Absolute neutrino mass scale from *FLA*vour *SY*mmetry

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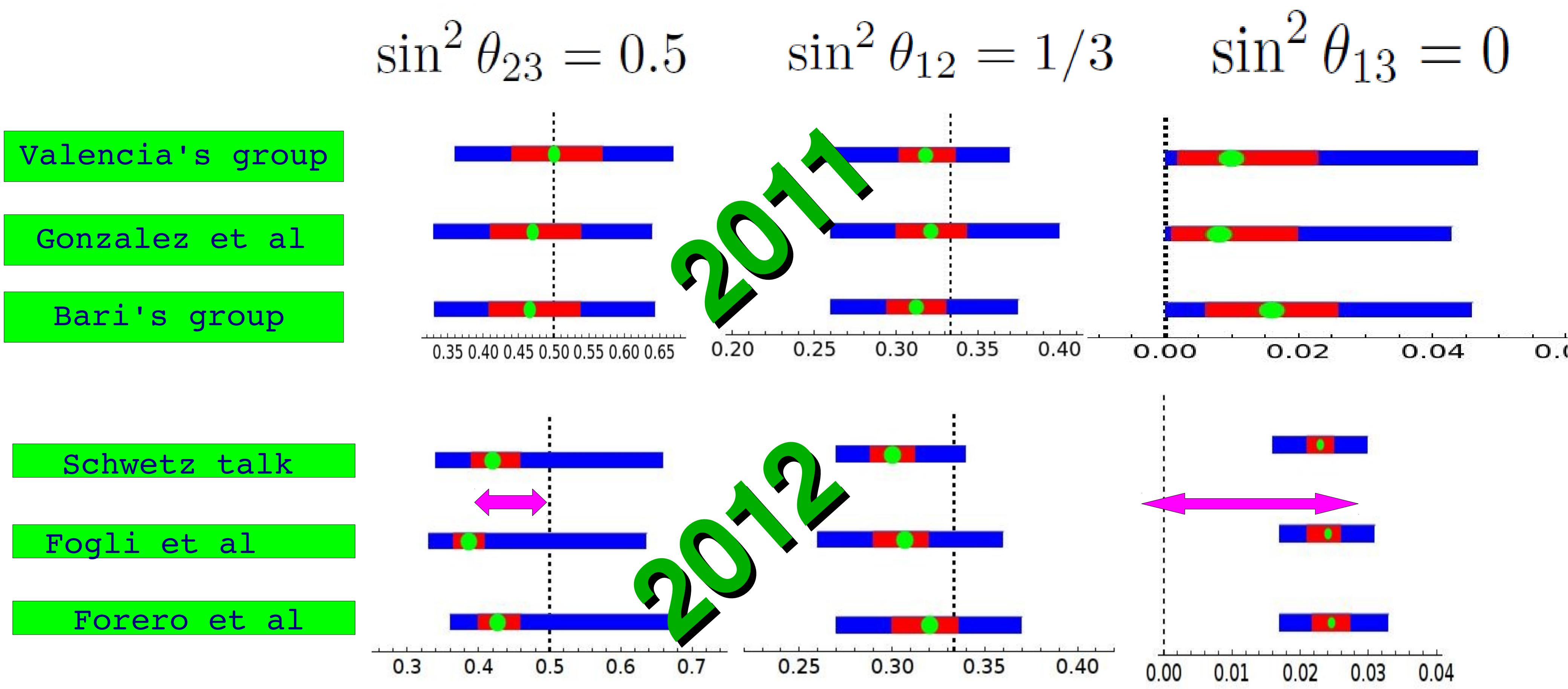
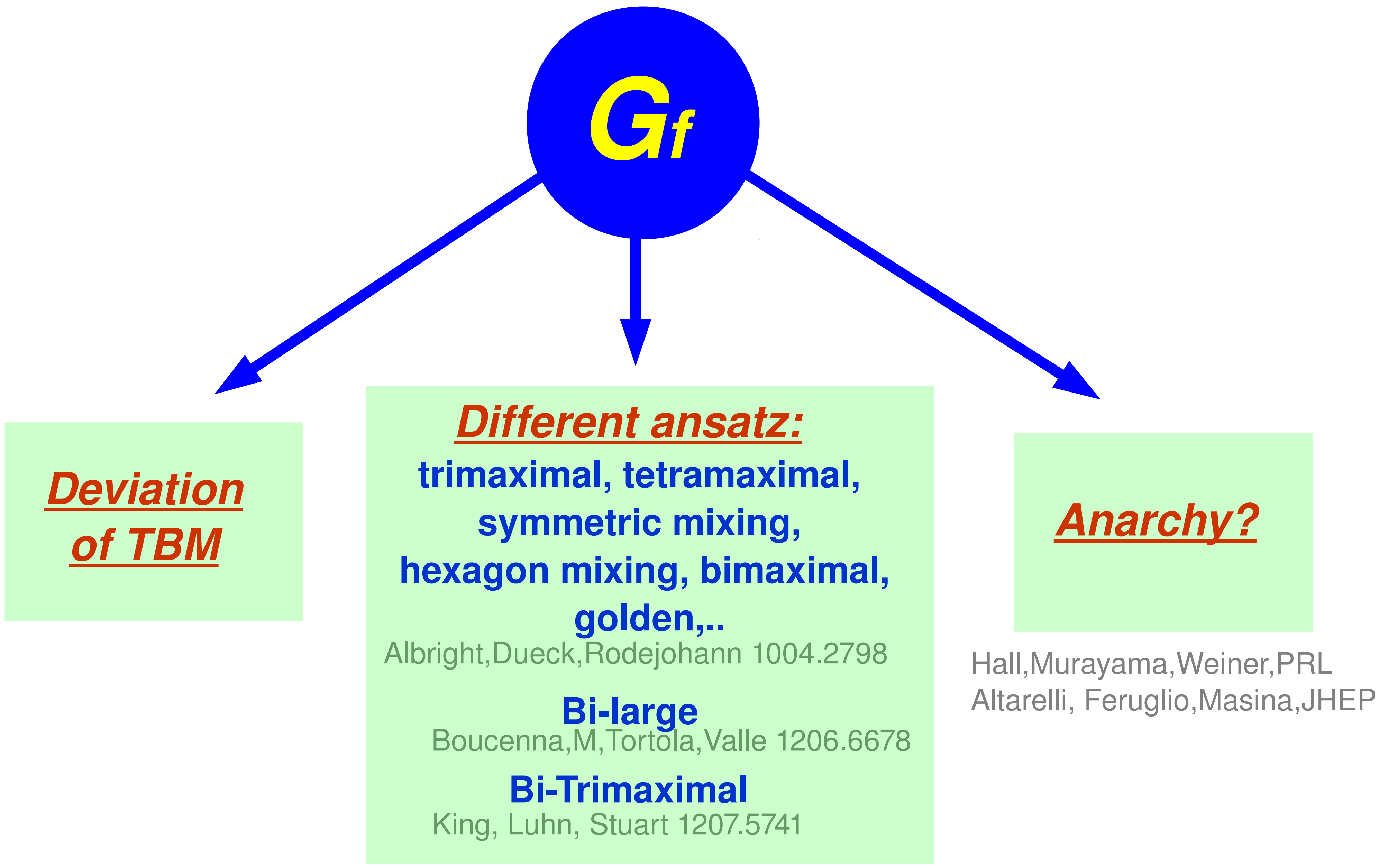
Hirsch, M, Valle, ***PRD 78*** ***(2008)***
Hirsch, M, Valle, ***PLB 679*** ***(2009)***
Bazzocchi, Merlo, M, ***NPB816*** ***(2009)***
Bazzocchi, Merlo, M, ***PRD80*** ***(2009)***
Dorame, M, Peinado, Valle, ***NPB861*** ***(2012)***

For about 10 years data have biased us towards TBM mixing



TBM is ruled out since

- ϑ_{13} is not zero
- ϑ_{23} is not maximal @ 1*sigma*



Gf
Deviation of TBM
Different ansatz:
trimaximal, tetramaximal, symmetric mixing, hexagon mixing, bimaximal, golden,..
Albright,Dueck,Rodejohann 1004.2798
Bi-large
Boucenna,M,Tortola,Valle 1206.6678
Bi-Trimaximal
King, Luhn, Stuart 1207.5741
Anarchy?
Hall,Murayama,Weiner,PRL
Altarelli, Feruglio,Masina,JHEP

G_f

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We assume neutrino exactly TBM with deviation from the charged sector

G_f

Sum mass rules like

$$m_1^\nu + m_2^\nu = m_3^\nu$$

Prediction for the absolute neutrino mass scale

See talk of Rodejohann

$$\begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix} \cdot \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} \cdot \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix}^T$$

$$= \frac{m_1}{6} \begin{pmatrix} 4 & -2 & -2 \\ -2 & 1 & 1 \\ -2 & 1 & 1 \end{pmatrix} + \frac{m_2}{3} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} + \frac{m_3}{2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -1 \\ 0 & -1 & 1 \end{pmatrix}$$

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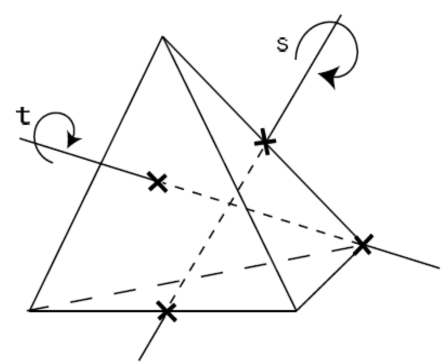
A4

Discrete group
even permutations
four objects



tetrahedron

Smallest discrete group with ***triplet*** irreducible representation: ***1, 1', 1'', 3***

$$\begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix} \cdot \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} \cdot \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix}^T$$

$$= \frac{m_1}{6} \begin{pmatrix} 4 & -2 & -2 \\ -2 & 1 & 1 \\ -2 & 1 & 1 \end{pmatrix} + \frac{m_2}{3} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} + \frac{m_3}{2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -1 \\ 0 & -1 & 1 \end{pmatrix}$$

__Have the same structure__

A4

$$m_\nu = a \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} + b \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

Altarelli, Feruglio, NPB720 (05), NPB741 (06)

$$\begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix} \cdot \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} \cdot \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix}^T$$

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x 1/2

x 3/2

A4

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x 1/6 **x 1/3** **x -1/2**

A4

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m1 = 3 a + b,   m2 = b,   m3 = 3 a - b

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A4

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m1 = 3 a + b,   m2 = b,   m3 = 3 a - b

$$\boxed{2\, m2 + m3 = m1}$$

mass sum rule

Barry, Rodejohann NPB842 (2011)

Types of mass relations

$$\chi m_2^\nu + \xi m_3^\nu = m_1^\nu$$

are free parameters that specify the model

A4

2 m2 + m3 = m1

$\Rightarrow$ χ **= 2** ξ **= 1**

Types of mass relations

$$\chi m_2^\nu + \xi m_3^\nu = m_1^\nu$$

A4

2 m2 + m3 = m1

$\Rightarrow$ χ = 2 ξ = 1

S4

m2 - m3 = m1

$\Rightarrow$ χ = 1 ξ = -1

D=5 op. LLHH & mass relations

suppose only two contractions

$$\mathcal{L} = \frac{y_a}{M}\epsilon^a_{ij}(L_i L_j)_a H H + \frac{y_b}{M}\epsilon^b_{ij}(L_i L_j)_b H H$$

CG from the flavor symmetry

$$M^\nu_{ij} = a\epsilon^a_{ij} + b\epsilon^b_{ij}$$

ν masses are ***linear*** conbinations of ***a*** and ***b***

$$\chi m^\nu_2 + \xi m^\nu_3 = m^\nu_1$$

Type-I seesaw & mass relations

Dirac prop to the identity I

$$m_\nu = -m_D \frac{1}{M_R} m_D^T$$

Majorana eigenvalues are ***linear*** conbination of two parameters ***a, b***

(ν masses)***-1*** are ***linear*** conbinations of ***a*** and ***b***

$$\frac{\chi}{m_2^\nu} + \frac{\xi}{m_3^\nu} = \frac{1}{m_1^\nu}$$

Type-I seesaw & mass relations

Dirac eigenvalues are ***linear*** conbination of two parameters ***a, b***

$$m_\nu = -m_D \frac{1}{M_R} m_D^T$$

Majorana prop to the identity I

$$m_i^\nu \propto (\alpha_i a + \beta_i b)^2$$

$$\chi \sqrt{m_2^\nu} + \xi \sqrt{m_3^\nu} = \sqrt{m_1^\nu}.$$

Hirsch, M, Valle, PRD78 (08)

Inverse seesaw & mass relation

prop to the identity I

$$m_\nu = m_D \frac{1}{M} \mu \frac{1}{M} m_D^T$$

Mohapatra,Valle PRD34

eigenvalues are ***linear***

conbination of two parameters ***a, b***

$$\frac{\chi}{\sqrt{m_2^\nu}} + \frac{\xi}{\sqrt{m_3^\nu}} = \frac{1}{\sqrt{m_1^\nu}}$$

Dorame, M, Peinado, Rojas, Valle, NPB, 1203.0155

4 classes of mass relations

$$\chi m_2^{\nu} + \xi m_3^{\nu} = m_1^{\nu}$$

$$\frac{\chi}{m_2^{\nu}} + \frac{\xi}{m_3^{\nu}} = \frac{1}{m_1^{\nu}}$$

$$\chi \sqrt{m_2^{\nu}} + \xi \sqrt{m_3^{\nu}} = \sqrt{m_1^{\nu}}$$

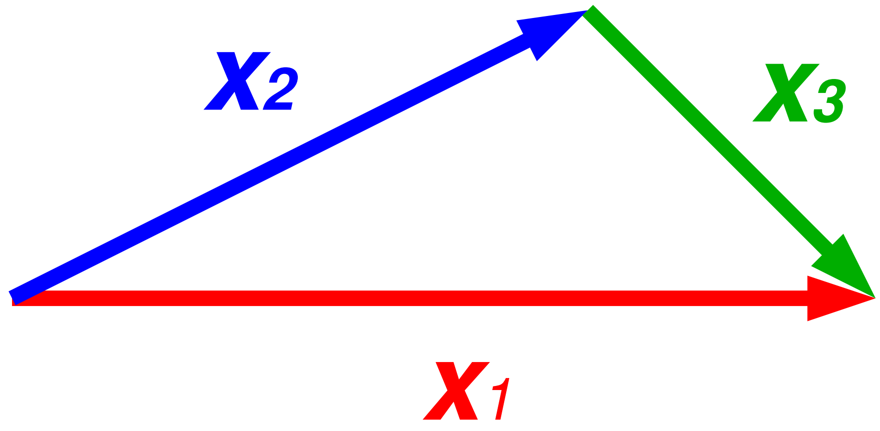
$$\frac{\chi}{\sqrt{m_2^{\nu}}} + \frac{\xi}{\sqrt{m_3^{\nu}}} = \frac{1}{\sqrt{m_1^{\nu}}}$$

Triangle inequality

Barry, Rodejohann NPB842 (2011)

Why are we interested in the mass-sum rules?

$$x_1 = x_2 + x_3$$

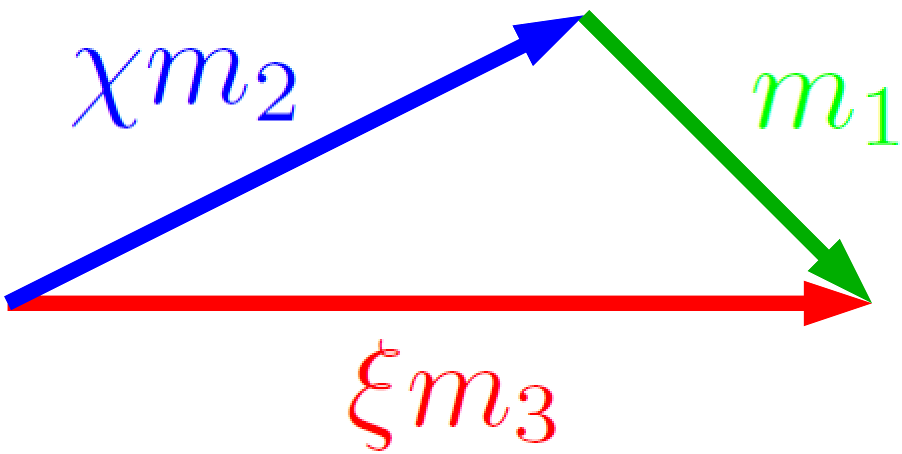


$$|x_1| < |x_2| + |x_3|$$

Triangle inequality

Barry, Rodejohann NPB842 (2011)

$$\chi m_2^\nu + \xi m_3^\nu = m_1^\nu$$

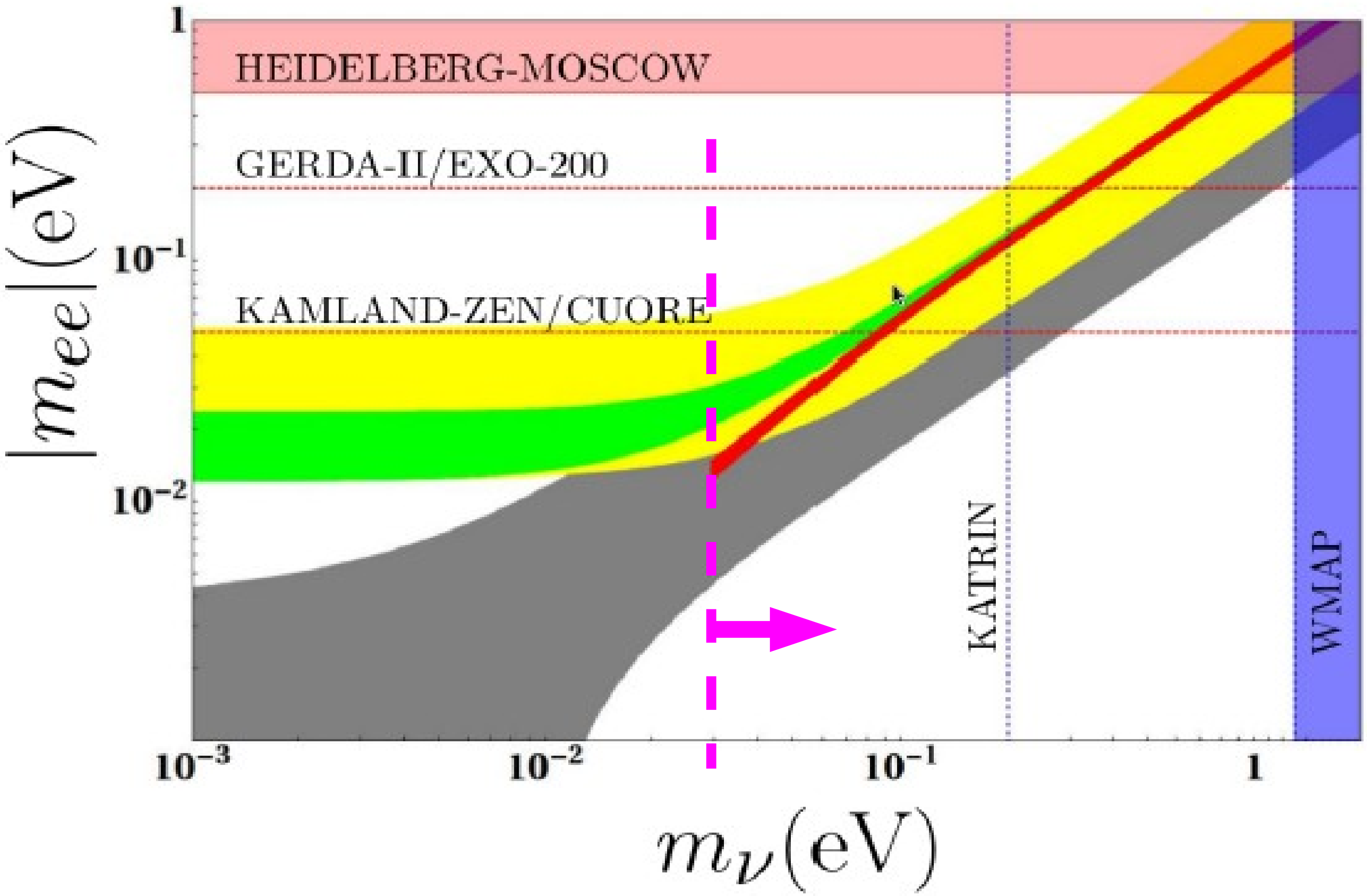


$$|\xi m_3| < |\chi m_2| + |m_1|$$

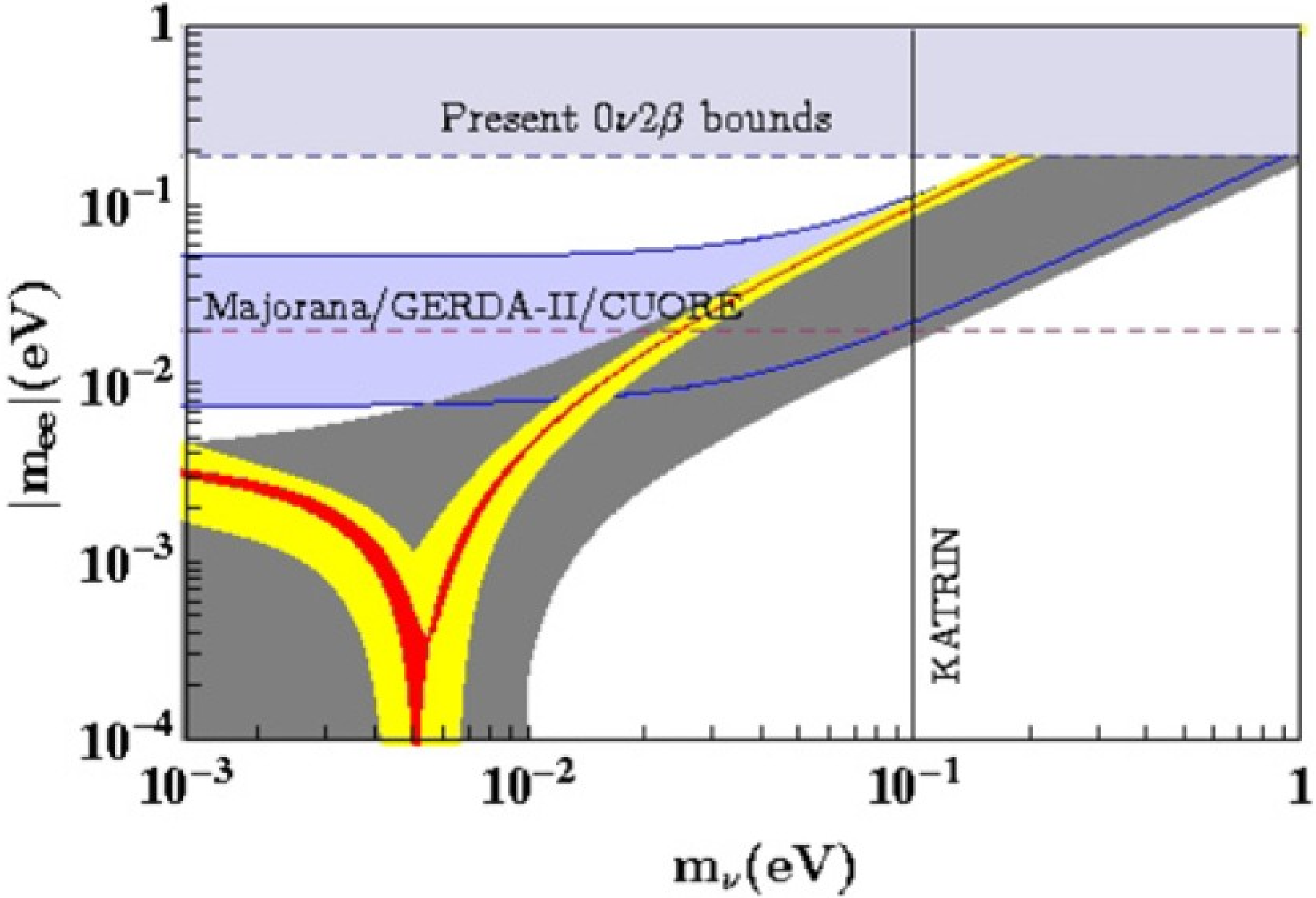
lower limit for the lightest neutrino mass

<u>lower limit for 0nubb</u>

$$m_1^\nu + m_2^\nu = m_3^\nu$$



$$2\sqrt{m_2} + \sqrt{m_3} = \sqrt{m_1}$$

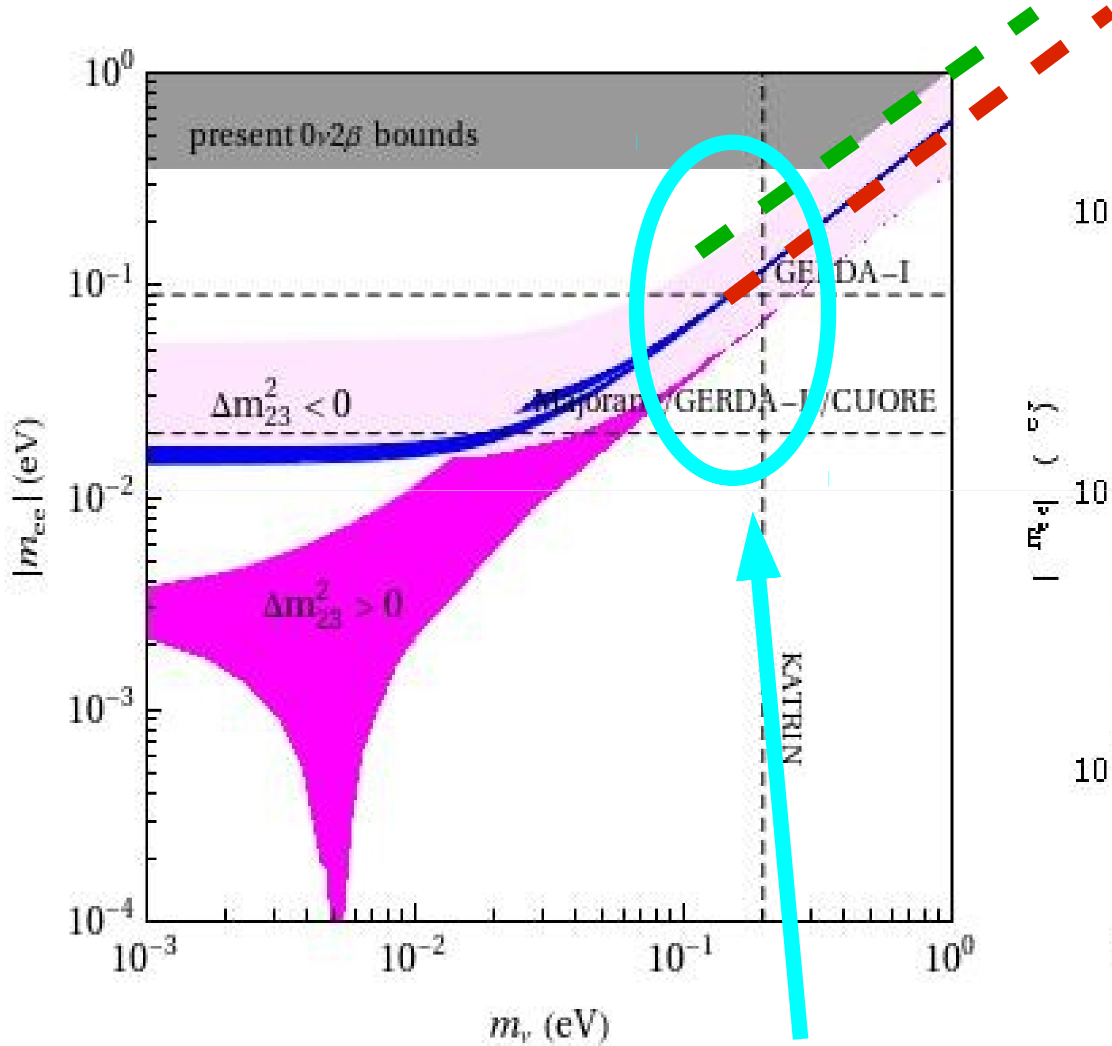


⋆ not possible – not studied

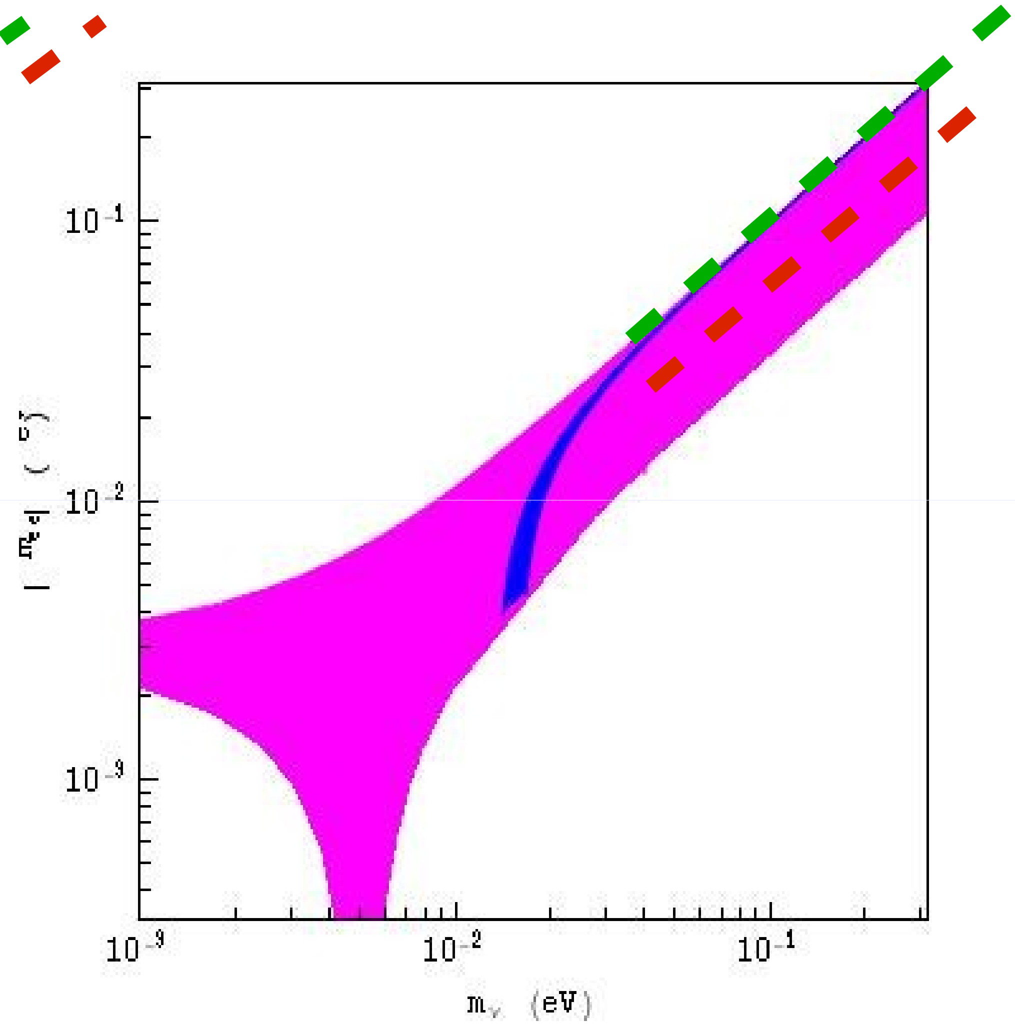
χ, ξ	A–NH	A–IH	Ref.	B–NH	B–IH	Ref.	C–NH	C–IH	Ref.	D–NH	D–IH
1, 1	0.010	0.044	[35–51]	0.008	0.036	[52–54]	0.006	0.029	–	0.005	0.008
1, 2	⋆	0.046	–	0.008	0.027	–	⋆	0.014	–	0.004	0.026
1, 3	⋆	0.011	–	0.030	0.005	–	⋆	0.014	–	0.018	0.025
2, 1	0.006	⋆	[35–42], [43,55]	0.006	0.007	[36,37,45], [51,56–70]	0.000	⋆	[84]	⋆	0.007
2, 2	0.019	0.026	–	0.023	0.008	–	0.017	⋆	–	0.003	0.015
2, 3	⋆	0.046	[90]	0.007	0.008	–	⋆	0.031	–	0.005	0.026
3, 1	0.004	⋆	–	0.004	0.008	–	⋆	⋆	–	⋆	⋆
3, 2	0.011	⋆	–	0.004	0.021	–	0.000	⋆	–	⋆	0.007
3, 3	0.023	0.061	–	0.029	0.031	–	0.011	0.019	–	0.018	0.016

0.061 eV

S4



A4



If **Q.D.** in principle it is possible to experimentally distinguish A4 from S4

Conclusions

- **Fortunately** or **unfortunately** data before 2011 allow the discovery of TBM mixing

- Now we are in front to a *crossroads*: TBM **YES** or **NO** as first order approximation?

- when the three mixing angles are fixed from the flavor symmetries, then we have *mass sum rules*, that give **predictions for 0nubb**

- 0nubb can give some indication to distinguish flavor models like A4, S4,...

Here we assume deviations of the TBM arising from the charged sector

$$V_l = \begin{pmatrix} 1 & \mathcal{O}(\lambda_C) & -\mathcal{O}(\lambda_C) \\ & 1 & \mathcal{O}(\lambda_C) \\ & & 1 \end{pmatrix} \otimes V_\nu = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$

See for instance Antusch, Maurer PRD84 (2011)

$$\sin^2\theta_{12} \sim 0.31, \quad \sin^2\theta_{13} \sim 0.025, \quad \sin^2\theta_{23} \sim 0.40$$

solar trimaximal

large deviation for reactor

atmospheric not maximal