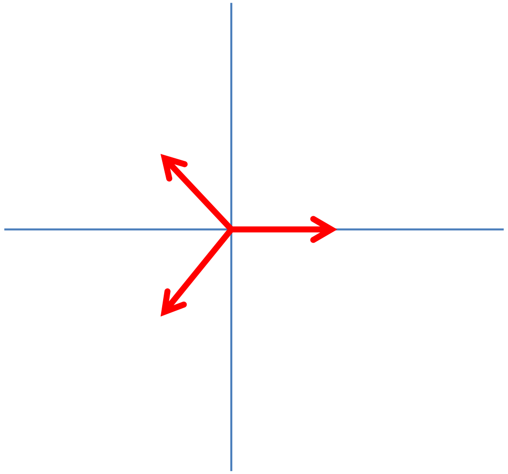
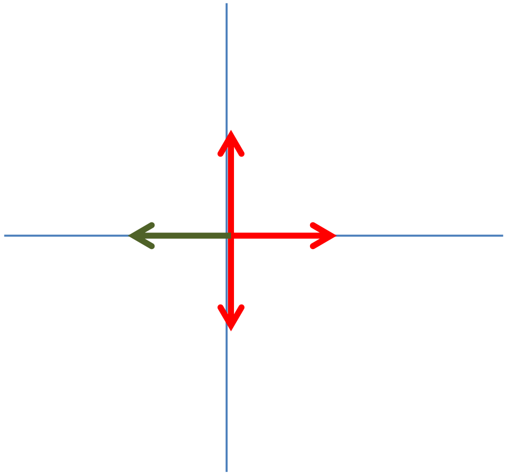
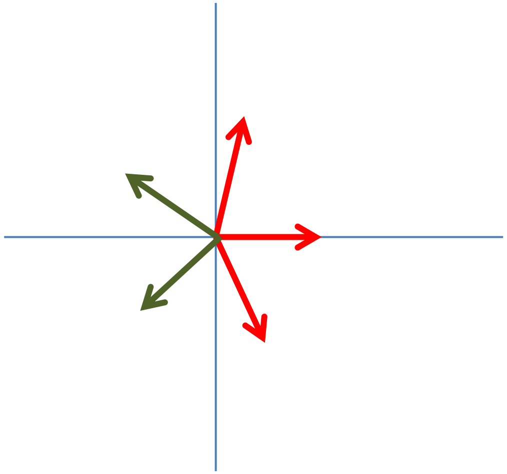


p=4



p=5



For instance, for $p = 3 \longrightarrow (\lambda - 1)(\lambda - \omega)(\lambda - \omega^2) = \lambda^3 - 1 \longrightarrow a = 0$

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The absolute values squared of one column are determined (two constraints plus unitarity)

$$|U_{l\nu}|^2 = \begin{array}{ccc} S_1 & S_2 & S_3 \\ \left(\begin{array}{c} |U_{e1}|^2 \\ |U_{\mu 1}|^2 \\ |U_{\tau 1}|^2 \end{array} \right. & \begin{array}{c} |U_{e2}|^2 \\ |U_{\mu 2}|^2 \\ |U_{\tau 3}|^2 \end{array} & \left. \begin{array}{c} |U_{e3}|^2 \\ |U_{\mu 3}|^2 \\ |U_{\tau 3}|^2 \end{array} \right) \end{array}$$

$$R_i = \mathrm{Re}\{\mathrm{Tr}[W_i + T]\}$$

$$I_i = \mathrm{Im}\{\mathrm{Tr}[W_i + T]\}$$

$$|U_{ei}|^2 = -\frac{R_i \cos\left(\pi \frac{k_1}{m}\right) - 2\cos\left(\pi \frac{k_1+2k_2}{m}\right) - I_i \sin\left(\pi \frac{k_1}{m}\right)}{4 \sin\left(\pi \frac{k_1-k_2}{m}\right) \sin\left(\pi \frac{2k_1+k_2}{m}\right)}$$

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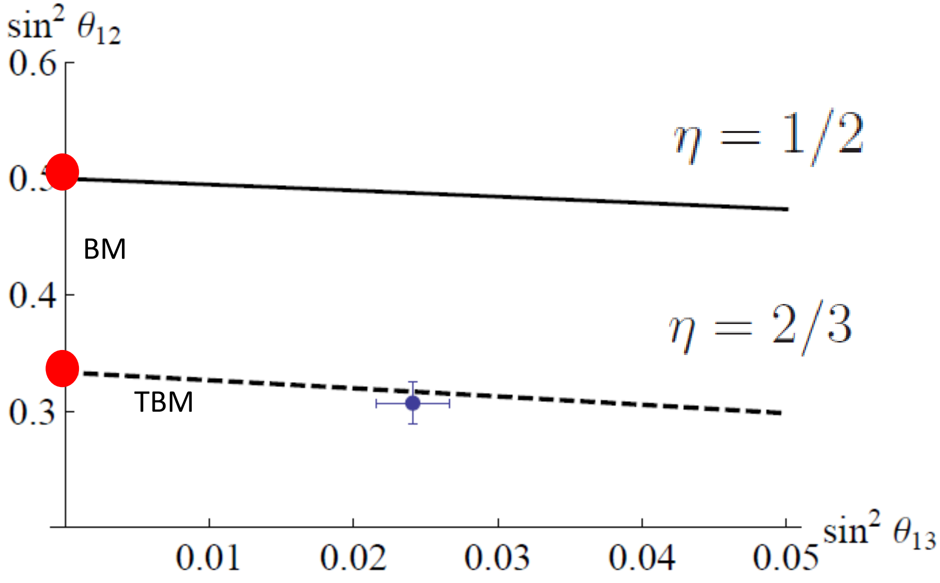

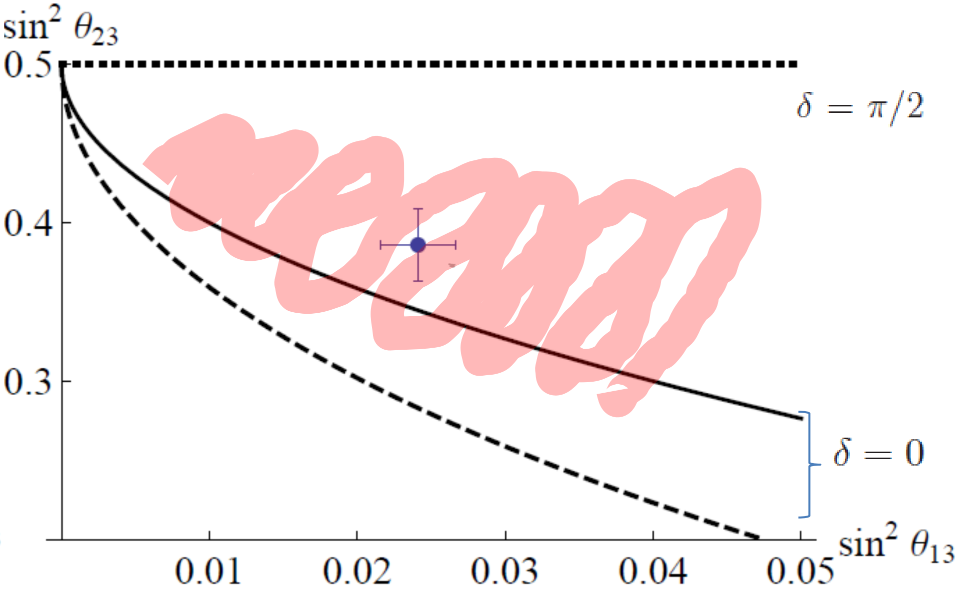

WHAT ABOUT THE MASSES?

IN DETAIL

1.- Identifying the accidental symmetries

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Neutrinos

$\frac{1}{2}\bar{\nu^c}_L m_\nu \nu_L$ invariant under $Z_2 \otimes Z_2$ accidental

ONLY IF THE THREE NEUTRINO MASSES ARE DIFFERENT!

FOR DEGENERATE NEUTRINO MASSES

$$m_\nu = \begin{pmatrix} m & & \\ & m & \\ & & m' \end{pmatrix}$$

$$m_\nu = S m_\nu S \qquad S = \begin{pmatrix} \cos\phi & -\sin\phi & 0 \\ \sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$S^n = 1\,, \quad \phi = \frac{2\pi}{n}$$

$$W_i = S_{iU}T = US_iU^\dagger T$$

So that the group is finite

$$S_{iU}^n = T^m = W_{iU}^2 = 1$$

$$\Downarrow$$

$$x = \cot\left(\frac{\pi k_n}{n}\right)\cot\left(\frac{\pi k_n}{m}\right)$$

Constraints on mixing

$$\left(|U_{\alpha i}|^2 \mp x\right)^2 - 2x\cdot\mathrm{Im}[U_{\beta j}U_{\beta k}^* - U_{\gamma j}U_{\gamma k}^* \mp 1] = 0 \qquad j,k \neq i$$

$$2\mathrm{Im}[U_{\alpha j}U_{\alpha k}^*] + y\cdot(|U_{\gamma i}|^2 - |U_{\beta i}|^2) = 0 \qquad \beta,\gamma \neq \alpha$$

$$x = \cot\left(\frac{\pi k_n}{n}\right)\cot\left(\frac{\pi k_n}{m}\right)$$

Actually, we get 4 constraints!

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$$\mathrm{Im}[U_{\beta j}U^*_{\beta k} - U_{\gamma j}U^*_{\gamma k}] = \pm 1$$

D.H., A. Yu. Smirnov, in prep.

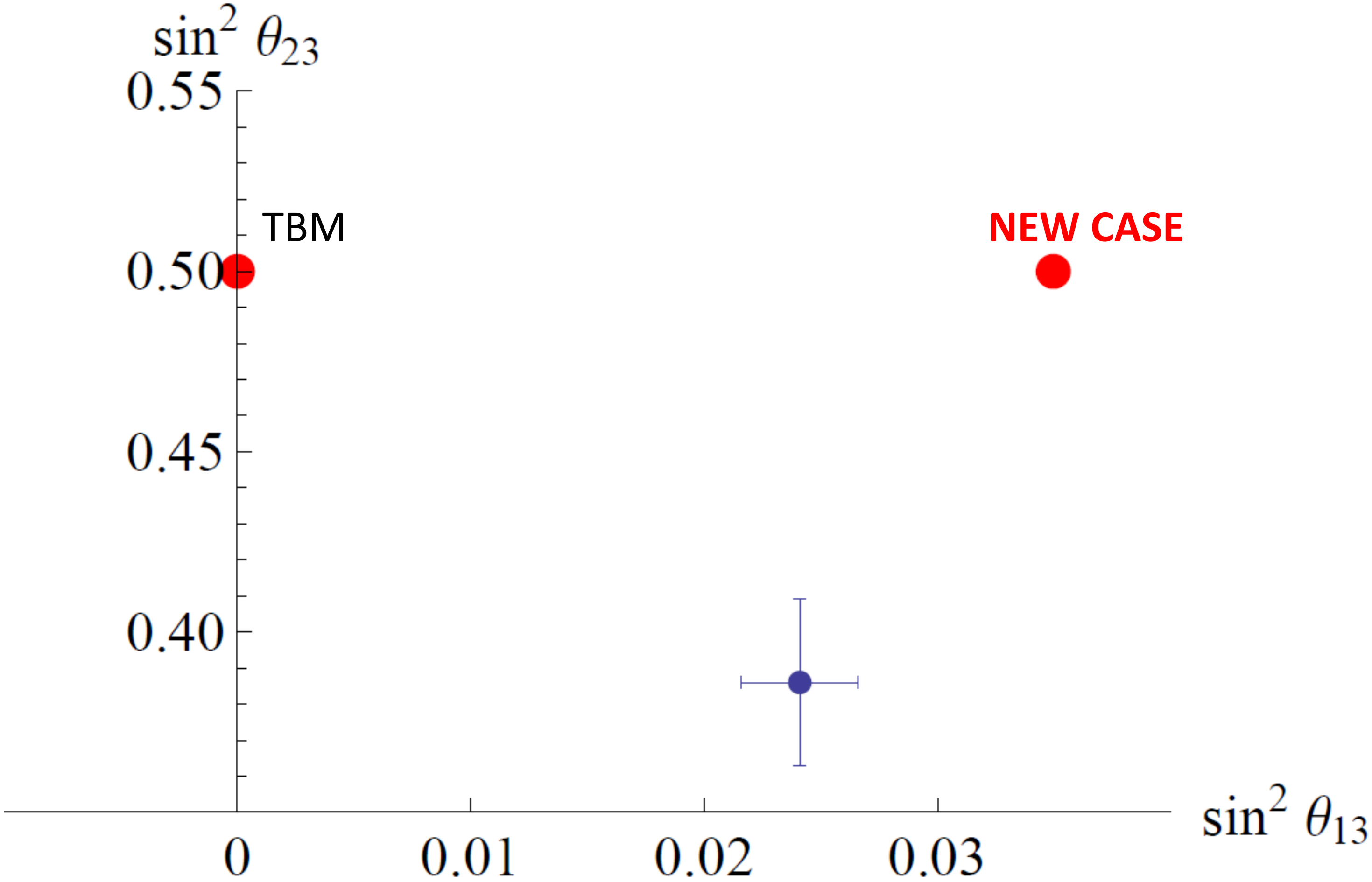
$$\alpha = e\,, \qquad i = 3$$

$$\sin\theta_{13} = \pm\cot\frac{\pi k_n}{n}\cot\frac{\pi k_m}{m}\,, \quad \theta_{23} = \frac{\pi}{4}\,, \quad \delta = \frac{\pi}{2}\,, \quad \kappa = 0$$

$$\Big\downarrow$$

$$m = 3, \quad k_m = 1\,; \qquad n = 5\,, \quad k_n = 2$$

$$\sin\theta_{13} = \cot\frac{\pi}{3}\cot\frac{2\pi}{5} = \sqrt{\frac{1}{3}\left(1 - \frac{2}{\sqrt{5}}\right)} \simeq 0.187$$


$\sin^2 \theta_{23}$
0.55
0.50
0.45
0.40
TBM
NEW CASE
$\sin^2 \theta_{13}$
0
0.01
0.02
0.03

Conclusions

- Constraints on mixing from discrete symmetries are model independent…
- … and can be obtained in a systematic, rather simple way
- Theta13 is not forced to be zero. In general, two parameters are defined out of 4 in the mixing matrix.
- Many results can be obtained: TBM, BM and analysis of less known groups made easy.

Conclusions

- IF a larger residual symmetry is imposed in the neutrino sector, up to 4 constraints in the mixing matrix.

- In this case, there's still compatibility with measured mixings. Masses predicted degenerate.