Neutrino-2008: Where are we? Where are we going?

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Abstract. Our present knowledge of neutrinos can be summarized in terms of the "standard neutrino scenario". Phenomenology of this scenario as well as attempts to uncover physics behind neutrino mass and mixing are described. Goals of future studies include complete reconstruction of the neutrino mass and flavor spectrum, further test of the standard scenario and search for new physics beyond it. Developments of new experimental techniques may lead to construction of new neutrino detectors from table-top to multi-Megaton scales which will open new horizons in the field. With detection of neutrino bursts from the Galactic supernova and high energy cosmic neutrinos neutrino astrophysics will enter qualitatively new phase. Neutrinos and LHC (and future colliders), neutrino astronomy, neutrino structure of the Universe, and probably, neutrino technologies will be among leading topics of research.

1. Introduction

"Where are we?" [1] is a beloved question of neutrino physicists, which may be explained by the elusive character of the subject of research. According to the HEP Spires from 52 papers with such a title, 13 are on neutrinos. John Bahcall keeps the record: 6 papers (all on solar neutrinos; in the field where real progress has been achieved). Of course, not only neutrino physicists are lost, however the number of papers in other fields is substantially smaller: "where we are" in particle physics, in heavy ion collisions, in non-baryonic dark matter, in high energy physics have been asked 2 times each. String theory? - 1 time ...

Encouraging: Glashow, Lederman and Weinberg were among those who asked. Variations on the theme: "How it started and where we are?" "Where we are and where do we stand?" "Where should we go?" "Where are we coming from?" and even more profound: "Who we are?" (J. Ellis, with reference to P. Gauguin).

Let us elabotare further: Where are we in time? By the way, the New Zealand time was introduced in 1868 - 40 years before the year of the Rutherford's Nobel prize award - our starting point. Then

1928 - Dirac equation.
1938 - Majorana, his disappearance.
1948 - Gardner and Lattes: artificial production of pions.
1958 - Goldhaber, Grodzins, Sunyar: Helicity of neutrino (50th anniversary!).
1968 - Davis: the first solar neutrino result - the birth of the solar neutrino problem.
1978 - Wolfenstein: "Neutrino oscillations in matter".

[1] The author does not take responsibility for the title of his talk. Still, he will do his best to make sense out of it.

1988 - Kamiokande-II: the birth of the atmospheric neutrino problem [2] .

1998 - Discovery of oscillations in atmospheric neutrinos.

2008 - Discovery of New Zealand by the neutrino community; the start of LHC.

Where are we in space? about 5000 km (baseline) from IceCube in 3D, somewhere in the electroweak brane, in extra D.

Where are we in the field of neutrino physics? The answer includes: "conquest territory" - the standard neutrino scenario (sec. 2); understanding neutrino masses and mixing (sec. 3); beyond the standard scenario (sec 4); a future which we know (sec. 5); a future which we can only imagine (sec. 6).

2. Standard neutrino scenario

2.1. Standard scenario

"Standard neutrino scenario" can be formulated in the following way:

- Neutrino interactions are described by the standard electroweak model.
- There are only 3 types of light neutrinos (three flavor and three mass states).
- Neutrinos are massive. Neutrino masses are in the sub-eV range - much smaller than masses of charged leptons and quarks.
- Neutrinos mix. There are two large mixing angles and one small or zero angle. The pattern of lepton mixing strongly differs from that of quarks.
- The observed masses and mixing have pure vacuum origin; they are generated at the electroweak, and probably, higher energy scales are involved. These are "hard" masses.

The standard scenario is a result of work of several generations of neutrino physicists, the collective effort of experimentalists and theoreticians [1]. This scenario is our "conquest territory", basis and starting point for further advance, summary of results of the first phase of studies of neutrino mass and mixing. The following comments are in order.

1). Interactions: The gauge interactions of neutrinos are well known and well checked. In contrast, there is no information about the Yukawa couplings with the Higgs boson (if the RH neutrinos exist); these couplings can be relevant for leptogenesis. Neutrino interactions with complex systems: nucleons and nuclei are not completely understood and open questions are related to the physics of strong interactions. As a probe, neutrinos are unique being sources of the axial vector currents. The open questions include the value of axial mass in the quasi-elastic scatterings [2], the coherence in a single pion forward production [3], the role of the axial vector anomaly in interactions of Z, γ, ω in explanation of the low energy excess observed in the MiniBooNE experiment [4]. Significant progress has been achieved in nuclear physics for $\beta\beta$-decays [5]. Rare neutrino processes and processes at extreme conditions relevant for astrophysics, e.g., $\nu\nu-$ pair production in nucleon collisions, are under consideration.

2). Propagation: There are still some discussions about the theory of neutrino oscillations even in vacuum. "Eternal questions" include the equality of momenta or energies in consideration of interference, validity and applications of the stationary source approximation, relevance of the wave packets, coherence, role of recoil of accompanying particles, *etc.*. Some of these issues have just an academic interest in normal situation, but but become important for oscillations at extreme conditions, *e.g.*, oscillations of "Moessbauer neutrinos" [6], where the uncertainty in energy is much smaller than the oscillation frequency: $\Delta E \ll \Delta m^2/2E$ [7].

Concerning propagation in a medium, the forefront of studies has shifted to extreme conditions - high densities, temperatures, magnetic fields, propagation in neutrino gases, *etc.*.

[2] L. Sulak has informed me on some earlier indications of the anomaly in the IMB results.

Collective non-linear effects induced by the $\nu\nu-$ scattering are in explorative phase and serious progress has been achieved since 1993 [8] - [11].

3). Mass and mixing. The main line of thinking is that the right handed components of neutrinos exist, neutrinos are the Majorana particles, seesaw is realized and smallness of mass is due the existence of some high mass scales (large masses of RH neutrinos). The difference of the quark and lepton mass spectra and mixing patterns is related somehow to the smallness of neutrino mass. In general,

$$m_\nu = m_{hard} + m_{soft}(E, n), \tag{1}$$

where $m_{soft}(E, n)$ is the medium-dependent soft component which can be substantial for neutrinos but not for other particles. An important phenomenological and experimental problem is to put model independent limits on (or discover?) m_{soft}.

2.2. Phenomenology.

To a large extend phenomenology of the standard scenario has been elaborated, in some cases - in great details. Still some area exist (cosmic, supernova neutrinos) where active research continues now. Few spots have not been covered yet.

1). Solar neutrinos. Complete description of physics of conversion has been elaborated and very precise analytic results have been obtained. From experimental side some points are still missing. This includes detection of

- the Earth matter effect: day-night asymmetry, zenith angle dependence of signal;
- upturn of the energy spectrum of boron neutrinos at low energies (see, however, recent BOREXINO result [12]) ;
- neutrinos in the so called "vacuum-to-matter" transition region (N, O, pep);
- the pp-neutrinos, and on the other side - the hep-neutrinos.

These measurements will provide further tests of the LMA solution and matter effects in general, they will open additional possibilities to search for new physics. The measurements may shed some light on various astrophysical issues, e.g., the role of CNO cycle, abundance of the heavy elements at the surface of the Sun and initial conditions for solar evolution [13], *etc.*.

2). Atmospheric neutrinos. Comprehensive description of neutrino propagation through the Earth is given in terms of neutrino oscillograms of the Earth - lines of equal probabilities in the neutrino energy - nadir angle, $E - \Theta_\nu$, plane fig. 1. The oscillograms give global view on the oscillation phenomena inside the Earth being relevant also for the accelerator and cosmic neutrinos[14]. The oscillograms are the neutrino images of the Earth. The Earth is unique and the structures of oscillograms seen in fig. 1 are unique and well defined. They are defined by the generalized amplitude and phase conditions. The former is reduced to the MSW resonance condition for one layer (mantle) and to the parametric resonance condition for 3 layers (mantle crossing trajectories).

The CP-violation properties of the oscillograms have the domain structure (see fig. 2 for the $\nu_\mu \to \nu_e$ channel). The δ-dependence appears via the interference term: $P_{\mu e}^{int} \sim |A_A A_S| \cos(\phi - \delta)$, where A_A and A_S are (in the first approximation) the "atmospheric" and "solar" $2\nu-$amplitudes correspondingly and $\phi \equiv arg(A_S^* A_A)$ is the interference phase. To assess the δ-dependent terms, one can consider the difference of the oscillation probabilities for two different values of the CP-phase: $\Delta P_{\mu e}^{CP}(\delta) \equiv P_{\mu e}(\delta) - P_{\mu e}(\delta_0)$. The equality $\Delta P_{\mu e}^{CP} = 0$ holds, if at least one of the following three conditions is fulfilled

$$A_S(E_\nu, \Theta_\nu) = 0, \quad A_A(E_\nu, \Theta_\nu) = 0, \quad \phi(E_\nu, \Theta_\nu) = (\delta + \delta_0)/2 + \pi l\,. \tag{2}$$

These equalities determine the solar and atmospheric "magic" lines and the interference phases lines [14] in fig. 2 along which the CP-violation effects are zero. These lines give the borders of

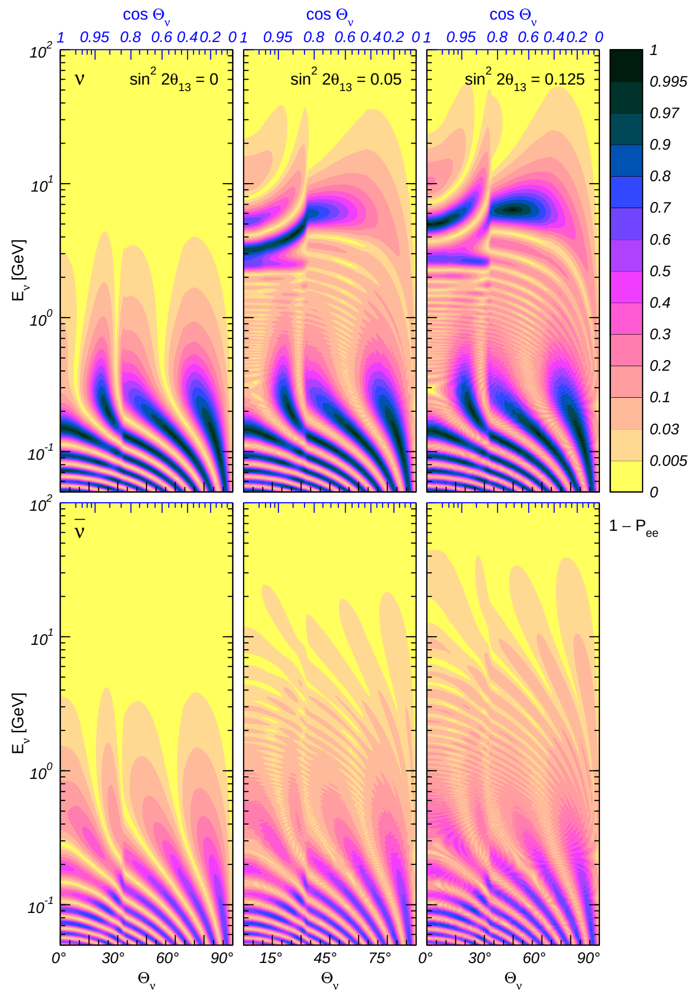

Figure 1. Neutrino oscillograms in the 3ν-mixing case. Shown are the contours of constant probability $1 - P_{ee}$ (upper panels) and $1 - P_{\bar{e}\bar{e}}$ (lower panels) for $\Delta m^2_{21} = 8 \times 10^{-5}$ eV^2, $\tan^2\theta_{12} = 0.45$ and three different values of θ_{13}. Here P_{ee} is the $\nu_e - \nu_e$ survival probability. Normal mass hierarchy is assumed. Up to small interference effect the inverted mass hierarchy would correspond to interchange of the upper and lower panels. From ref. [14].

the CP-violation domains, the CP-violation has different sign in the neighboring domains and strong CP-violation is in their central parts.

3). Long baseline experiments. Physics is well understood (see oscillograms). A number of analytic and semianalytic results have been obtained and approximate expressions for probabilities were derived which use various expansions (perturbation theories) in specific ranges of energies and baselines [15]. We can speak about the LBL industry: numerical codes have been developed which allow one to determine sensitivities of experiments to unknown parameters: e.g. θ_{13} or phase δ using characteristics of experiment (neutrino energy, baseline, experimental uncertainties, etc.) as input parameters [16].

4). Supernova neutrinos. The $\nu\nu-$ scattering leads to the flavor exchange and variety of collective (non-linear) effects [8] - [11]. One of them uncovered recently is the spectral split [9, 10] or swap according to terminology in [11]. An example of the split in a system of neutrinos and antineutrinos is shown in figs. 3, 4. In fig. 4 from [10] the evolutions of the **B**–components (or projection on the mass axis) of the polarization vectors are shown as functions of strength of the $\nu\nu-$ interactions $\mu \equiv \sqrt{2}G_F n_\nu$, where "up" ($+1$ projection) corresponds approximately to the e–flavor and "down" (-1)- to the x–flavor. According to the figure, all modes with frequencies below the split frequency: $\omega \equiv \Delta m^2/2E < \omega_{\rm split}$ change flavor, whereas the ones with $\omega > \omega_{\rm split}$ first evolve in flavor space but then return to their original flavor. The split may lead to observable consequences. Relevance of these effects for real supernovas still should be

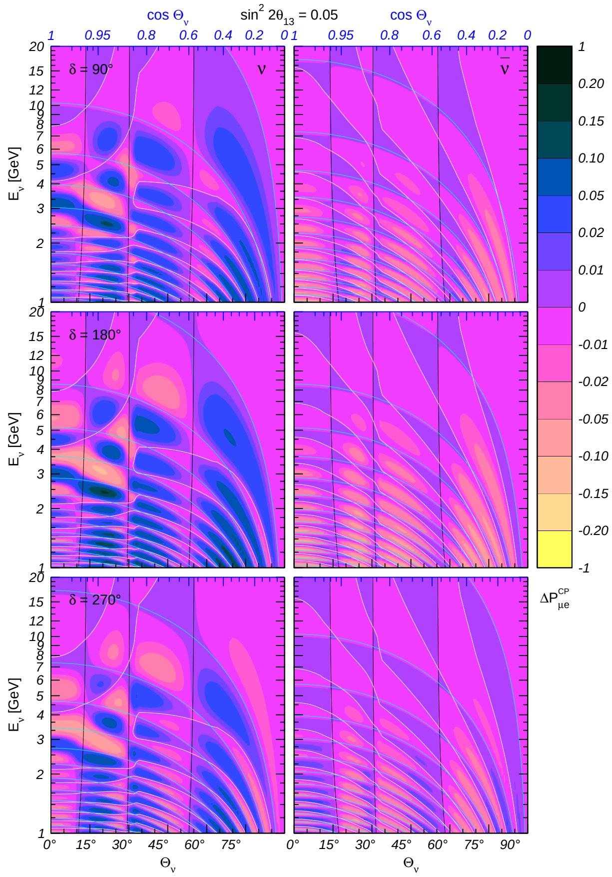

Figure 2. Oscillograms for the difference of probabilities $\Delta P^{CP}_{\mu e}(\delta) = P_{\mu e}(\delta) - P_{\mu e}(\delta_0)$ with $\delta_0 = 0°$. Shown are the solar (black), atmospheric (white) and interference phase condition (cyan) lines. The lines form the borders of the CP-domains. Non-coincidence of the lines and contours of $\Delta P^{CP}_{\mu e}(\delta) = 0$ from numerical computations is mainly due to the level crossing phenomenon. From ref. [14].

clarified.

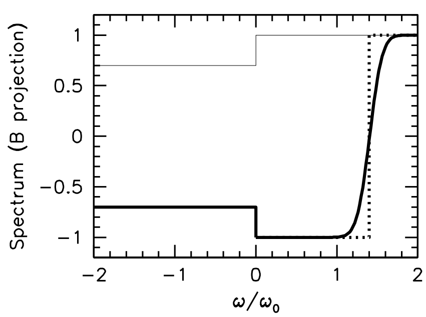

Figure 3. Neutrino spectra for an initial box spectrum with 70% antineutrinos and initial mixing angle $\sin 2\theta_{\rm eff} = 0.05$. Negative frequencies correspond to antineutrinos. Thin line: initial. Thick dotted: final adiabatic. Thick solid: numerical example.

4). Cosmic neutrinos. This is the field of active studies which moves now to qualitatively new level. A number of developments is related to recent results in the $\gamma-$ astronomy ($\nu - \gamma$ connection, implications of the EM radiation data). The developments were also triggered by forthcoming large scale experiments (IceCube, ANTARES). Among possible sources of neutrinos are AGN, GRB, core collapse supernova, SN remnants, microquasars, blasars [17]. Detailed computations of the neutrino yield have been performed for different conditions in the sources. Various effects of neutrino propagation are under consideration: vacuum oscillations, conversion in matter of source, effects of non-standard interactions. For maximal 2-3 mixing and the original flavor ratio equals $F_e, F_\mu, F_\tau \approx 2 : 1 : 0$, which is realized in the case of free decays $\pi \rightarrow \mu\nu_\mu \rightarrow e2\nu_\mu\nu_e$. Oscillations "equilibrate" flavors and the ratio becomes $1 : 1 : 1$.

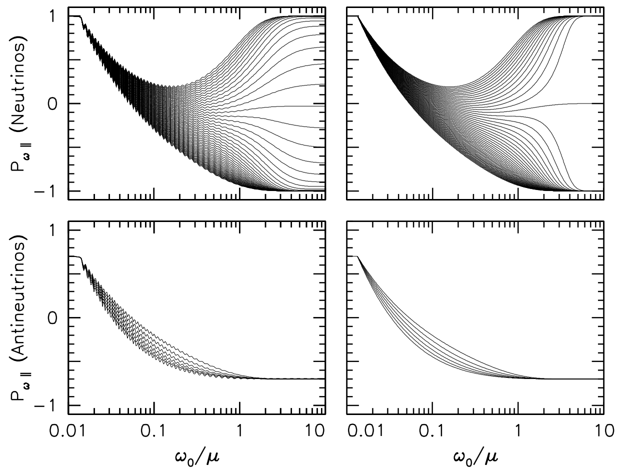

Figure 4. $P_{\omega B}(\mu)$ for individual modes for the case of neutrinos plus antineutrinos. *Left:* Numerical solution; for $\sin 2\theta_{\rm eff} = 0.05$. *Right:* Adiabatic solution for $\sin 2\theta_{\rm eff} = 0$. In each case neutrinos with 51 modes (top) and antineutrinos with 6 modes (bottom). From ref.[10].

Measurements of the ratio and searches for deviations from equilibration will be one of the main goals of neutrino astronomy [18]. The deviation can be due to matter effects in the source, various non-standard interactions, deviation of 2-3 mixing from maximal, contributions from other possible mechanisms of neutrino production. One of interesting possibilities is neutrino from thick sources: Protons are accelerated in the relativistic jets by the inner shocks and neutrinos are produced in the $pp-$ and $p\gamma-$ collisions. Flavor conversion occurs in the He- and H- envelopes [19]. It leads to breaking of flavor democracy. There are new recent developments related to establishing the GZK cut-off and evidences that AGN are the sources of the cosmic rays. Perspectives to see the cosmogenic neutrinos will be further clarified.

3. Where are we in understanding neutrino mass and mixing?

3.1. Theory of neutrino mass

In recent years it was enormous theoretical activity in attempt to understand origins of neutrino mass and mixing, to explain smallness of neutrino mass and peculiar mixing pattern. The simplest possibilities have been explored. A number of approaches and scenarios of physics beyond the standard model were proposed. Clearly, with only one theoretical talk [20] the program of the conference does not reflect this activity. Reason? Nothing is really accomplished? No progress? Recall, we measure allo these θ_{13}, δ, *etc.*, to uncover eventually the underlying physics, to make on this basis new testable prediction. Another aspect of the measurements is neutrino applications. Whole excitement was that neutrino mass and mixing are manifestations of physics beyond the standard model. Dramatically, after many years of studies and many trials the underlying physics has not been identified. We should explore how the progress can be achieved.

3.2. Bottom-up

There are three lines of studies in the bottom-up approach with different implications for fundamental physics and different connections between leptons and quarks.

1). Tri-bimaximal mixing (TBM). Immediate implication: flavor symmetry. Majority of models proposed so far are based on the discrete symmetry group A_4. Other possibilities explored in this connection include the groups T', D_4, S_3, S_4, $\Delta(3n^2)$. Extension of these symmetries to quarks is, however, problematic, it requires further complication of models. TBM may indicate that quarks and leptons are fundamentally different. Mixing and masses are not related at least in straightforward way.

2). Quark-Lepton Complementarity (QLC) is based on observations that $\theta^l_{12} + \theta^q_{12} \approx \pi/4$ and

$\theta^l_{23} + \theta^q_{23} \approx \pi/4$. A general scheme is "the lepton mixing = bi-maximal mixing - CKM". Two extreme realizations of the complementarity, QLC_ν and QLC_l, are determined by the order of the bi-maximal and CKM rotations:

$$U_{PMNS} = U_{bm} U^\dagger_{CKM} \quad (QLC_l), \qquad U_{PMNS} = U^\dagger_{CKM} U_{bm}, \quad (QLC_\nu). \tag{3}$$

Implications: Quark-lepton symmetry, or grand unification (GUT), plus existence of structure which produces the bi-maximal mixing. The latter may require some symmetry. Again there is no straightforward connection between mixing and masses.

3). Quark-lepton universality. This approach does not rely on any specific symmetry in the lepton sector. Mass (Yukawa coupling) matrices of quarks and leptons have no fundamental distinction. Whole difference is related to the seesaw mechanism itself which explains simultaneously the smallness of neutrino mass and large lepton mixing. Mass matrices of quarks and leptons are constructed on the basis of the same principles (e.g. Froggatt-Nielsen mechanism, $U(1)-$ flavor symmetry), and furthermore, masses and mixing are related with each other. Large lepton mixing can be associated to the weak mass hierarchy of neutrinos.

TBM and two versions of QLC differ by predictions of the mixing angles $(\theta_{12}, \theta_{13})$:

$$QLC_\nu: \ (35.4^\circ, 9^\circ), \quad TBM: \ (35.2^\circ, 0), \quad QLC_l: \ (32.2^\circ, 1.5^\circ). \tag{4}$$

Notice that $\theta_{12}(QLC_l) = \pi/4 - \theta_C$ and $\theta_{12}(QLC_\nu) \approx \theta_{12}(TBM)$. All three possibilities (subject of RGE corrections) agree with the present data within 1σ. Clearly, combination of future precise measurements of these angles will disentangle the schemes. In specific models, some additional corrections appear due to violation of the underlying symmetry. Small deviations from the predictions do not exclude the context. Exact confirmation would be very demanding and restrictive.

There is no reason to consider TBM but ignore the Koide relations which are, in contrast to TBM, the pure mass relations [21]. Furthermore, it may happen that some connection between the Koide relation and TBM exists. Recall, the equality

$$\frac{m_e + m_\mu + m_\tau}{(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2} = \frac{2}{3} \tag{5}$$

is satisfied with accuracy 10^{-5} on the mass shell and with 10^{-3} - at M_z. The equality (5) has been obtained in attempts to explain relation between the Cabibbo angle and lepton masses. Both relations can be reproduced if

$$m_i = m_0 (z_i + z_0)^2, \quad \sum_i z_i = 0, \quad z_0 = \sqrt{\sum_i z_i^2/3}, \tag{6}$$

where z_i are some numbers. Brannen [22] has generalized the relation to neutrinos:

$$\frac{m_1 + m_2 + m_3}{(-\sqrt{m_1} + \sqrt{m_2} + \sqrt{m_3})^2} = \frac{2}{3}, \tag{7}$$

where minus sign in front of the first term in denominator is crucial. According to (7) neutrinos have hierarchical spectrum with $m_1 = 3.9 \cdot 10^{-4}$ eV. Non-abelian flavor symmetry and specific VEV alignment can be behind the relations.

3.3. Flavor symmetries

Flavor features of various symmetry groups have been explored: Discrete groups A_4 (subgroup of SO_3) and T_7 - Frobenius group (subgroup of SU_3) [23] look rather promising. It was argued that minimal group which leads to TBM mixing is S_4 [24]. The "successful" models imply tuning of symmetries and patterns of their breaking. The following aspects are of special interest.

1). Fundamental *versus* effective. The required symmetry may appear only at the *effective* level after decoupling of heavy degrees of freedom. No flavor symmetry or some other symmetry exist at the fundamental level. In the case of decoupling of the RH neutrinos the emerging symmetry can be called the "see-saw symmetry" [25]. This idea is along with the line of Ref. [26], where it was argued that symmetries at the effective level may follow from certain hierarchies of masses at the fundamental level.

2). Real *versus* accidental? Are the observed flavor features, such as maximal 2-3 mixing, tri-bimaximal mixing, small (zero) 1-3 mixing, Koide relations accidental? Some value of mixing angle is accidental if it is a combination of two or more independent contributions. If some value or relation appears as immediate "one-step" consequence of symmetry (the group structure), we conclude that they are not accidental, that is, real. The decisive criteria are new testable predictions from symmetries. Discovery of the degenerate mass spectrum would be convincing evidence of real symmetry.

3). Flavors and GUT. The scale of RH neutrino masses is in favor of GUT. In fact, value of mass of the heaviest RH neutrino can coincide with the GUT scale $M_R \approx M_{GUT} \sim 10^{16}$ GeV, which can be achieved in the presence of mixing of three generations. Alternatively, the scale of RH neutrino masses can be related to M_{GUT} via the Planck scale M_{Pl}: $M_R \approx M_{GUT}^2/M_{Pl} \sim 10^{14}$ GeV (the latter is realized, e.g., in the double seesaw scenario). Another indication of GUT is QLC. Generic problem of unification of quarks and leptons is the difference of their mixing patterns. To explain data with flavor symmetries the quarks and leptons, the RH components of charged leptons and neutrinos should have different flavor properties This prevents from their unification, or the original flavor symmetry should be broken differently in quark and lepton sectors, for up and down components of multiplets.

Data on masses and mixing show both order (regularities) and some degree of randomness, and no simple parametrization is found. Therefore no simple "one-step" explanation is expected. Furthermore, different pieces of data testify for different underlying physics. This may indicate that several unrelated contributions to the neutrino mass matrix exist (zero order structure plus small corrections?). Keeping this in mind one can develop the following approach: (i) refrain from attempts to explain all the data at once; (ii) take the most symmetric and minimal context "GUT plus flavor symmetry", (iii) explore how far one can go in explanation of data. One possibility is $SO(10)$, without **126** Higgses but with non-renormalizable operators, with flavons and singlet fermions. Flavons and singlet fermions (their number can be bigger that three) can compose a hidden sector of theory with certain symmetries and dynamics. In this context one can disentangle the hierarchies of quark and neutrino masses and, e.g., connect geometrical hierarchy of the up quark masses and nearly maximal 2-3 leptonic mixing [27].

4). Energy scales of new physics. In the "seesaw approach" the smallness of neutrino mass is in general related to existence of some new large scale, Λ. In the simplest version Λ is just bare mass of the RH neutrino. In general, there is some particle sector and dynamics behind. Various realizations have been proposed with Λ equals M_{Pl} (which requires many RH neutrinos), or M_{GUT}, or $\sqrt{M_{Pl} M_{EW}}$, or M_{EW}. In νMSM scenario [28] $\Lambda < 0.1 - 0.5$ GeV. Even the extreme possibility, $\Lambda = few$ eV, is not excluded [29]. All this means that "Physics behind neutrino mass" is not yet identified.

4. Beyond the standard scenario

There are two aspects of further experimental and phenomenological studies: tests of the standard scenario and searches for new physics. Ways new physics appears in our considerations can be classified as follows: 1). Neutrino anomalies. Recall that neutrino anomalies were driving force of the developments for more than 40 years. 2). New physics related to explanation of neutrino masses. 3). New physics motivated by other fields. This includes various extensions of the standard model: Left-Right symmetric models, supersymmetry, GUT, extra dimensions. 4). Unmotivated (explicitly) speculations.

4.1. Neutrino anomalies

Neutrino anomalies can be considered as potential seeds of new developments. The anomalies up to date are summarized in the Table 1.

Table 1. Neutrino anomalies

Name:	Feature	possible interpretations
LSND	excess of e^+ events	$(exotics)^2$, see text
MiniBooNE	excess of events at $E < 400$ MeV	see text
NuTeV	value of $\sin\theta_W$	structure functions, new heavy leptons
Homestake	low rate, tension with other data	mixing with very light sterile neutrino; unparticle physics
Gallium	deficit of observed signal in calibration experiments	cross-section; small scale oscillations
Unnamed	time variations of solar neutrino signals	neutrino magnetic moment, periodicity of the energy release
SN1987A	angular, time distribution, LSD signal	astrophysics?
Z^0-width	$N_\nu^{eff} < 3$	new heavy leptons
GSI	modulation of exponential decay	systematics ? unrelated to neutrinos (?)

LSND after MiniBooNE [30], and MiniBooNE after LSND. LSND can be reconciled with MiniBooNE in model with two sterile neutrinos and CP-violation [31]. Here the problem still exists with short baseline experiments and astrophysics. After MiniBooNE an explanation of LSND requires even more speculative schemes, so to say, $(exotics)^2$: e.g., sterile neutrinos and extra dimensions [32], sterile neutrinos with energy dependent masses, [33], CPT- violation and sterile neutrinos [34], 3 sterile neutrinos and light vector boson [35], soft decoherence [36]. In the last case both "decoherence" and "soft" are exotic. Do we deal here with something unusual, not connected to known physics processes? An interesting task is to reconstruct from the data $L-$ and $E-$ dependence of the underlying effect in model independent way and check consistency with the other data.

4.2. New physics

Broadly it can be classified as (i) non-standard interactions (NSI); (ii) new neutrino states, (iii) new dynamics.

(i) Possible existence of non-standard neutrino interactions is related to extensions of SM at the EW scale and terascale as well as to new particles motivated by astrophysics. NSI have rich phenomenology influencing both propagation and detections of neutrinos. In particular, they can modify the refraction phenomena, especially at high energies where usual mixing is suppressed, see fig. 5 from [37],

(ii) New neutrino states or sterile neutrinos. If light, these states can have direct observable consequences: be produced in various neutrino processes, participate in oscillations, and decays, *etc.*. Mixing of new states with usual neutrinos leads to indirect effects: modifications of the mass matrix of active neutrinos (induced mass: $m_{ind} \approx m_S \sin^2 \theta_S$), breaking of universality, appearance of FCNC. Light sterile neutrinos both participate in low energy phenomenology and modify mass matrix of active neutrinos. The heavy ones produce indirect effects only.

For $m_S \lesssim 200$ MeV the strong bounds on mixing of sterile neutrinos from astrophysics and cosmology exclude significant influence on mass and mixing of active neutrinos. In contrast, for $m_S \gtrsim 1$ GeV, the indirect effects dominate. The induced mass terms can generate the dominant elements of active neutrino mass matrix.

3). New dynamics: this includes violation of fundamental symmetries and principles, such as CPT, Lorentz invariance, Pauli principle, as well as non-standard decoherence, effects of unparticle physics, etc.. According to the unparticle physics scenario [38] the hidden sector (HS) of theory exists which includes the gauge theory with fermions. The number of fermions in the HS is such that the effective gauge coupling g increases with decrease of energy and at the energies below certain scale Λ_U approaches the infrared fixed point $g \to g^*$. If $g^* \gg 1$ fermions form composite (confined) states. To some extend this transition is similar to the transition from quarks to hadrons below $\sim \Lambda_{QCD}$.

Particles of HS couple to the SM particles via exchange of messenger fields with mass

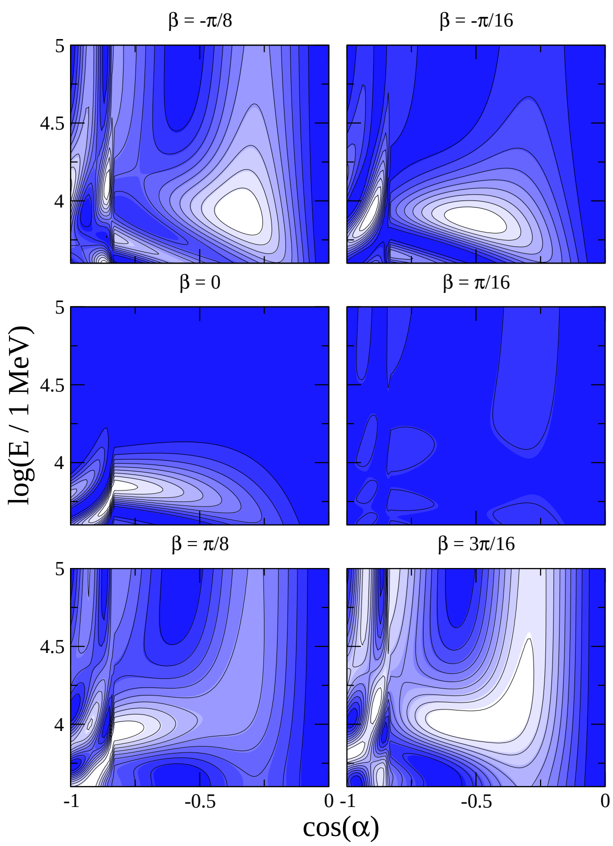

Figure 5. Neutrino oscillograms of the Earth in the presence of NSI. The electron neutrino survival probability, P_{ee}, as function of zenith angle α and energy. Different panels correspond to different strength of NSI, $\sin 2\beta \approx -2\epsilon_{e\tau}$, $\theta_{13} = 8°$. Panel with $\beta = 0$ corresponds to the the standard interactions only. Strong transitions are in white regions. For $\beta = -\pi/8$ and $\beta = -3\pi/16$ these regions extend to high energies. From ref. [37].

$M \gg \Lambda_U$. At energies below M the interaction of SM particles with HS particles are described by the effective interactions $\frac{1}{M^k} O_{SM} O_{UV}$, where O_{SM} and O_{UV} are the operators which depend on the SM and HS fields correspondingly. In analogy with QCD one can consider, e.g., that O_{SM} is leptonic operator, whereas O_{UV} is the quark operator. Below Λ_U the operator O_{UV} transforms into operator of composite (confined) states O_U (e.g., "pion"): $O_{UV} \to O_U$ and the interaction becomes

$$C \frac{\Lambda_U^{d_{UV} - d_U}}{M^k} O_{SM} O_U, \tag{8}$$

where d_{UV} and d_U are dimensions of operators O_{UV} and O_U correspondingly. The key difference from the hadron case is that here due to scale invariance (no energy gap) the confined states have continuous mass spectrum [39, 40]. As a result, individual mass modes have infinitesimal effect. Finite rates of production and exchange of unparticles appears as a consequence of integration over mass spectrum of composite states.

As far as applications to neutrinos are concerned, several processes have been considered: the neutrino decays $\nu_i \to \nu_j + U$ [41] [42], scattering on electrons $\nu_\alpha e \to \nu_\beta e$ [42], and neutrino annihilation $\nu\nu \to \gamma\gamma$, $\nu\nu \to ff$ [43] via an unparticle exchange. The exchange of unparticles influences refraction: modifies matter potential (in the case of vector operators) and effective neutrino mass (in the case of scalar operators). This, in turn, modifies conversion probabilities in matter [44]. The present data give various bounds on unparticle properties.

5. Future which we know

5.1. Reconstruction of neutrino mass and flavor spectrum

Clear phenomenological and experimental goal is to accomplish reconstruction of the neutrino mass and mixing spectrum. It includes measurements of 1-3 mixing, deviation of 2-3 mixing from maximal, CP-phase, absolute scale of mass, searches for the $\beta\beta_{0\nu}$ decay and determination of nature of neutrinos, measurements of m_{ee} and Majorana phases. The program has emerged more that 10 years ago. It is well motivated and elaborated. On the basis of these measurement one can reconstruct neutrino mass matrix (in the flavor basis) at least partially.

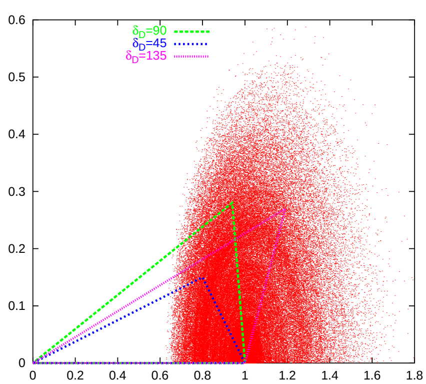

Figure 6. Possible shape of the leptonic unitarity triangle now.

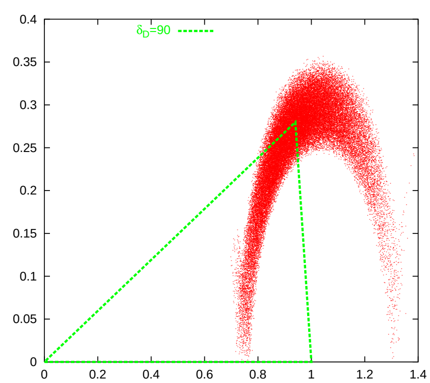

Figure 7. The unitarity triangle in future (see text).

The situation can be presented using the leptonic unitarity triangle. In the fig. 6 we show possible form of the triangle as it follows from the existing data [45]. Three $e\mu$-triangles correspond to $\sin\theta_{13} = 0.15$, and three different values of the CP- phase δ. The scatter-plot gives possible position of the vertex of the triangle. Large number of points along the horizontal axis corresponds to zero value of the phase (or $\theta_{13} = 0$). The fig. 7 shows possible situation after next generation of the experiments (Double CHOOZ, Daya-Bay, J-PARK, NOνA) assuming certain set of the results. Here there are no points along the horizontal axis, which means that non-zero value of CP-phase can be established, if it is not small. The triangle is not just illustration, it may provide a method to measure δ and test unitarity.

Future experimental programs are mainly based on the long-baseline experiments and the oscillograms give a global view of the situation. Operating and expected accelerator experiments (superbeams, beta beams, muon factories) cover the energy range (0.5 - 30) GeV and several baselines at $\cos\Theta_\nu < 0.3$, that is, the peripheral regions of oscillograms with poor structure. This is the origin of degeneracies of the oscillation parameters. Interesting new proposal is the low energy neutrino factory $E \sim few$ GeV [46], which opens a possibility to turn the beam.

Another approach could be based on studies of the atmospheric neutrinos which cover huge ranges of energies, $E = (0.1 - 10^4)$ GeV and base-lines, $(10 - 10^4)$ km. The problem here is low statistics (especially at high energies) and uncertainties in the original neutrino fluxes. The present large-scale underground and under-ice detectors (AMANDA, IceCube, ANTARES) have high energy thresholds, $E > (50 - 100)$ GeV, thus missing the most interesting and structured region of oscillograms at $E = (2 - 10)$ GeV. Both problems can be resolved with multi-Megaton detectors of the TITAND type [47] with energy threshold below (1 - 2) GeV: high statistics will allow one to measure oscillograms in wide $E - \Theta_\nu$ range and determine both unknown neutrino parameters and original fluxes (which can be parameterized by few quantities) simultaneously. In such a detector one may expect about 2000 events, e.g., in the parameter space $\Delta(\cos\theta_\nu) =$ 0 - 0.2 and $\Delta E = 2 - 3$ GeV.

Measurements of oscillograms open a possibility to (i) study various oscillation effects, e.g. parametric enhancement of oscillations; (ii) determine unknown neutrino parameters: 1-3 mixing, mass hierarchy and CP-phase; (iii) search for non-standard interactions; (iv) perform tomography of the Earth with spatial resolution > 100 km.

5.2. Searches for new physics beyond the standard scenario

The interplay of the results of precise neutrino measurements, data on rare processes like $\mu \to e\gamma$, cosmological and astrophysical data, as well as results from LHC and other colliders is expected to be very fruitful. Present bounds will be improved and hopefully signals/signatures of new physics identified.

Neutrinos and LHC. Here expectations range from complete identification of the mechanism of neutrino mass generation to practically nothing. The first case will be realized, if, e.g., the Higgs triplet with few hundreds GeV mass and small VEV generates neutrino mass and mixing. In the second one, the outcome could be that some EW scale mechanisms with certain values of parameters are excluded. We will not be able to detect the RH neutrinos responsible for the type-I seesaw mechanism. If some heavy neutral leptons with terascale mass are observed, they will not be immediately related to the light neutrino mass generation and in addition some new physics should be involved. The $\nu MSM-$ scenario [28] implies yet another scenario of future developments.

5.3. Neutrino astrophysics and astronomy

Detection of neutrino bursts from galactic supernova may have very strong impact on neutrino physics, astrophysics and particle physics. It can contribute to determination of the neutrino parameters. It may shed some light on nucleosynthesis in SN as well as on SN explosion mechanism via the neutrino monitoring of the shock wave propagation. It will be important test of theory of neutrino propagation and flavor conversion. It is rather plausible that we will discover something unexpected. There are good chances to measure the relic SN neutrino fluxes.

The detection of high energy neutrinos from astrophysical sources will be one of the major discoveries of this century. This will trigger further more focused theoretical studies, and experimental developments.

6. Future which we can only imagine

Trying to imagine future one can proceed in different ways: (i) "project from the past", e.g. study programs of previous neutrino conferences; (ii) follow logic of the field; (iii) use some historical parallels in neutrino physics and other fields; (iv) imagine new neutrino sources and new detectors; (v) identify seeds of new developments.

1). The breakthrough in the field can be related to developments of new experimental techniques: invention of new neutrino sources and detectors. This includes widely discussed beta-beams and neutrino factories. Experiments with strong sources of low energy neutrinos (radioactive nuclei) look very appealing [48]. One can imagine some particular processes at particular conditions which will open new perspectives. One example along this line (its practical realization still should be proved) is neutrino pair emission from metastable atoms [49]. It looks intriguing in view of closeness of scales of atomic transition energies and neutrino mass. One can expect strong enhancement of the processes - superradiance due to coherence in large volume. The processes of photon (laser) irradiated neutrino pair emission from metastable atoms $\gamma + A_i \to \nu_i \nu_j + A_f$ and radiative pair emission $A_i \to \nu_i \nu_j + \gamma + A_f$ have been considered [49]. The rates are proportional to neutrino masses and to Pauli blocking factor due to presence of relic neutrinos. The later can be used, in principle, to detect relic neutrinos.

On the other side, future significant progress can be due to developments of large scintillator observatories and the multi-Megaton scale water Cherenkov detectors with flavor (may be charge) identification and low energy thresholds. One can imagine new methods of light collection, volume detection of event, *etc.*. Further developments of the balometric techniques, construction of large scale array of calorimeters look very perspective [50]. The use of radioactive nuclei for neutrino detection with zero threshold [51] opens some perspectives to detect relic neutrinos. The neutrino Moessbauer effect can be used to study neutrino oscillations, measure 1-3 mixing, determine mass hierarchy, search for sterile neutrinos, study gravitational redshift of neutrinos, and even study quantum gravity effects [52]. Coherent neutrino interactions can be the key feature of future techniques. One can imagine new methods of decrease of background and detection of very weak signals. Array of km-cube size detectors of cosmic neutrinos (with KM3NET as the first step) is not out of discussion.

High precision of measurements will open new horizons to discover sub-leading effects and search for new physics. This in turn will trigger new phenomenological and theoretical studies.

2). Neutrino structure of the Universe. Some work has already been done. One expects clumping of neutrinos depending on their masses [53]. That can lead to formation of neutrino halos, and neutrino "stars". Possible new interactions (e.g., with accelerons) can lead to neutrino condensates and superfluidity [54]. The issue is important for the direct detection of relic neutrinos.

The presence of relic neutrinos has been established indirectly by counting the number of relativistic degrees of freedom in the epoch of transition from radiation to matter dominated Universe. Future cosmological probes will be able to reconstruct structure of the Universe in the earlier epochs, thus resolving various degeneracies and improving bounds on neutrino parameters. Connections neutrinos - dark energy, neutrinos - dark matter will be further studied.

3). With our present advanced knowledge of neutrino properties (interactions, masses and mixing) the aspect "neutrinos as unique probe" of micro and macro worlds becomes again important - now at qualitatively new level. Future experiments with large fluxes and high energy neutrinos can be used for further studies the nucleon structure and precision measurements of the electroweak parameters; NuSoNG proposal [55] is one step in this direction. With large-scale high statistic solar neutrino detectors one can have further advance in studies of deep interior of the Sun, and stellar evolution (detection of fluxes of N-, O-, pep-, hep - neutrinos, searches for time variations, correlations with solar flairs, etc.) High statistics supernova neutrino detection may allow one to monitor the shock wave propagation. Detection of SN bursts from other Galaxies may become reality. Direct detection of the relic neutrinos will provide unique probe of the Early Universe.

4). Toward the neutrino technologies. Technology (applied physics) is associated with something which can be copied and be of multiple use. Some "technologies" were proposed long time ago, and now with our accumulated knowledge the proposals become more realistic. Some examples:

- monitoring nuclear reactors [56];
- oscillation and absorption tomography of the Earth;
- study of geoneutrinos [57]: creation of the neutrino maps of the Earth;
- use of Moessbauer neutrinos for precision measurements;
- neutrino communication systems, Galactic communication [58];
- creation of the solar scanners to search for oil and minerals [59], *etc.*.

Practical realizations at least some of these proposals look at present extremely challenging. At this point one can, however, recall the story of neutrinos themselves: in thirties of the last century their discovery seemed to be impossible, and another story of establishing non-zero neutrino mass, when solution came not from the direct kinematic measurements but from the discovery of long time "exotic" and "non-standard process"- neutrino oscillations.

7. Conclusion

Neutrino physics is in the transition phase. Significant territory is already conquered which can be described in terms of the standard neutrino scenario. Tests of this scenario and searches for physics beyond it are the main objectives for further studies. Precision measurements and exploration of extreme conditions (energies, densities, distances) will open new horizons.

And what emerges? - Unclear implications of results for fundamental theory, origins of neutrino mass and mixing, existence of flavor symmetries, unification, *etc.* The question what should be done to achieve progress in understanding neutrino mass and mixing is already, and will be in future a driving force of future developments. LHC and other high energy experiments may clarify the situation.

In spite of these problems we can start to think seriously about applied neutrino physics and and neutrino technologies.

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