Quo vadis, neutrino flavor models

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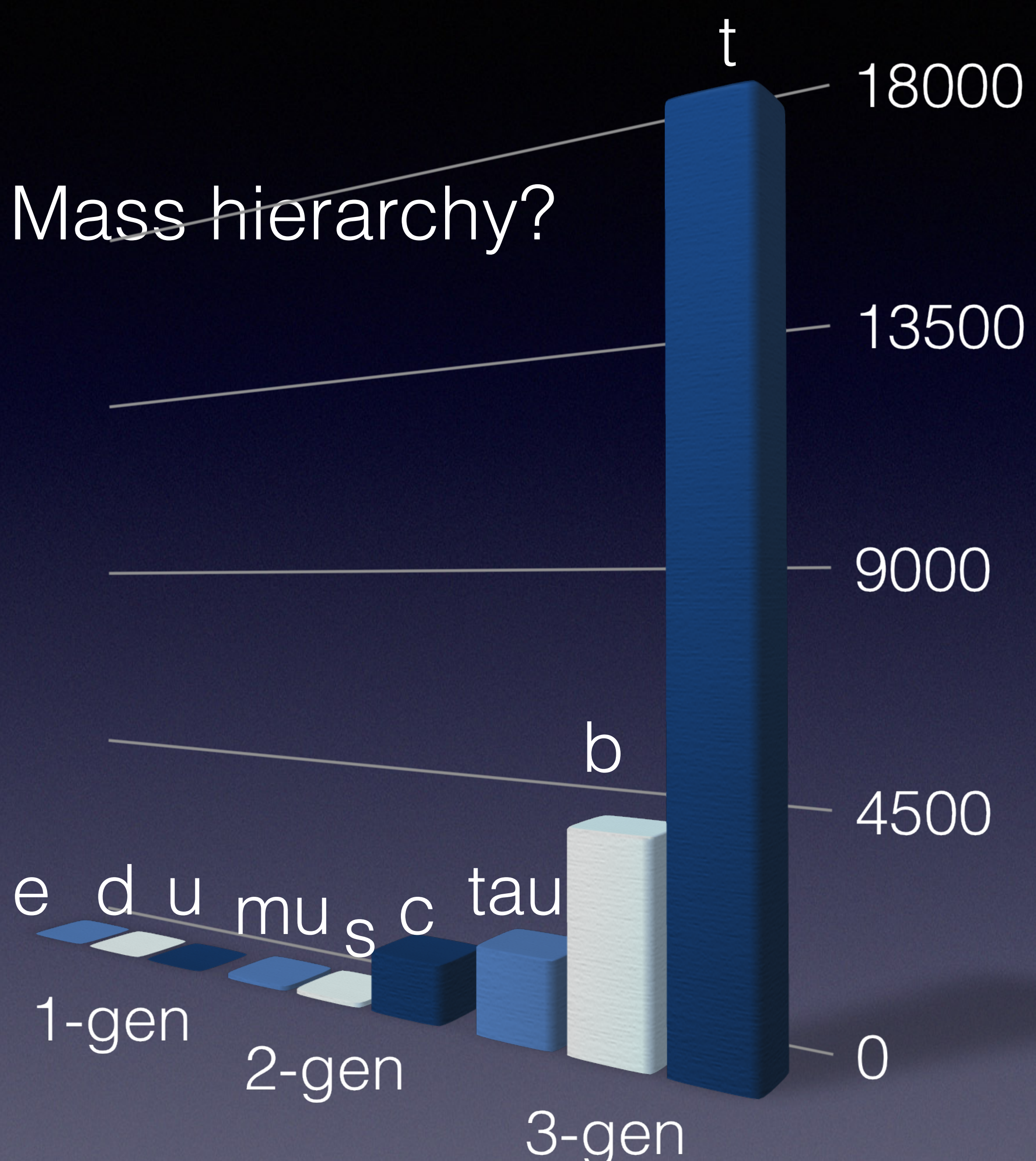
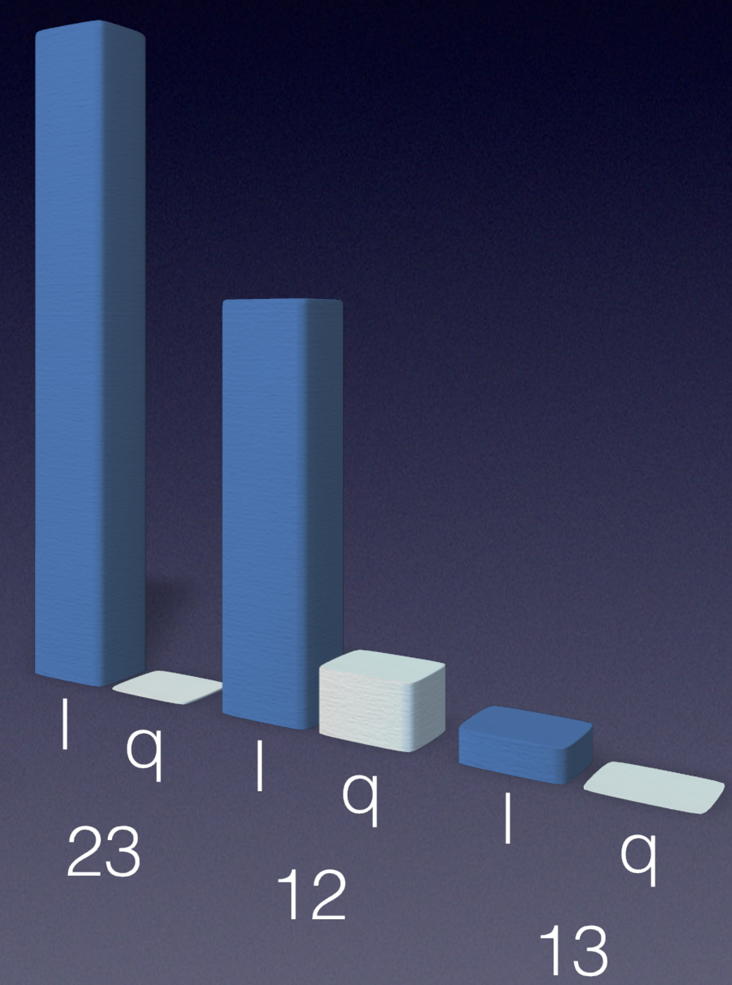
The flavor problem

Mass hierarchy?



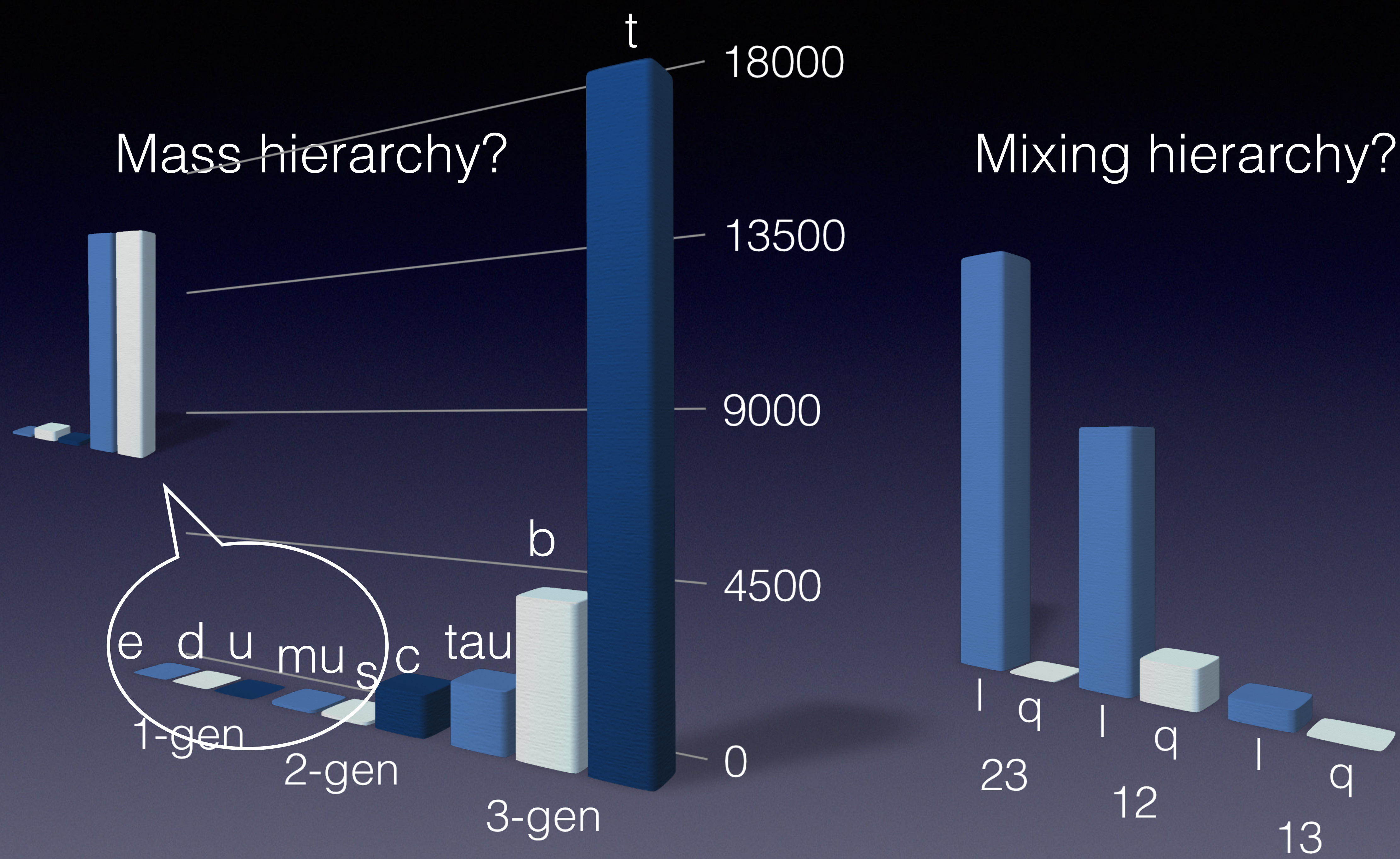
Mixing hierarchy?



why 3 generations?

origin of neutrino mass?

The flavor problem



why 3 generations?

origin of neutrino mass?

The flavor problem

Mass hierarchy?

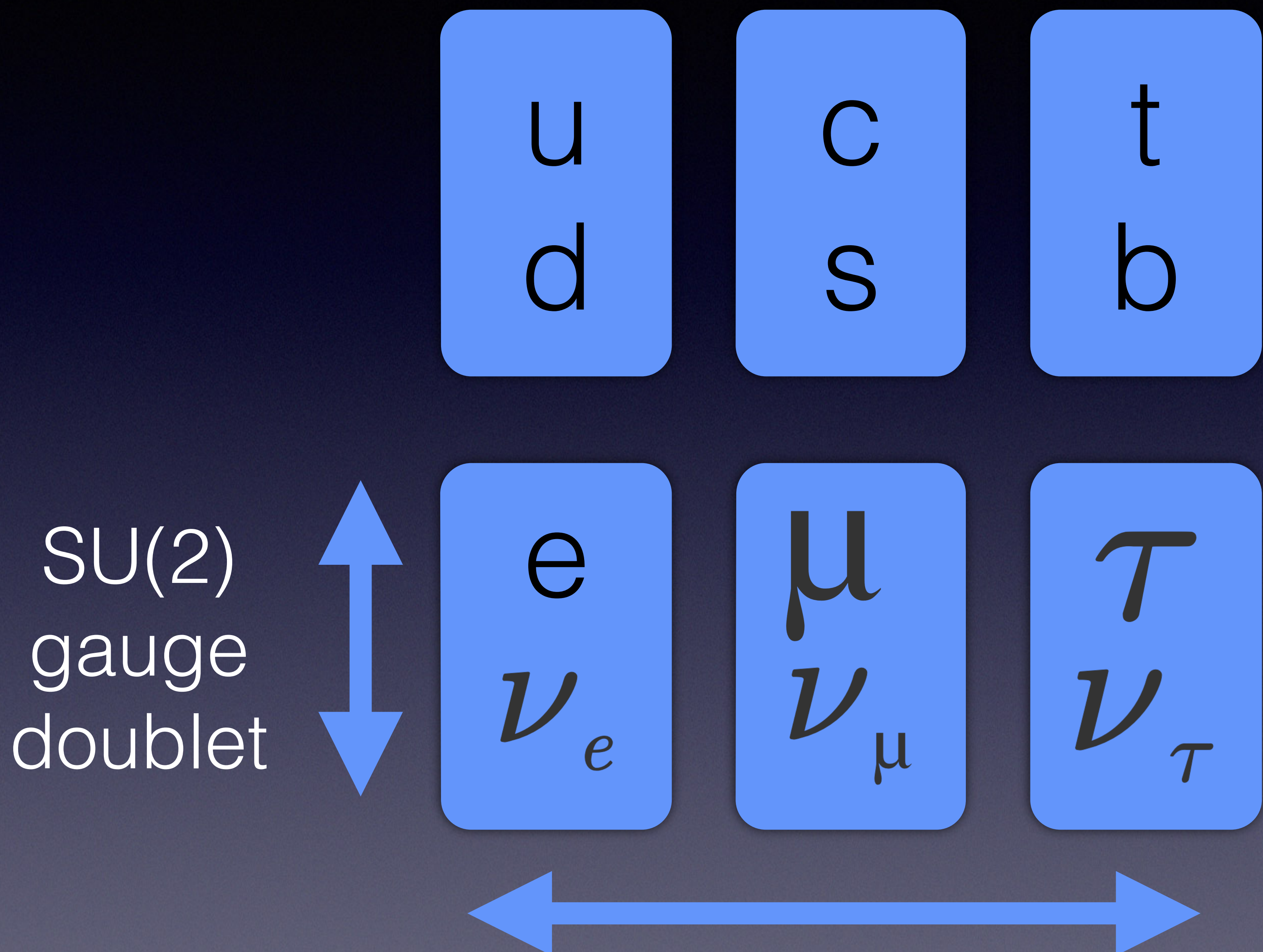
Mixing hierarchy?

Is the flavor problem the evidence of some underlying symmetry?

why 3 generations?

origin of neutrino mass?

Flavor symmetry

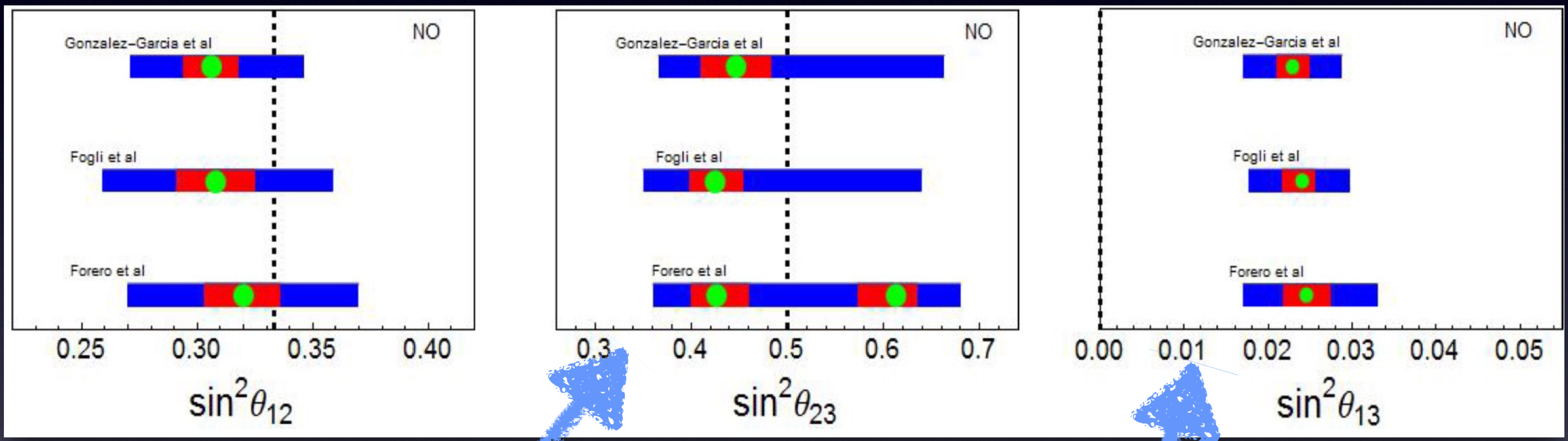


triplet irreducible representation of a flavor group?

Lepton mixing: status

M, proceeding NOW12

large solar | large atmospheric | small reactor



Is the atmospheric angle maximal?

Reactor angle not zero!

Is the atmospheric angle maximal?

Yes

With abelian flavor symmetry difficult to get maximal mixings

Strong indications in favor of non abelian flavor symmetry

No

everything is possible: there are no particular indication on the flavor symmetry...

maximal mixing & mu-tau symmetry

$$\sin\theta_{23} = \frac{1}{\sqrt{2}}$$

$$\sin\theta_{13} = 0$$

→

$$\nu_\mu \leftrightarrow \nu_\tau$$

exchange symmetry
In the neutrino sector

$$m_\mu \ll m_\tau$$

→

$$\mu \not\leftrightarrow \tau$$

exchange symmetry
broken in the
charged sector

Babu, Ma, Valle 02
Grimus, Lavoura, 04
Altarelli, Feruglio 05
Caravaglios, M, 05
......

maximal mixing & mu-tau symmetry

Difficult to get because

$$\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$$

$$\nu_\mu \leftrightarrow \nu_\tau$$

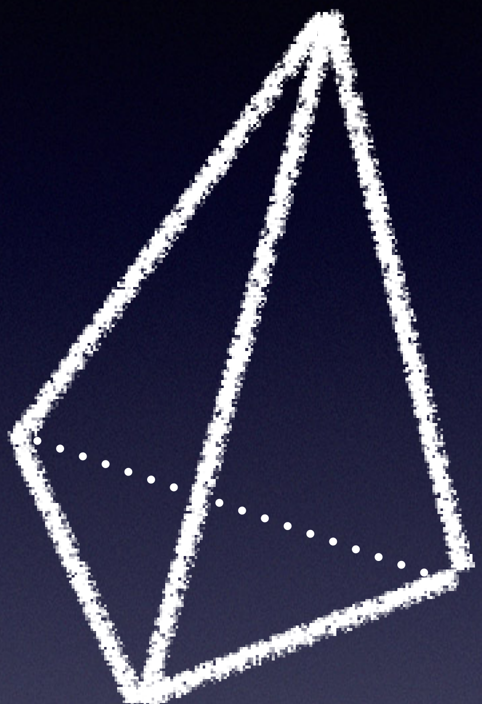
exchange symmetry In the neutrino sector

$$\mu \not\leftrightarrow \tau$$

exchange symmetry broken in the charged sector

maximal atmospheric mixing

origin of mu-tau neutrino symmetry



A4

Non-abelian symmetry
Symmetry of tetrahedron
Triplet representation
Finite subgroup of SU(3)

$$\mu \not\leftrightarrow \tau$$

Broken in the charged lepton sector: but **Z3** preserved

$$\nu_\mu \leftrightarrow \nu_\tau$$

In the neutrino sector

maximal atmospheric mixing and reactor angle

$$\sin\theta_{13} \simeq \lambda_c \neq 0$$

M, Patel, Peinado 11
Boucenna, M, Tortola, Valle 11
King, 12
King, Luhn 12

We expect deviations of the

$$\nu_\mu \leftrightarrow \nu_\tau$$

exchange symmetry in the neutrino sector

What if the atmospheric angle is not maximal?

Anarchy:
neutrino mass matrix
has random entries

$$M = m \begin{pmatrix} O(1) & O(1) & O(1) \\ O(1) & O(1) & O(1) \\ O(1) & O(1) & O(1) \end{pmatrix}$$

Hall, Murayama, Weiner 99

implies mixing and ratio of masses of order one
in rough agreement with data

discrete non abelian symmetries so far are not excluded

connection between atmospheric and reactor angles, i.g.

$$\sin\theta_{23} = \frac{1}{\sqrt{2}} + \sin\theta_{13}\cos\delta$$

mixing sum rule

Ballet, King, Luhn, Pascoli, Schmidt 13

Discrete symmetries & Mass sum rules

$$\alpha m_1 + \beta m_2 = m_3$$

$$\frac{\alpha}{m_1} + \frac{\beta}{m_2} = \frac{1}{m_3}$$

$$\alpha\sqrt{m_1} + \beta\sqrt{m_2} = \sqrt{m_3}$$

$$\frac{\alpha}{\sqrt{m_1}} + \frac{\beta}{\sqrt{m_2}} = \frac{1}{\sqrt{m_3}}$$

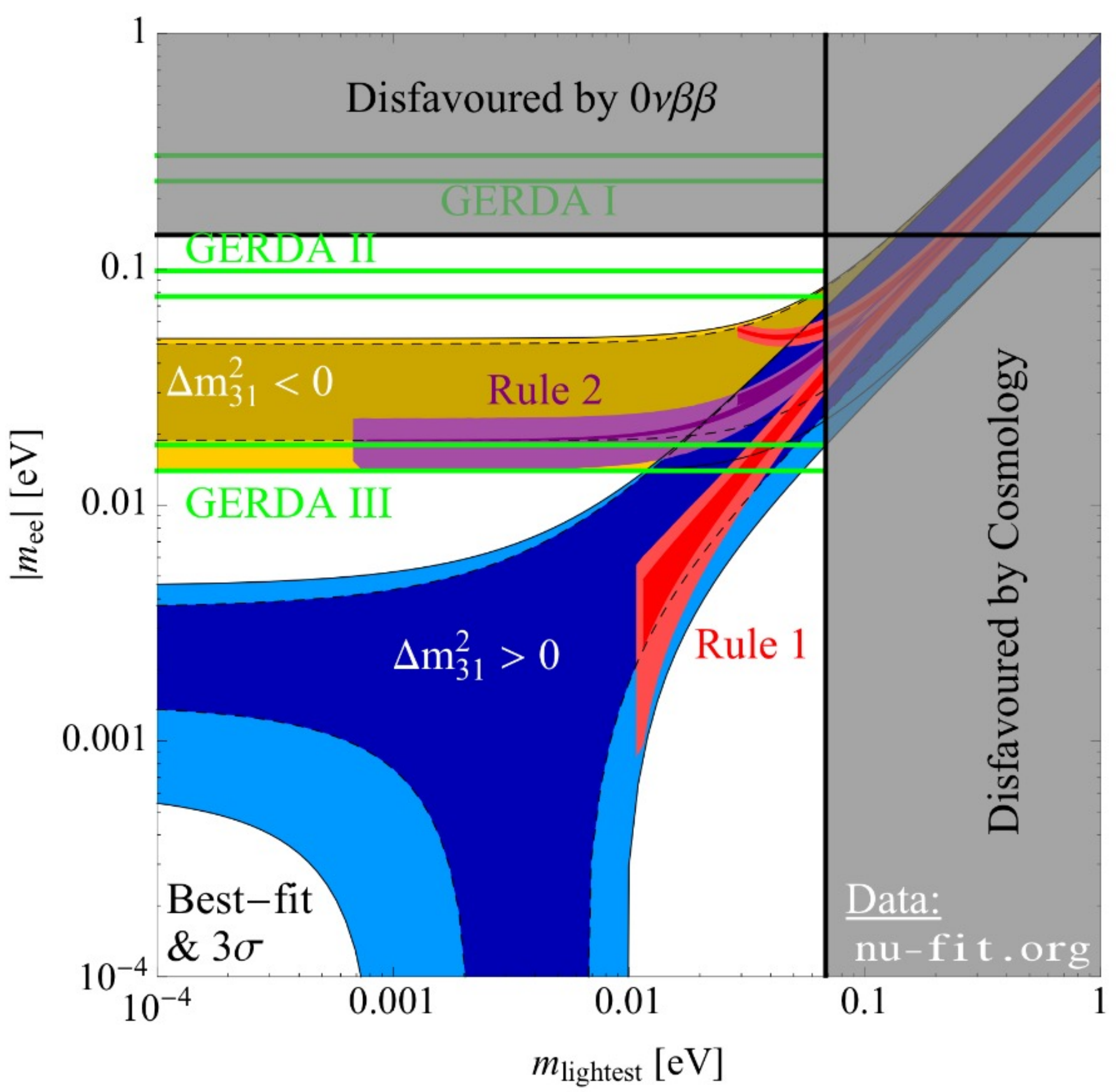
Altarelli, Feruglio, Hagedorn 08
Hirsch, M, Valle 08
Bazzocchi, M, Merlo 09
Altarelli, Meloni 09
Barry, Rodejohann 10/11
Dorame, Meloni, M, Peinado,Valle11

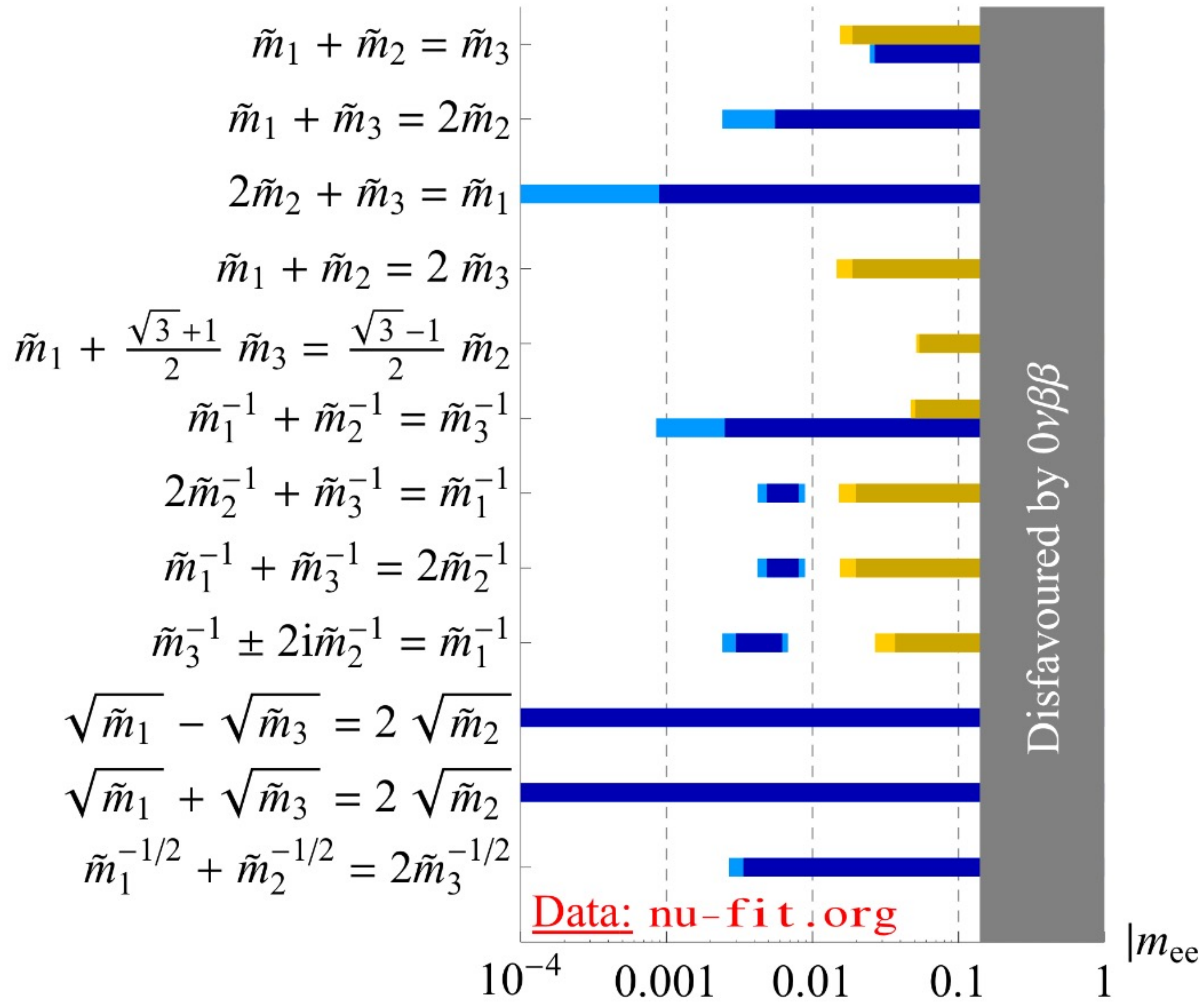
See talk of Merle

Mass sum rules & 0nubb

King, Merle, M, Shimizu, Tanimoto 14

See talk of Merle





Flavor symmetries: multi-Higgs vs flavon

$$y_{ijk}\,\bar{L}_i l_{Rj} H_k$$

$$\frac{1}{\Lambda} y_{ijk}\,\bar{L}_i l_{Rj} H \varphi_k$$

Flavor symmetries: multi-Higgs vs flavon

$$y_{ijk} \bar{L}_i l_{Rj} H_k$$

$$\frac{1}{\Lambda} y_{ijk} \bar{L}_i l_{Rj} H \varphi_k$$

↓

No signal at LHC,...

Flavor symmetries: multi-Higgs vs flavon

$$y_{ijk}\,\bar{L}_i l_{Rj} H_k$$

$$\frac{1}{\Lambda} y_{ijk}\,\bar{L}_i l_{Rj} H \varphi_k$$

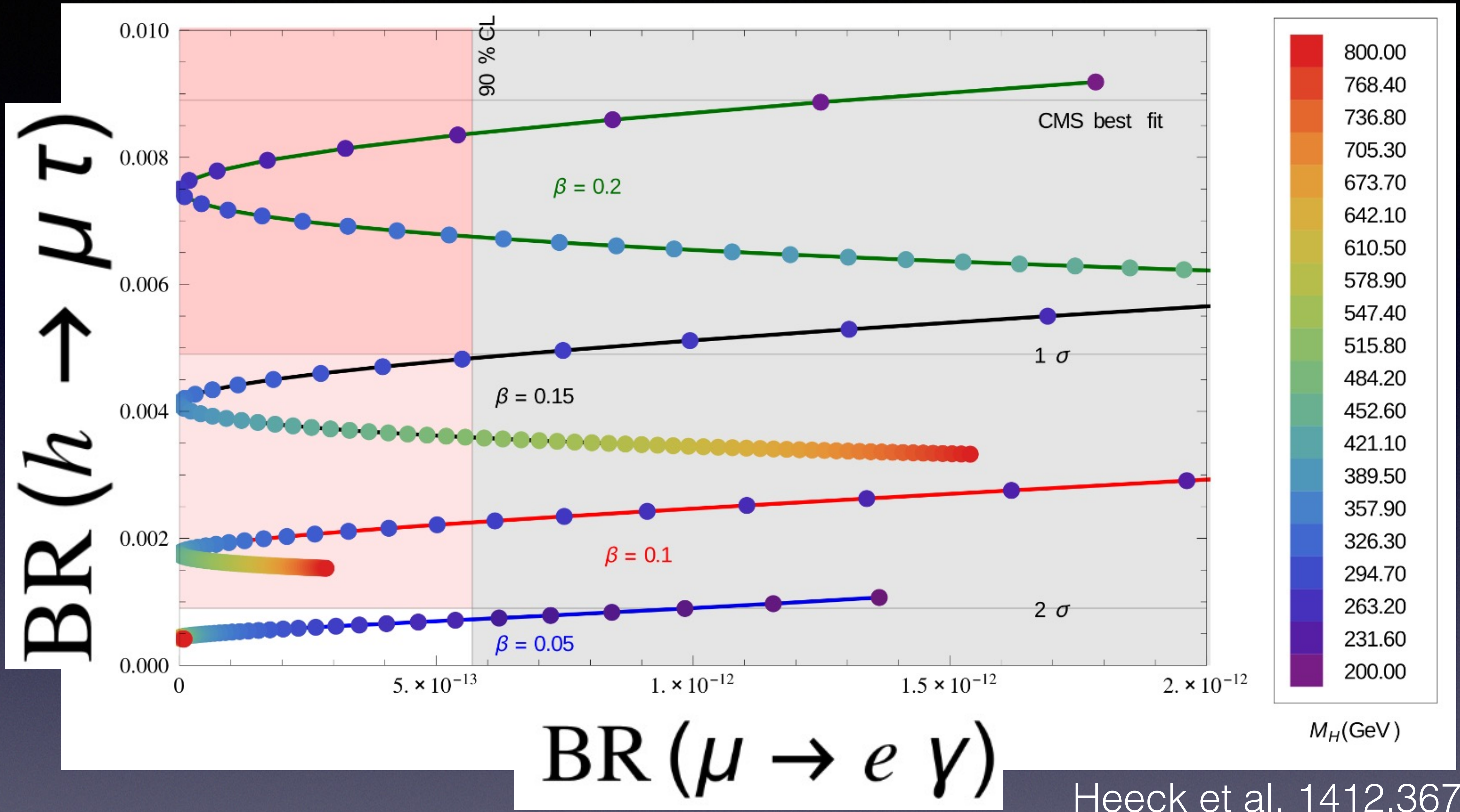
New Higgs at the weak scale FCNC, LFV,...

$$H \to ee, H \to \mu\mu, ...$$

Flavor symmetry gives relations between branching ratios

See talk of Vicente

Higgs decay and flavor symmetry, i.g.



Heeck et al, 1412.3671

Based on A4: it is distinguishable and falsifiable

See also: triality, Ma PRD (10)

Higgs decay in S3, Bhattacharyya et al PRD (12)

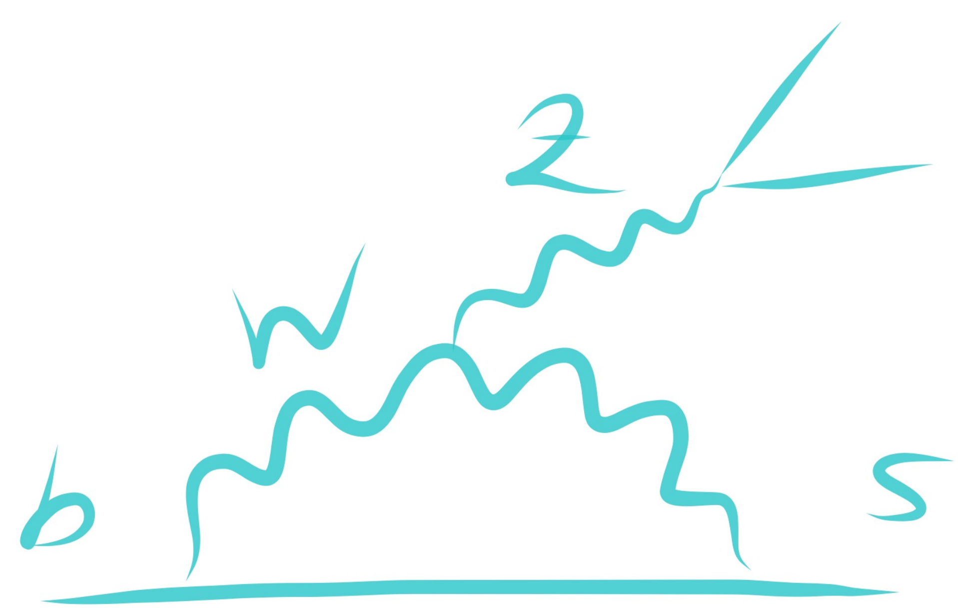
Lepton non-universality and flavor symmetry

$$R_K = \frac{\mathrm{BR}(B \to K\mu^+\mu^-)}{\mathrm{BR}(B \to K e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

Only 2,6 sigma

LHCb collaboration PRL (14)

R = 1 in the SM



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LHCb collaboration PRL (14)

- Minimal Flavor Violation:

Alonso et al 1505.05164
Lee, Tandeon 1505.04692

- Z'

Celis et al1505.03079
Crivellin et al 1504.07928

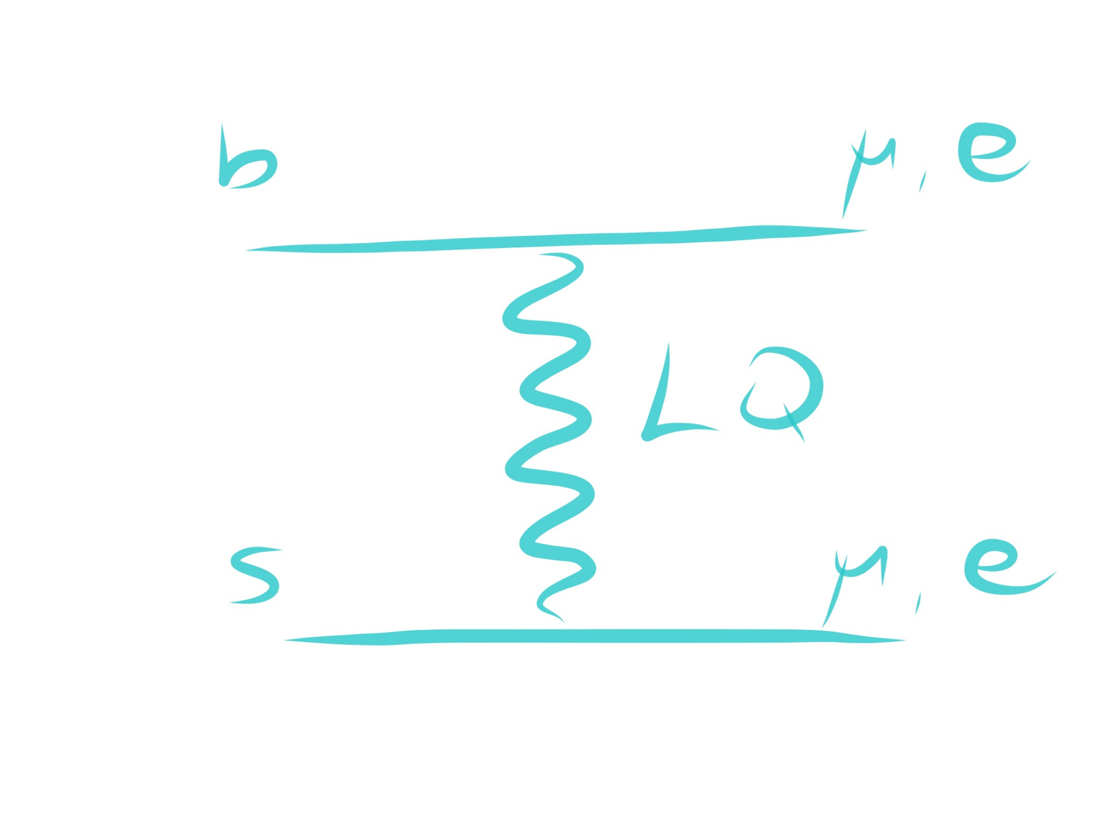
- Neutrino oscillation

Boucenna et al 1503.07099

Lepton non-universality and flavor symmetry

Leptoquark

Hiller, Schmaltz JHEP (15)



$$\mathcal{L} = -\lambda_{q\ell}\,\Delta\,(\bar{q}P_L\ell)$$

SU(2) doublet

$$\mathcal{L} = -\lambda_{q\ell}\,\Delta^*\,(\bar{q}\ell)$$

SU(2) triplet

Lepton non-universality and flavor symmetry

Non-Abelian flavor symmetry

$$\lambda \equiv \begin{pmatrix} \lambda_{de} & \lambda_{d\mu} & \lambda_{d\tau} \\ \lambda_{se} & \lambda_{s\mu} & \lambda_{s\tau} \\ \lambda_{be} & \lambda_{b\mu} & \lambda_{b\tau} \end{pmatrix} \sim \lambda_0 \begin{pmatrix} \rho_d\kappa & \rho_d & \rho_d \\ \rho\kappa & \rho & \rho \\ \kappa & 1 & 1 \end{pmatrix}$$

De Medeiros, Hiller 1503.01084

$$\mathcal{B}(B \to K\mu^\pm e^\mp) \simeq 3 \cdot 10^{-8}\, \kappa^2 \left(\frac{1-R_K}{0.23}\right)^2 ,$$

$$\mathcal{B}(B \to K e^\pm \tau^\mp) \simeq 2 \cdot 10^{-8}\, \kappa^2 \left(\frac{1-R_K}{0.23}\right)^2 ,$$

$$\mathcal{B}(B \to K\mu^\pm \tau^\mp) \simeq 2 \cdot 10^{-8} \left(\frac{1-R_K}{0.23}\right)^2 ,$$

$$\mathcal{B}(\mu \to e\gamma) \simeq 2 \cdot 10^{-12}\, \frac{\kappa^2}{\rho^2} \left(\frac{1-R_K}{0.23}\right)^2 ,$$

$$\mathcal{B}(\tau \to e\gamma) \simeq 4 \cdot 10^{-14}\, \frac{\kappa^2}{\rho^2} \left(\frac{1-R_K}{0.23}\right)^2 ,$$

$$\mathcal{B}(\tau \to \mu\gamma) \simeq 3 \cdot 10^{-14}\, \frac{1}{\rho^2} \left(\frac{1-R_K}{0.23}\right)^2 ,$$

$$\mathcal{B}(\tau \to \mu\eta) \simeq 4 \cdot 10^{-11}\, \rho^2 \left(\frac{1-R_K}{0.23}\right)^2 .$$

Flavor symmetries: from neutrino to quarks

While large neutrino mixing seems to give indication of non-abelian family symmetry

Typically the neutrino flavor symmetries do not naturally fit the quark sector

Non abelian symmetries must be introduced to fit also the quark sector

$$G_f \equiv A_4 \otimes Z_n \otimes U(1)_{fn} \otimes \ldots$$

Flavor symmetries: from neutrino to quarks

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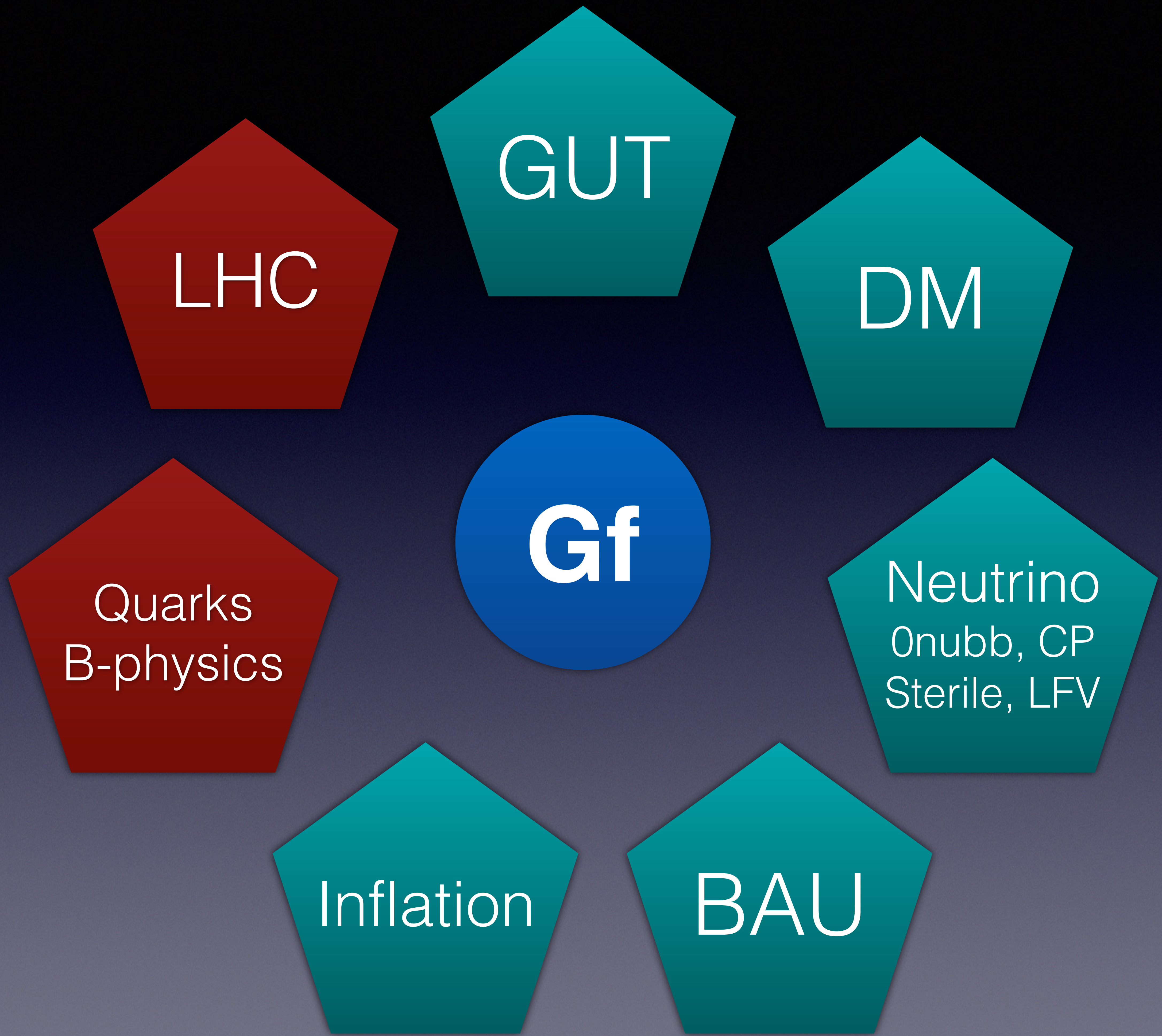
The problem is to find a simple common framework

$$G_f \equiv A_4 \otimes Z_n \otimes U(1)_{fn} \otimes \ldots$$


GUT
LHC
DM
Gf
Quarks
B-physics
Neutrino
0nubb, CP
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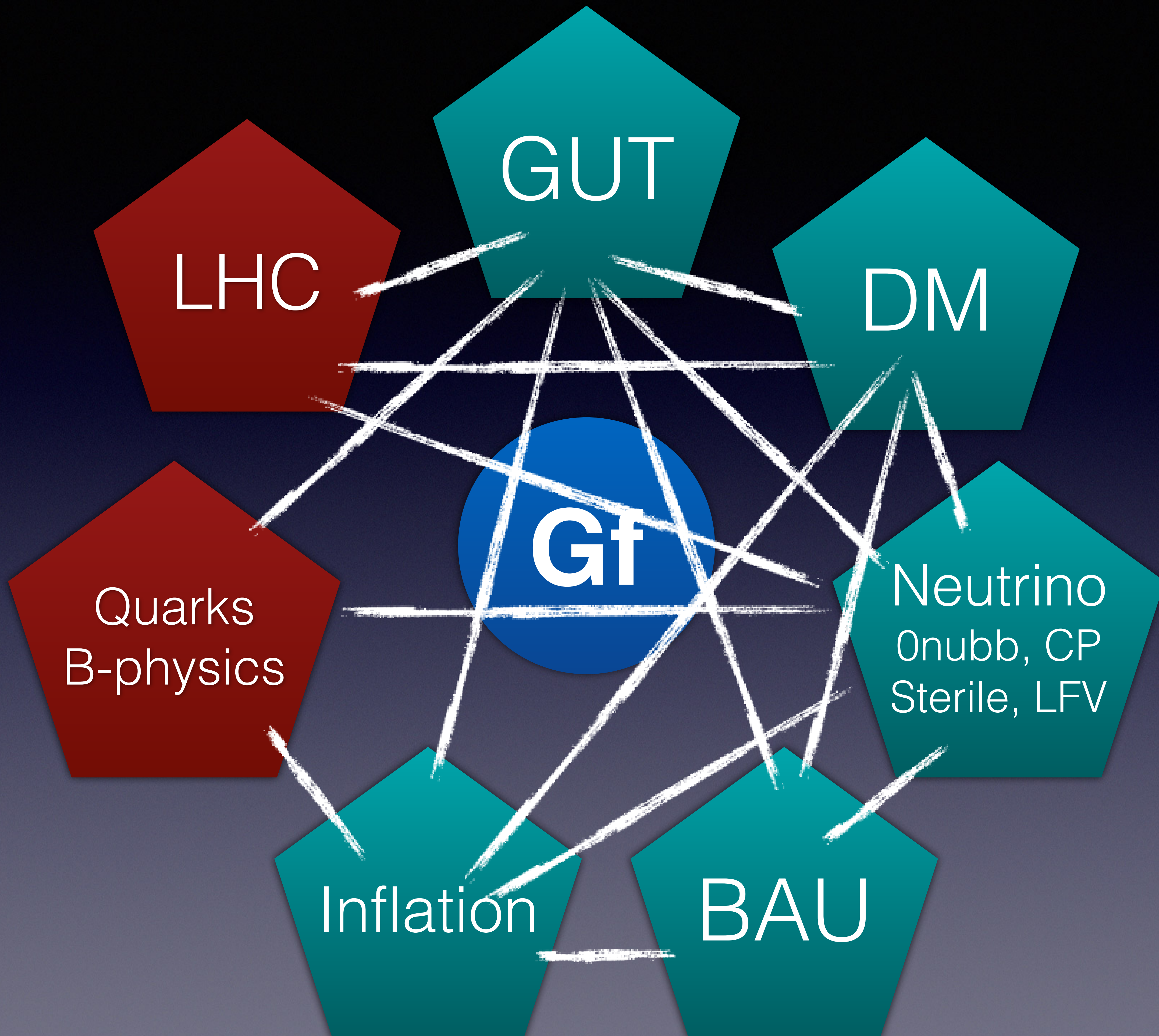
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Summary

The future direction of flavor model building will strongly depend on experimental results:

atmospheric mixing, leptonic CP violation,mass hierarchy,......

If the atmospheric angle is VERY close to be maximal, evidence of a neutrino mu-tau symmetry

If the atmospheric angle is NOT maximal, even anarchy is possible

BUT
flavor symmetries imply testable mixing & mass sum rules

Summary

In the multi-Higgs case,
hopefully LHC will give us some indication

We can also have indications from
Flavor Physics like B decays

From the theoretical point of view, a possible criteria to proceed is to link very different topics and problems like dark matter and neutrino and so on....

Tri-bi-maximal mixing: theoretical ansatz

$$\sin\theta_{12} = \frac{1}{\sqrt{3}}$$

tri-maximal solar angle

reactor angle zero

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

$$\sin\theta_{23} = \frac{1}{\sqrt{2}}$$

maximal atmospheric Angle