NEUTRINO MASS AND NEW PHYSICS

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Implications of the recent results on neutrino masses and mixing to underlying new physics are considered. Various approaches to physics behind neutrino mass are described which include the tri-bimaximal mixing and flavor symmetries, the quark-lepton complementarity and weak complementarity, the quark-lepton universality and unification. Some recent results from string phenomenology are discussed and the issue of model building versus “string engineering” is outlined.

1 Introduction

It is about 11 years since the discovery of neutrino mass. Still, in spite of enormous efforts of many theoreticians and experimentalists the “Physics behind neutrino mass” has not been identified. It should be some “New physics” beyond the Standard Model. It can be the old “new physics” invented many years ago and studied in details theoretically. It can be new “New physics” proposed recently, or something we have not thought about.

The not-yet excluded new physics covers enormous range of possibilities:
- from the eV to Planck mass of the underlying scale (27 orders of magnitude);
- from exact flavor symmetry to anarchy and randomness;
- from quark-lepton unification to fundamental difference of quarks and leptons;
- from attempts to explain the observed features in a single QFT context to idea that nothing can be explained in details and the observed features are result of complicated “evolution” from Planck or string scales to low energies. The only what we really know is that all existing proposals can not be correct simultaneously.

The paper is organized as follows: In Sec. 2 the existing information about masses and mixing is presented and its immediate implications are discussed. In Sec. 3 possible physics behind smallness of neutrino mass is considered. Sec. 3 is devoted to different approaches to explain lepton mixing. Some recent results obtained in the string phenomenology are described and the issue of whether the ends (the bottom-up and top-down approaches) meet is addressed in Sec. 5.

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Data and Implications

Analysis of results from neutrino propagation experiments with neutrinos from the sun, atmosphere, reactors and accelerators, in terms of oscillations and adiabatic conversion (the MSW effect) gives now rather precise determinations of mass squared differences \( \Delta m_{ij}^2 \) and mixing angles \( \theta_{ij} \). (For recent analysis see [8].) Few conclusions follow immediately.

1). The absolute mass scale: From MINOS and atmospheric neutrino data we have \( m_i > \sqrt{\Delta m_{31}^2} > 0.045 \) eV \((i = 1, 3)\). Cosmology gives an upper bound on the sum of masses which implies \( m \approx 1 \text{ eV} \). Consequently, the heaviest neutrino should have the mass in the range
\[
m = (0.04 - 0.3) \text{ eV},
\]
and the upper part of this region will be explored by KATRIN.

2). Mass hierarchy: \( \Delta m_{31}^2 \) and small mass split, \( \Delta m_{21}^2 \), that follows from the solar neutrino experiments and KAMLAND give
\[
m_2 \geq \sqrt{\frac{\Delta m_{21}^2}{\Delta m_{31}^2}} \approx 0.18,
\]
which means that neutrinos have the weakest mass hierarchy (if any) among the known fermions (quarks and leptons). The latter may be related to the large lepton mixing.

3). Nature of neutrino mass: The smallness may indicate that nature of neutrino mass (or at least what we extract from oscillation experiments) differs from the one of other fermions. Is \( m_\nu \) of the same nature as the mass of electron or top quark? Is \( m_\nu \) of oscillations = \( m_\nu \) of kinematics? In general,
\[
m_\nu = m_{\text{standard}} + m_{\text{soft}}(E, n),
\]
where \( m_{\text{soft}}(E, n) \) is the medium (environment) dependent ("soft") component. Can \( m_{\text{soft}} \) dominate? E.g. in [14] it was shown that the density-dependent soft masses of the form \( m_i = m_0 \tanh(\lambda_i \rho(g/cm^3)) \) with \( m_0 = 5 \cdot 10^{-2} \) eV and \( \lambda_i = (0, 0.06, 3) \) allow one to explain most of the oscillation data.

Of course, the outstanding dilemma is Dirac versus Majorana.

4). Mixing: Information about mixing is encoded in the Fig. 1, where one can see few salient features: (i) admixture of the \( \nu_e \) flavor in the third state is small or zero; (ii) the muon and tau flavors are mixed in this third state almost equally; (iii) all three flavors are mixed in the second flavor nearly equally:
\[
|U_{e3}|^2 \equiv \sin^2 \theta_{13} < 0.05; \quad |U_{\mu 3}|^2 \approx |U_{\tau 3}|^2 \approx \frac{1}{2}; \quad |U_{e2}|^2 \approx |U_{\mu 2}|^2 \approx |U_{\tau 2}|^2 \approx \frac{1}{3}.
\]

As a consequence, \( \tan^2 \theta_{12} = |U_{e2}|^2/|U_{e1}|^2 \approx 1/2 \), \( \tan^2 \theta_{23} = |U_{\mu 2}|^2/|U_{\tau 3}|^2 \approx 1 \). In the case \( |U_{e3}|^2 = 0 \) and exact other equalities in [5] we deal with the tri-bimaximal mixing (TBM) scheme. The latest experimental results, however, testify for certain deviation from the TBM-scheme. In particular, complete three neutrino analysis of the atmospheric neutrino data, which includes the 1-2 mass split, leads to
\[
\sin^2 \theta_{23} \sim 0.43 - 0.47 \quad (0.5).
\]
(We show in brackets the TBM predictions.) Recent results from solar neutrinos, in particular, lower than before ratio of the charged to neutral current rate, give \( \sin^2 \theta_{12} \approx 0.31 \quad (0.33) \). There
Figure 1: Neutrino mass and mixing spectrum which corresponds to the tri-bimaximal mixing (left) and the best fit values of the mixing angles (right).

are certain indications that the 1-3 mixing is nonzero and actually not very small. According to the global analysis of the oscillation data in [8]

$$\sin^2 \theta_{13} \approx 0.016 \pm 0.010.$$  \hspace{1cm} (7)

MINOS [16] has found some excess of the $e-$like events which can be interpreted as due to non-zero 1-3 mixing. Adding this to (7) leads to

$$\sin^2 \theta_{13} \approx 0.02 \pm 0.01 \ (1\sigma).$$  \hspace{1cm} (8)

An independent analysis [9] shows essentially no hint from atmospheric neutrino data. Exact TBM agrees with data at about $(2 - 3)\sigma$ level. Are the deviations from TBM small? In terms of $\sin^2 \theta_{13}$ they indeed look small. However, from theoretical point of view $\sin \theta_{13}$ is more appropriate for which we obtain from Eq. (8) 0.15 (to be compared with $\sin \theta_{12} \sim 0.55$).

One clear conclusion is that the patterns of lepton and quark mixings are strongly different.

The same data considered in terms of mixing angles favor another interpretation: comparing quark and lepton mixings one finds that the 1-2 and 2-3 mixing angles in quark and lepton sector sum up to maximal mixing angle:

$$\theta_{12}^q + \kappa \theta_{12}^l \approx \pi/4, \quad \theta_{23}^q + \kappa \theta_{23}^l \approx \pi/4$$  \hspace{1cm} (9)

with $\kappa = 1/\sqrt{2}$ or 1 depending on the way of summation [17].

What can be inferred from the data? Few observations are in order. (i) The data show both order, regularities and some degree of randomness. (ii) No simple relations between all masses and mixings have been found which could testify for simple underlying scenario. (iii) Different pieces of data indicate different underlying physics. Indeed, the scale of neutrino masses may testify for

- Grand Unification (quark-lepton correspondence) via seesaw;
- extra dimensions, especially if masses are of the Dirac type;
- certain symmetry which suppresses the electroweak scale for neutrino mass;
- absence of the RH neutrino components.

The pattern of lepton mixing indicates two completely different possibilities:

- existence of flavor symmetries (in addition, this is supported by fermion mass hierarchy, and Koide relations [18] for the masses of charged leptons);
- “anarchy” [19].
3 Mass scales and mechanisms

There are two issues related to the scale of neutrino mass: (i) suppression of “natural” electroweak scale; (ii) generation of small mass measured in oscillations. Seesaw mechanism\textsuperscript{20} does these two things simultaneously. No additional symmetry is needed. On the other hand, the seesaw can only work as a mechanism of suppression if, e.g., the RH neutrino masses are at the Planck scale. Then dominant contribution to neutrino mass comes from some other mechanism. Apart from the seesaw, suppression of the EW scale mass can be due to certain symmetry (which looks unnatural if it is introduced for the RH neutrinos only), or multi-singlet mechanisms which rely on existence of new neutral leptons, singlets - of the SM symmetry group.

There are several different versions of the seesaw mechanism. If at the effective level neutrino masses are generated by the D=5 operator with only SM fields, $LLHH/M^2$, there are three tree level realizations related to the type of exchanged heavy particles: type-I (with exchange of singlet RH neutrinos)\textsuperscript{20}, type-II (with $SU(2)$-triplet scalar boson)\textsuperscript{22}, type-III\textsuperscript{23} (with neutral fermion from the $SU(2)$ triplet).

One can invent other mechanisms which lead at the effective level to the D=5 operators with higher representations for the scalar fields $\Phi_k$ ($k$ being the dimension of representation): $M^{-1}LL\Phi_k\Phi_n$. Also high dimension operators can be used with more than two scalar fields which would require lower scale of the underlying physics (see, e.g.\textsuperscript{24}).

The extra (spatial) dimension mechanisms are based on the overlap suppression and natural for the Dirac neutrinos. Indeed, different localizations of the LH the RH neutrino components can be related to their different gauge properties ($N_R$ have no SM interactions). The Yukawa coupling is proportional to degree of overlap of the LH and RH wave functions $\alpha$, so that in 4D we have

$$m_{EW} = \alpha \bar{f}_L f_R + h.c.. \tag{10}$$

Different versions of this suppression depend on an extra-dimensions setup. In the ADD case (flat extra dimensions)\textsuperscript{25}, $N^c$ being a singlet of SM symmetry group can reside in the bulk of extra dimensions, whereas $\nu_L$ is localized on the brane, so the overlap equals $\alpha = M_s/M_{PL}$ where $M_s$ is the fundamental scale of theory. In the RS scenario, $\nu_L$ and $N^c$ are localized on different branes (the EW and Planck ones)\textsuperscript{26} with exponentially decreasing wave functions with distance from the corresponding branes. Here $\alpha \sim M_{PL}(v_{EW}/M_{PL})^{\nu+0.5}$, where $\nu = 1.1 - 1.6$.

Small effective Yukawa couplings can be a consequence of certain symmetry which suppresses the couplings at the renormalizable level. Then non-renormalizable operators

$$a\bar{L}\nu RH \frac{S}{M} \tag{11}$$

produce effective Yukawa coupling $h = a\langle S \rangle/M$. For $a = O(1)$, we need $\langle S \rangle/M \sim 10^{-13}$. This smallness can appear e.g. as the ratio of SUSY and GUT (or Planck) scales: $h \sim m_{3/2}/M_{Pl}$, etc.. One can consider higher dimensional operators

$$a\bar{L}\nu RH \frac{S_1...S_n}{M^n}. \tag{12}$$

Supersymmetry opens various new possibilities: there are genuine SUSY mechanisms of neutrino mass generation with rather particular features. SUSY provides new mass scales: the SUSY breaking scale, $m_{3/2}$, as well as the SUSY conserving mass term for two Higgses $\mu$\textsuperscript{27}. The neutrino mass can appear as

$$m_\nu \sim \frac{1}{M_{GUT}}\mu v_{EW} \text{ or } m_\nu \sim \frac{1}{M_{GUT}} m_{3/2} v_{EW}. \tag{13}$$

In SUSY neutrinos are not unique: the neutralinos, have similar properties. Neutrinos can mix with neutralinos (if R-parity is broken) which leads to yet another mechanism of neutrino mass generation\textsuperscript{28}. 

4 Mixing and new physics

There are several approaches to understand neutrino mixing which have different implications for the fundamental theory. They differ by possible relations between masses and mixings and also by degree of connection of quarks and leptons.

4.1 Tri-bimaximal mixing

• It is assumed that the (approximate) TBM is not accidental but rather straightforward consequence of some flavor symmetry $G_f$.

• This implies the form-invariant mass matrices and absence of relation between masses and mixing. Extensions to quarks are usually problematic.

The symmetry $G_f$ should be broken spontaneously or be valid in some part of the Lagrangian only. The most popular and minimal (?) is $G_f = A_4$ (see general statements in [30][31]). The group has triplet (real) representation and three inequivalent singlet representations. This is somehow minimal set which gives enough freedom to construct viable models. Other possibilities include $G_f = S_4, T_7, \Delta(3n^2)$, etc..

General idea to explain mixing is the following. Mixing appears as a result of different ways of the original flavor symmetry breaking in the neutrino and charged lepton sectors. Symmetry is not broken completely: there are certain residual symmetries in both (Yukawa) sectors:

$$G_f \rightarrow \begin{cases} G_l & \text{for charged leptons} \\ G_\nu & \text{for neutrinos.} \end{cases}$$

(14)

Furthermore, the residual symmetries are different: $G_l \neq G_\nu$. These symmetries determine certain structures of the mass matrices which then lead to the required mixing: E.g. $G_l$ ensures that the charged lepton mass matrix $M_l$ is diagonal, whereas the neutrino mass matrix $M_\nu$ is of the TBM-type. Usually (at least in the case of $A_4$) $G_\nu$ is not enough to fix the TBM form and some additional symmetry, like $\nu_\mu \leftrightarrow \nu_\tau$, $A_{\mu\tau}$, is needed. It can appear as an “accidental” symmetry which is a consequence of specific choice of the flavon representations and particular configuration of VEV’s.

In turn, different ways of the symmetry breaking in the neutrino and charged lepton sectors originate from different flavor (symmetry) assignments for the right handed components of leptons: $N^c$ and $l^c$, and correspondingly, different Higgs multiplets which give masses to charged leptons and neutrinos. Thus, origins of mixing are in different symmetry assignments for the RH components. In many cases this is inconsistent with the L-R symmetry and grand unification. At the same time, the RH components have different EW hypercharges. So, one can somehow correlate different Yukawa sectors with hypercharges. All this looks rather complicated but, in fact, something similar may follow from string theory (see below). The difference of mixings can also be related to existence of the Majorana mass terms of RH neutrinos (whereas the Dirac sectors could be similar in quark and lepton sectors).

Let us illustrate realization of this idea using model[32], which is probably the simplest and the most advanced, in a sense that most of the features are explained using symmetry (choice of field multiplets and symmetry assignments). The model is based on the $A_4 \times Z_4$ flavor group. Mixing originates both from different symmetry properties of the RH components of charged leptons and neutrinos and from the Majorana mass terms of the RH neutrinos. A general structure of the Yukawa sector of the model is shown in Fig. 2.

Indeed, $l^c$ are singlets 1 of $A_4$ and transform as with 1, i, −1 under $Z_4$ transformations. In contrast, $N^c$ form triplet of $A_4$ and all three components transform with −1 under $Z_4$. Higgs
Figure 2: The Yukawa sector and flavon content of the model. Colors indicate transformation properties of the corresponding multiplets with respect to $A_4$; complex numbers at the notations of multiplets give the transformation properties with respect to $Z_4$.

sectors for neutrinos and charged leptons are not symmetric. Flavor symmetry is broken by flavons. The charged lepton masses are generated by non-renormalizable terms

$$\frac{1}{\Lambda^{n+k}_f} L^c(\phi_T)^n(\xi^c)^kH_d.$$  \hspace{1cm} (15)

In contrast, the neutrino Dirac mass is generated without violation of flavor at three level: $LN^cH_u$. The Majorana masses have both flavor conserving and flavor violating contributions:

$$N^cN^c(M + g\xi) + N^cN^c\phi_S$$  \hspace{1cm} (16)

($g$ is constant). Notice that flavons involved here are different from those for charge leptons.

The symmetry $Z_4$ (in some other versions $U(1)$) is required to produce hierarchy of charged lepton masses as well as to forbid “unwanted” interactions.

Some comments which have generic character for this model building follow.

1). Symmetry properties assignment is done essentially ad hoc which should be considered as another “discrete” degree of freedom. According to Fig.2 the assignment looks rather accidental (there is no guide or system or rule), some simple representations are missed. It is rather doubtful that this can be embedded in an extended group structure. The assignment prevents from immediate grand unification like $SO(10)$ or even L-R symmetry, and further substantial complications are required.

2). Vacuum alignment of flavons. Flavor symmetry should be broken (see however for scenario with unbroken or softly broken symmetry). Therefore the observed flavor structure depends both on symmetry of couplings and also on vacuum configuration. To achieve the required alignment one needs to further extend the model: introduce “driving” scalar fields (flavons), and to use supersymmetry. (Flavons and driving flavons differ by $R$–charges with respect to $U(1)_R$ symmetry). Still, masses of neutrinos are not defined and only some bounds exist.

An alternative would be to employ physics of extra dimensions. In fact, extra D offer a different origin of 3 generations. That changes whole approach to fermionic masses.

Complexity of models and deviations of angles from TBM values add some more doubts in correctness of interpretation of the observed tri-bimaximal mixing. Still several possibilities
exist: (i) TBM is exact and it implies existence of underlying flavor symmetry; (ii) TBM is only the first approximation and deviations exist which are consequences of the flavor symmetry violation and RGE effects; (iii) the approximate TBM is just numerical coincidence without any fundamental implications. Immediate flavor symmetry is misinterpretation. TBM may be a result of interplay of different factors not related to symmetry; (iv) large deviations from TBM are possible and the observed mixing has origins unrelated to the flavor symmetries.

4.2 Quark-lepton complementarity

This concept is based on observations in Eq. (9). Qualitatively one finds certain correlation of angles:

the 2-3 leptonic mixing is close to maximal because the 2-3 quark mixing is small;
the 1-2 leptonic mixing deviates from maximal substantially because the 1-2 quark mixing is relatively large.

In other words “lepton mixing = bi – maximal mixing – quark mixing”. Possible implications of QLC

- Quark - lepton symmetry or unification, or alternatively, common flavor symmetry.
- Existence of structure in theory which generates the bi-maximal mixing.

One can develop some perturbative realization of QLC. In the lowest order the quark mixing is absent and the lepton mixing is the bi-maximal $V_{BM} = V_{23}V_{12}$ (product of the two rotations on the angles $\pi/4$):

$$U^0_{CKM} = I, \quad U^0_{PMNS} = V_{bm}. \quad (17)$$

The CKM mixing, the deviations of lepton mixing from bi-maximal and possibly generation of light fermion masses have the same origin. In the context of seesaw certain structure of the RH neutrino mass matrix can produce the bi-maximal mixing. The Dirac mass matrices (related by GUT) are origins of CKM and the deviations.

The deviations may not be (at least directly) related to GUT or quark-lepton symmetry, but be a generic features of flavor physics. Indeed, (i) QLC relations are not exact (though the deviations can be well due to RGE effects or some other corrections). (ii) There are relations of the type

$$\sqrt{m_d/m_s} \sim \sqrt{m_t/m_\tau} \sim \theta_c. \quad (18)$$

That is, the same parameter of the Cabibbo angle size appears in various places, and it can be considered as a kind of “quantum” of flavor physics. This feature was called “Cabibbo haze” in Ref. 38 and recently, the “weak complementarity” in Ref. 39.

Again it may have some perturbative realization: the deviations are due to the high order corrections. In models with flavor symmetry and flavons the lowest order generates mixing given in Eq. (17). The first order corrections $\sim \langle \phi \rangle / \Lambda_f$ generate simultaneously the Cabibbo mixing and deviation from bi-maximal mixing: GUT is not necessary. Due to residual or accidental symmetry some corrections may appear in higher orders, thus producing hierarchies of three generations. Model of this type has been proposed in 40.

4.3 Quark-lepton universality and unification

In this approach there is no fundamental difference between quarks and leptons. No special symmetries in the quark and/or lepton sectors exists.

- There is the quark-lepton symmetry, or correspondence, or unification with SO(10) being the most appealing.
• The differences between quark and lepton mixings and mass spectra originate from differences of known (gauge) properties of quarks and leptons, in particular, neutrality of neutrinos.

The arguments in favor of this point are (i) apparent quark-lepton correspondence which can be described in terms of the Pati-Salam symmetry - consideration of leptons as 4th color; (ii) embedding of known fermions plus well motivated RH neutrino into 16-plet of SO(10). (iii) unification of three different interaction. It is difficult to believe that these facts are accidental.

Smallness of neutrino mass itself can testify for GUT. In the context of seesaw, the required values of masses of the RH neutrinos indicate existence of mass scale which is close or coincides with the GUT scale. There are two possibilities here. In the presence of mixing the largest RH neutrino mass can simply coincide with the GUT scale: $M_R \approx M_{GUT}$. In this case masses should have strong (quadratic) hierarchy $M_2 \sim (10^{12} - 10^{13})$ GeV and $M_1 \sim 10^8$ GeV, which in turn, can lead to the large lepton mixing via the seesaw enhancement. The CP-violating decays of $N_1$ can realize the leptogenesis in the Universe. Another possibility: $M_R \approx M_{GUT}^2 / M_{PI}$. It can be realized if singlet fermions with masses at the Planck scale exist and mix with RH neutrinos at $M_{GUT}$ (double seesaw).

The difference of mass and mixing spectra of quarks and leptons can be related to the neutrality of neutrinos. There are various realizations of this idea.

1. Seesaw itself: due to neutrality the RH neutrinos have large Majorana masses, which leads to smallness of neutrino mass, and simultaneously, particular structure of the RH neutrino mass matrix enhances mixing.

2. Singlet fermions (from hidden sector) can exist. Due to neutrality only neutrinos can mix with these singlets. Possible scenario is, e.g. the SO(10) model with 16 plets of fermions plus some number (which, in fact, can be as big as several hundreds) of singlet fermion fields. These singlets can mix both with usual LH and RH neutrino components. Such a mixing can (i) decrease the effective scale of seesaw; (ii) enhance mixing; (iii) produce zero order mixing; (iv) “screen” the Dirac mass hierarchies in the context of seesaw; (v) produce randomness (anarchy) in the light neutrino mass matrix, and consequently, lepton mixing; (vi) explain smallness of neutrino mass; (vii) generate accidental seesaw symmetries.

5 Do the ends meet?

In the previous sections we have described attempts to identify new underlying physics starting from the data. Does it matches with what string theory can offer? String theory is expected to provide a guidline and context which should help to select among different bottom-up scenarios. It can indicate that something is missed in our QFT considerations.

In general, string theory offers the following “menu” for the effective field theory: (i) GUT, (ii) existence of a number O(100) of singlets of the Standard Model as well GUT symmetry group, (iii) several U(1) gauge factor; (iv) existence of discrete symmetries; (v) heavy vector-like families; (vi) various non-renormalizable interactions (with Planck/string cutoff scale); (vii) explicit violation of symmetries; and extradimensional mechanisms of symmetry breaking; (viii) incomplete GUT multiplets, etc..

Do results of bottom-up approach match with what string theory can offer? Do the ends meet? Many of these elements have been already employed in the model building. String engineering versus model building is the key issue.

The engineering means essentially a play with geometry of the internal space and here we outline one interesting possibility. The F-theory whose phenomenology was elaborated recently can give important insight into underlying physics. The F-theory is certain version of the strongly coupled type IIB string theory. Compactification is “engineered” in such a way that
F-theory leads to $N = 1$ supersymmetry. The corresponding internal space (bulk) where gravity propagates is a complex threefold $B_3$ (6 real dimensions). So, the staring point is 10D field theory.

The gauge field degrees of freedom reside on 8 dimensional surfaces, $S$, $S'$, etc., embedded in 10D bulk and wrapped by seven-branes (the internal dimension of $S$ is 4). Different gauge groups are associated with different surfaces. The GUT group is engineered to be $SU(5)$ or of higher rank.

In F-theory an additional condition is imposed that gravity decouples from the GUT. Decoupling implies that theory does not contain adjoint chiral superfields to break $SU(5)$. Therefore breaking of F-theory $SU(5)$ (with the decoupling) requires introduction of a flux in the hypercharge direction $U_Y(1)$. This leads to GUT symmetry breaking down to the SM symmetry group and also to important consequences for the Yukawa couplings.

The matter and Higgs fields are localized on complex curves in $S$ (2 real internal dimensions). These curves are formed by intersections of the surfaces $S$, $S'$, etc., (see Fig. 3 from [45]). The Yukawa interactions appear at the intersections of these complex curves (real planes).

The main features of the fermion masses and mixing in this context can be formulated in the following way.

1. In the lowest order the Yukawa couplings are given by the overlap of the 6D fields localized on the “matter curves”. They appear at intersection of three matter curves which correspond to matter and Higgs fields. In the case of single intersection of lines of a given type, singular Yukawa matrices are generated

$$Y_{ij} \sim z_i z_j.$$ (19)

Consequently, only one eigenvalue (mass) is non-zero for each type of fermions.

2. Masses of lighter quarks and leptons and mixings appear as a result of corrections due to interactions of matter fields with the background gauge fields (hyperflux). Consequently, the corrections are determined by the gauge coupling. Indeed, the corrections are given by

$$\epsilon \sim \frac{1}{(M_s R_i)^2},$$ (20)

where $M_s$ is the compactification scale of F-theory and $R_i \sim 1/M_{GUT}$ are the lengths of the matter curves. So, $\epsilon \sim (M_{GUT}/M_s)^2$. Using relation between the GUT and string (compactification) scale:

$$M_s^4 = \alpha_{GUT}^{-1} M_{GUT}^4$$ (21)

we obtain

$$\epsilon \sim \sqrt{\alpha_{GUT}}.$$ (22)

Mass matrix elements appear then as powers of this parameter.
3. The fact that GUT symmetry is broken in the hypercharge direction implies that expansion parameters for fermions with different hypercharges are different. So, the origin of Yukawa structures (hierarchies) is in the gauge sector.

4. Large lepton mixing is related to weak mass hierarchy of neutrinos and originates from particular properties of RH neutrinos or objects which play the role of the RH neutrinos in the F-theory context. Notice that the lines of $N_R$ are not in the $SU(5)$ surface but they can cross this surface in one point. This point can be rather far from the intersection of $L$ and $H$ curves which can be used to achieve smallness of the Yukawa coupling.

One interesting possibility is the Kaluza-Klein seesaw. The KK-mass term has the Dirac form $N_R N^c_R$, where only $N_R$ couples with usual lepton doublet and Higgs. Therefore the starting point is structure with covering symmetry and two different sectors with couplings $\bar{L} N_R H$ and $\bar{L'} N^c_R H'$. Then identification $N_R \leftrightarrow N^c_R$, $L \leftrightarrow L'$, etc. (see Fig. 3 right) leads after integration out of the RH neutrinos to the effective 5D operator

$$m = \frac{1}{\Lambda_{UV}} L H_u L H_u.$$ (23)

The fact that infinite tower of states contributes to neutrino mass explains an enhanced mixing and softer mass hierarchy. Up to O(1) coefficients the lepton mixing matrix has the form

$$U_{PMNS} \sim \begin{pmatrix}
1 & \epsilon^{1/2} & \epsilon \\
\epsilon^{1/2} & 1 & \epsilon^{1/2} \\
\epsilon & \epsilon^{1/2} & 1
\end{pmatrix}. $$ (24)

Therefore $\theta_{12} \sim \theta_{23} \sim \frac{\alpha_{GUT}}{4}$, $\theta_{13} \sim \frac{\alpha_{GUT}}{2}$. In quark sector $\sin \theta_C \sim \sqrt{\alpha_{GUT}}$.

The proposed F-theory scenario may have a perturbative field theory interpretation. This consideration is closer to the third (unification) bottom-up approach. The model obtained should include additional heavy fields and symmetries and looks rather complicated and artificial. Structure of the mass and mixing matrices can be described by the $U(1)$ Peccei-Quinn symmetry with expansion parameter $\epsilon$. This to a large extend reproduces features of the Froggatt-Nielsen mechanism. Although here the expansion parameter, the Cabibbo angle, is determined by the gauge coupling. Some discrete symmetries, like $S_4$, can appear as a result of symmetry with respect to rotations in the high dimensions.

6 Conclusions

What is new physics behind neutrino mass? No quick and simple answer, no unique and convincing scenario. Neutrinos did not yet help us to resolve flavor problem, but added new puzzle. Approximate tri-bimaximal mixing or quark-lepton complementarity - appealing phenomenological schemes. Still they can be accidental and misleading, without any fundamental implications. Plausible scenario of the underlying physics could include (i) see-saw with high mass scales, (ii) (broken) flavor symmetry, (iii) quark-lepton symmetry, unification.

Further real progress requires checks of the proposed ideas. This will be done to some extend with forthcoming results on lepton number violating decays, (MEG started to release the first results), measurements of leptonic EDM, results from B-physics, proton decay searches, LHC and other high energy accelerator experiments, Cosmology and leptogenesis. Precision studies of neutrinos may reveal some new features.

Identification of the correct scenario will require further phenomenological and experimental developments, and probably long way of exclusion of different possibilities. LHC and other high energy experiments may shed some more light on to the problem and probably identify correct context.
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References

1. B. T. Cleveland et al., Astrophys. J. 496, 505 (1998); J. N. Abdurashitov et al. [SAGE Collaboration], J. Exp. Theor. Phys. 95, 181 (2002); V. N. Gavrin, J. Phys. Conf. Ser. 120, 052012 (2008); W. Hampel et al. [GALLEX Collaboration], Phys. Lett. B 447, 127 (1999); M. Altmann et al. [GNO Collaboration], Phys. Lett. B 616, 174 (2005); J. P. Cravens et al. [Super-Kamiokande Collaboration], Phys. Rev. D 78, 032002 (2008); B. Yang [Kamiokande Collaboration], arXiv:0909.5469 [hep-ex]; B. Aharmim et al. [SNO Collaboration], Phys. Rev. Lett. 101, 111301 (2008).
2. C. Arpesella et al. [Borexino Collaboration], Phys. Rev. Lett. 101, 091302 (2008), and arXiv:0808.2868 [astro-ph].
3. J. Hosaka et al. [Super-Kamiokande Collaboration], Phys. Rev. D 74, 032002 (2006); K. Abe et al. [Super-Kamiokande Collaboration], Phys. Rev. Lett. 97, 171801 (2006); M. Ambrosio et al. [MACRO Collaboration], Eur. Phys. J. C 36, 323 (2004); M. C. Sanchez et al. [Soudan 2 Collaboration], Phys. Rev. D 68, 113004 (2003).
4. S. Abe et al. [KamLAND Collaboration], Phys. Rev. Lett. 101, 131802 (2008); M. V. Diwan, arXiv:0904.3706 [hep-ex].
5. B. Pontecorvo, Zh. Eksp. Theor. Fiz. 33, 549 (1957); ibidem 34 (1958) 247; Z. Maki, M. Nakagawa and S. Sakata, Prog. Theor. Phys. 28, 870 (1962). B. Pontecorvo, ZETF, 53, 1771 (1967) [Sov. Phys. JETP, 26, 984 (1968)].
6. L. Wolfenstein, Phys. Rev. D 17, 2369 (1978); in “Neutrino -78”, Purdue Univ. C3, (1978), Phys. Rev. D 20 (1979) 2634; S. P. Mikheev and A. Y. Smirnov, Sov. J. Nucl. Phys. 42, 913 (1985); Sov. Phys. JETP 64, 4 (1986) arXiv:0706.0454 [hep-ph].
7. G. L. Fogli, E. Lisi, A. Marrone, A. Palazzo and A. M. Rotunno, arXiv:0905.3549 [hep-ph], and Phys. Rev. Lett. 101, 141801 (2008).
8. MINOS Collaboration, arXiv:0909.4996 [hep-ex].
9. M. A. Tortola and J. W. F. Valle, Phys. Rept. 460, 1 (2008).
10. T. Schwetz, M. A. Tortola and J. W. F. Valle, New J. Phys. 10, 113011 (2008).
11. M. Maltoni and T. Schwetz, arXiv:0812.3161 [hep-ph].
12. U. Seljak, A. Slosar and P. McDonald, arXiv:astro-ph/0604335 G. L. Fogli et al., Phys. Rev. D 78, 033010 (2008).
13. A. Osipowicz et al. [KATRIN Collaboration], arXiv:hep-ex/0109033.
14. P. C. de Holanda, JCAP, 0907 024 (2009).
15. L. Wolfenstein, Phys. Rev. D 18, 958 (1978); P. F. Harrison, D. H. Perkins and W. G. Scott, Phys. Lett. B 458, 79 (1999), Phys. Lett. B 530, 167 (2002).
16. MINOS Collaboration, arXiv:0909.4996 [hep-ex].
17. A. Y. Smirnov, arXiv:hep-ph/0402264; M. Raidal, Phys. Rev. Lett. 93 161801 (2004); H. Minakata and A. Y. Smirnov, Phys. Rev. D 70, 073009 (2004).
18. Y. Koide, Lett. Nuovo Cim. 34 (1982) 201; Phys. Rev. D 28, 252 (1983).
19. L. J. Hall, H. Murayama and N. Weiner, Phys. Rev. Lett. 84, 2572 (2000).
20. P. Minkowski, Phys. Lett. B 67, 421 (1977); M. Gell-Mann, P. Ramond and R. Slansky, in Supergavity, eds P. van Niewenhuizen and D. Z. Freedman (North Holland, Amsterdam 1980);
P. Ramond, *Sanibel talk*, retroprinted as hep-ph/9809459.
T. Yanagida, in *Proc. of Workshop on Unified Theory and Baryon number in the Universe*, eds. O. Sawada and A. Sugamoto, KEK, Tsukuba, (1979);
S. L. Glashow, in *Quarks and Leptons*, Cargèse lectures, eds M. Lévy, (Plenum, 1980, New York) p. 707;
R. N. Mohapatra and G. Senjanović, *Phys. Rev. Lett.* 44, 912 (1980).

21. S. Weinberg, *Phys. Rev. Lett.* 43, 1566 (1979).
22. W. Konetschny and W. Kummer, *Phys. Lett.* B 70, 433 (1977); M. Magg and C. Wetterich, *Phys. Lett.* 94B, 61 (1980); J. Schechter and J. W. F. Valle, *Phys. Rev.* D 22, 2227 (1980).
23. R. Foot, H. Lew, X. G. He and G. C. Joshi, *Z. Phys.* C 44, 441 (1989).
24. K. S. Babu, S. Nandi and Z. Tavartkiladze, arXiv:0905.2710 [hep-ph].
25. N. Arkani-Hamed, S. Dimopoulos, G. R. Dvali and J. March-Russell, *Phys. Rev.* D 65, 02432 (2002); K. R. Dienes, E. Dudas and T. Ghergetta, *Nucl. Phys.* B 557, 25 (1999).
26. Y. Grossman and M. Neubert, *Phys. Lett.* B 539, 102 (2002).
27. R. Kitano, *Phys. Lett.* B 539, 102 (2002).
28. See review R. Barbier et al., *Phys. Rept.*, 420 1 (2005).
29. E. Ma and G. Rajasekaran, *Phys. Rev.* D 64, 113012 (2001); E. Ma, *Mod. Phys. Lett.* A 17, 2361 (2002).
30. C. S. Lam, *Phys. Rev.* D 78, 073015 (2008).
31. W. Grimus, L. Lavoura and P. O. Ludl, *J. Phys.* G 36, 115007 (2009).
32. G. Altarelli and D. Meloni, *J. Phys.* G 36, 085005 (2009).
33. W. Grimus and L. Lavoura, it JHEP 0904, 013 (2009).
34. J. M. Frere, M. V. Libanov and S. V. Troitsky, *Phys. Lett.* B 512, 169 (2001), *JHEP* 0111, 025 (2001); Z. q. Guo and B. Q. Ma, *JHEP* 0808, 065 (2008).
35. M. A. Schmidt and A. Y. Smirnov, *Phys. Rev.* D 74, 113003 (2006).
36. R. N. Mohapatra and A. Y. Smirnov, *Ann. Rev. Nucl. Part. Sci.* 56, 569 (2006).
37. W. Rodejohann, *Phys. Rev.* D 69, 033005 (2004).
38. A. Datta, L. Everett and P. Ramond, *Phys. Lett.* B 620, 42 (2005).
39. G. Altarelli, arXiv:0905.2350 [hep-ph].
40. G. Altarelli, F. Feruglio and L. Merlo, *JHEP* 0905 020 (2009).
41. A. Y. Smirnov, *Phys. Rev.* D 48, 3264 (1993).
42. M. Fukugita and T. Yanagida, *Phys. Lett.* B 147, 45 (1986).
43. R. N. Mohapatra and J. W. F. Valle, *Phys. Rev.* D 34, 1642 (1986).
44. C. Hagedorn, M. A. Schmidt and A. Y. Smirnov, *Phys. Rev.* D 79 036002 (2009).
45. V. Bouchard, J. J. Heckman, J. Seo and C. Vafa, arXiv:0904.1419 [hep-ph]; J. J. Heckman and C. Vafa, arXiv:0811.2417 [hep-th]; J. J. Heckman, A. Tavanfar and C. Vafa, arXiv:0906.0581 [hep-th].
46. L. Randall and D. Simmons-Duffin, arXiv:0904.1584 [hep-ph].
47. J. Adam et al. [MEG collaboration], arXiv:0908.2594 [hep-ex].