The history of neutrino oscillations

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Convincing evidence of neutrino oscillations obtained in:

- **SK, SNO, KamLAND**
- **other solar and atmospheric neutrino experiments**
- **accelerator K2K experiment**

Neutrino oscillations are direct consequence of small neutrino masses and mixing

It took about 40 years from original ideas of neutrino oscillations to discovery

History *(very schematically…)*

- **Original ideas of neutrino oscillations and neutrino mixing *('50s, '60s)***
- **Phenomenological theory of neutrino mixing and oscillations *('70s)***
- **The solar neutrino puzzle *('70s)***
- **Nonzero neutrino masses in GUT models *('70s, '80s)***
- **The see-saw mechanism of neutrino mass generation *(1979)***

- **K-ton detectors (Kamiokande, IMB)** ***('80s)***
- **Reactor and accelerator experiments to search for neutrino oscillations** ***('80s)***
- **Importance of matter in the case of neutrino mixing, MSW effect** ***('70s, '80s)***
- **Atmospheric neutrino anomaly** ***('80s)***
- **Strong evidence for oscillations of the atmospheric neutrinos**
  - **SK** ***(1998)***
  - **solar neutrinos SNO** ***(2001)***
  - **reactor neutrinos KamLAND** ***(2002)***

I will try to discuss the evolution of original ideas of neutrino masses, mixing and oscillations

W. Pauli (1930) **neutrino ("neutron") is a light neutral particle with mass less than electron mass**

E. Fermi and Perren (1934) **proposed the first method of the measurement of neutrino mass (the high-energy part of β–spectra)**

In the first experiments *G. Hanna and B.Pontecorvo* / *S. Curran, J. Angus and A. Cockroft* *(1949)* :

$$m_\nu \lesssim 500 \text{ eV}$$

At the time of the discovery of parity violation *(1956-57)*

$$m_\nu \lesssim 200\,\text{eV} \simeq 4 \cdot 10^{-4}\,\text{m}_\text{e}$$

The two-component neutrino theory (Landau, Lee and Yang, Salam, 1957) was the first theoretical idea about neutrino mass

The theory was proposed after

- **large *parity violation* in the β–decay *(Wu et al., 1957)* and other processes was discovered**
- **It was known that neutrino mass is *much smaller* than the electron mass**

If neutrino is massless there is a beautiful possibility to explain large violation of parity

At $m_\nu \neq 0$ for $\nu_L(x)$ and $\nu_R(x)$ ***two coupled Dirac equations:***

$$i\,\gamma^\alpha\,\partial_\alpha\,\nu_L(x) - m_\nu\,\nu_R(x) = 0$$

$$i\,\gamma^\alpha\,\partial_\alpha\,\nu_R(x) - m_\nu\,\nu_L(x) = 0$$

For $m_\nu \neq 0$ we have ***decoupled Weil equations:***

$$i\,\gamma^\alpha\,\partial_\alpha\,\nu_{L,R}(x) = 0$$

Neutrino field can be

$$\nu_L(x)\ \ or\ \nu_R(x)$$

If neutrino field is $\nu_L(x)$ ($\nu_R(x)$)

- The Hamiltonian of the β-decay has the form

$$\mathcal{H}_I^\beta = \sum_i G_i\,(\bar{p}\,O_i\,n)(\bar{e}\,O^i\,\frac{1}{2}(1 \mp \gamma_5)\nu) + h.c.$$

large (maximal) violation of parity is ensured

- Neutrino (antineutrino) *helicity* is equal to

  -1 (+1) left-handed field

  +1 (-1) right-handed field

Neutrino helicity was measured in a spectacular M.Goldhaber et al. experiment *(1958)*

$$
\begin{array}{lll}
e^- + \mathrm{Gd} \to \nu_e + & \mathrm{Sm}^* & \\
 & \downarrow & \\
 & \mathrm{Sm} & + \gamma
\end{array}
$$

It was found that

helicity = -1 ± 0.3 ➔

Neutrino field is $\nu_L(x)$

A two-component massless particle was discussed by Pauli in encyclopedia article "General Principles of Quantum Mechanics" *(1933)*

"...because the equation for $\nu_L(x)$ ($\nu_R(x)$) is not invariant under space reflection it is not applicable to the physical reality"

From the point of view of the two-component theory large violation of parity in the β–decay and other leptonic processes is ultimately connected with $m_\nu = 0$

V-A theory

Feynman and Gell-Mann, Marshak and Sudarshan, (*1958*):

left-handed components of *all fields* enter into Hamiltonian

- **Violation of parity is not connected with exceptional properties of neutrinos**
- **there are other reasons for left-handed fields in the Hamiltonian**

It was natural to turn up arguments and assume that neutrino like other fermions has

different from zero mass

- **Two-component neutrino theory was in perfect agreement with experiment**
- **It was a nice and the simplest theoretical possibility**
- **During many years there was a general opinion that neutrinos are massless two-component particles**
- **The Standard Model *(Glashow 1961, Weinberg, Salam, 1967)* was build under the assumption of massless two-component neutrino**

- First idea of neutrino masses, mixing and oscillations belong to *B.Pontecorvo (1957)*
- B.P. believed that in the lepton world exist a phenomenon analogous to the famous

$$K^0 \rightleftarrows \bar{K}^0 \text{ oscillations}$$

- The natural candidate was neutrino oscillations.
- Only one neutrino type was known at that time
- Possible oscillations are

$$\nu_L \rightleftarrows \bar{\nu}_L \quad \text{and} \quad \bar{\nu}_{\mathrm{R}} \rightleftarrows \nu_{\mathrm{R}}$$

- However, according to the two-component neutrino theory the states like ν_R do not exist
- Such states were a problem for B.Pontecorvo
- We will see how he solved it

- **In *1957-1958* R. Davis was performing reactor experiment to search for**

$$\bar{\nu}_e + {}^{37}\mathrm{Cl} \to \mathrm{e}^- + {}^{37}\mathrm{Ar}$$

- **A rumor reached B. Pontecorvo that R. Davis observed production of argon ^{37}Ar**

In 1958 B.P. published the paper on neutrino oscillations

“ Recently the question was discussed whether there exist other mixed neutral particles beside the K^0 mesons, i.e. particles that differ from the corresponding antiparticles, with the transitions between particle and antiparticle states not being strictly forbidden. It was noted that neutrino might be such a mixed particle, and consequently there exists the possibility of real neutrino $\leftrightarrow$ antineutrino transitions in vacuum, provided that lepton (neutrino) charge is not conserved. This means that the neutrino and antineutrino are mixed particles, i.e., a symmetric and antisymmetric combination of two truly neutral Majorana particles ν_1 and ν_2. “

" The flux of neutral leptons consisting mainly of antineutrino when emitted from a reactor will consist at some distance R from the reactor of half neutrinos and half antineutrinos. "

" It will be extremely interesting to perform C.L. Cowan and F. Reines experiment at different distances from reactor. "

In the paper that was written at the time when the *two-component theory* had just appeared and the Davis experiment was not finished, B.P. wrote

"...it is not possible to state a priori that some part of the flux can initiate the Davis reaction"

Later he concluded that due to oscillations neutrino and antineutrino can transfer into states (ν_R, *etc*) which can not be detected via the standard weak interaction.

B. Pontecorvo was the first who introduced the notion of *sterile neutrinos* so popular nowadays

After ν_μ was discovered, it was not difficult for B.Pontecorvo to generalize the idea of neutrino oscillations for the case of ν_e *and* ν_μ *(1967)*

He considered oscillations into active and sterile states

$$\nu_\mu \rightleftarrows \nu_e, \; \nu_\mu \rightleftarrows \bar{\nu}_{\mu L} \text{ etc.}$$

Before the first results of Davis experiment was reported *(1970)* B.Pontecorvo pointed out that

due to neutrino oscillations the observed flux of solar neutrinos could be two times smaller than the expected flux:

“ **From an observational point of view the ideal object is the sun. If the oscillation length is smaller than the radius of the sun region effectively producing neutrinos, (let us say one tenth of the sun radius $R_{\odot}$ or *0.1 million km* for ^{8}B neutrinos, which will give the main contribution in the experiments being planned now), direct oscillations will be smeared out and unobservable. The only effect on the earth's surface would be that *the flux of observable sun neutrinos must be two times smaller than the total neutrino flux.“ (1967)***

“ Unfortunately, the relative weight of different thermonuclear reactions in the sun and its central temperature are not known well enough to permit a comparison of the expected and observed solar neutrino intensities. “

- **It was difficult at that time to envisage the SNO result: NC were not yet discovered**

- **In 1988 when there were difficulties with SNO B.P. wrote strong letter in the support of the experiment:**

Dr. Walter F. Davidson

High Energy Physics Section
National Research Council of Canada

Dear Dr. Davidson,

Thank you very much for sending me the SNO proposal.

Below I am writing a short comment on SNO in the hope that opinion of a person who already in 1946 worked in Canada on neutrinos may be of some value. The SNO proposal (1000 tons of D_2O immersed in H_2O in a mine 2 km deep) in my opinion is a wonderful proposal for several reasons.

First it is new, in the sense that with the help of large D_2O detector immersed in H_2O there becomes possible the investigation of reactions

1. $\nu_e d \rightarrow e^- pp$
2. $\nu_x e \rightarrow \nu_x e$
3. $\nu_x d \rightarrow \nu_x np$
4. $\bar{\nu}_e d \rightarrow e^+ nn$
5. $\bar{\nu}_e p \rightarrow e^+ n$

with main application to solar and star collapse neutrinos (1,2,3) and star collapse antineutrinos (4,5).

Second, the proposal is realistic, in a sense that at least one large Cerenkov counter filled with H_2O is known to work properly (Kamiokande)

Third, the proposal can be realized only in Canada, where for historical reasons large quantities of D_2O are available during a period of several years.

Finally, in my opinion the neutral current reaction (3) yielding the total number of neutrinos of all flavors, can be investigated in spite of serious difficulties of registration of neutrons.

In conclusion the SNO proposal is progressive and should be supported by all means.

Yours sincerely.

Bruno Pontecorvo, Dubna August 18, 1988

Z. Maki, M. Nakagawa and S. Sakata *(1962)*

Approach based on Nagoya model

$$p = < \nu B^+ >, n = < e^- B^+ >, \Lambda = < \mu^- B^+ >$$

"B^+ is a new sort of matter"

- **B-L symmetry (symmetry of weak current under $\nu \leftrightarrow p$, $e^- \leftrightarrow n$, $\mu^- \leftrightarrow \Lambda$) can be interpreted**
- **In *1962* there were indications that ν_e *and* ν_μ are different particles, ($\mu \rightarrow e\, \gamma$)**
- **The Brookhaven experiment was under preparation.**

- **MNS considered possible existence of two different neutrinos as a problem for the Nagoya model and barion-lepton symmetry *(four leptons and three hadrons)***

- **The standard weak current**

$$j_\alpha = 2\left(\bar{\nu}_{eL}\,\gamma_\alpha\, e_L + \bar{\nu}_{\mu L}\,\gamma_\alpha\, \mu_L\right)$$

determines weak neutrinos ν_e *and* ν_μ

“ **We assume that there exist a representation which defines the true neutrinos ν_1 and ν_2 through orthogonal transformation** ”

$$\nu_1 = +\nu_e \cos\delta + \nu_\mu \sin\delta$$
$$\nu_2 = -\nu_e \sin\delta + \nu_\mu \cos\delta$$

“ **The true neutrinos should be so defined that B^+ can be bound to ν_1 but can not be bound to ν_2 .** "

Modified model

$$p =< \nu_1 \, B^+ >, \; n =< e^- \, B^+ >, \; \Lambda =< \mu^- \, B^+ >$$

to lepton current

$$j_\alpha = 2 \, (\bar{\nu}_{1L} \, \gamma_\alpha \, e_L \, \cos\delta + \bar{\nu}_{1L} \, \gamma_\alpha \, \mu_L \, \sin\delta) + ...$$

corresponds hadronic current

$$j_\alpha = 2 \, (\bar{p}_L \, \gamma_\alpha \, n_L \, \cos\delta + \bar{p}_L \, \gamma_\alpha \, \Lambda_L \, \sin\delta) + ...$$

identical to Gell-Mann – Levy current
(pre-Cabibbo current)

MNS assumed additional interaction of ν_2 with a field *X* of heavy particles

$$\mathcal{L} = g\,\overline{\nu}_2\nu_2\,X^+X \qquad (1)$$

which provides mass difference between ν_2 *and* ν_1

" Weak neutrinos

$$\nu_e = \nu_1 \cos\delta - \nu_2 \sin\delta$$

$$\nu_\mu = \nu_1 \sin\delta + \nu_2 \cos\delta$$

are not stable due to occurrence of virtual transition

ν_e ←→ ν_μ caused by the interaction (1)"

(notice that δ is Cabibbo angle)

In connection with BNL experiment MNS noticed:

"... a chain of reactions

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\nu_\mu + Z \to Z' + (\mu^- \text{and/or } e^-)$$

is useful to check the two-neutrino hypothesis only when

$$|m_{\nu_2} - m_{\nu_1}| \leq 10^{-6}\ \text{MeV}$$

under the conventional geometry of the experiments. Conversely, the absence of e⁻ will be able not only to verify two-neutrino hypothesis but also to provide an upper limit of the mass of the second neutrino ν_2 if the present scheme should be accepted. "

B. Pontecorvo and collaborators

The first phenomenological theory of neutrino mixing was proposed by *V. Gribov* and *B. Pontecorvo (1969):*

- **Main assumption: ν_{eL} and $\nu_{\mu L}$ enter not only into the interaction but also into the mass term**

- **A wide-spread prejudice at that time that in the case of left-handed fields neutrino masses must be equal to zero. This is correct if total lepton number is conserved**

- **GP showed that neutrino masses can be introduced, if the total lepton number is changed by 2**

$$\mathcal{L}^{\mathrm{M}} = -\frac{1}{2}(m_{e\bar{e}}\,\overline{(\nu_{eL})^c}\,\nu_{eL} + m_{\mu\bar{\mu}}\,\overline{(\nu_{\mu L})^c}\,\nu_{\mu L} +$$
$$m_{e\bar{\mu}}\,((\overline{(\nu_{eL})^c}\,\nu_{\mu L} + \overline{\nu_{\mu L})^c}\,\nu_{eL})) + \mathrm{h.c.}$$

$m_{\mu\bar{\mu}}$, $m_{e\bar{e}}$, $m_{e\bar{\mu}}$ are parameters.

After diagonalization

$$\nu_{eL} = \cos\theta\ \ \nu_{1L} + \sin\theta\ \ \nu_{2L}$$
$$\nu_{\mu L} = -\sin\theta\ \ \nu_{1L} + \cos\theta\ \ \nu_{2L}$$

$\nu_{1,2}$ are fields of Majorana neutrinos with masses $m_{1,2}$

L^{M} is called Majorana mass term.

- Possible oscillations $\nu_e \leftrightarrow \nu_\mu$
- No transitions into sterile states
- The observables (mixing angle and Majorana neutrino masses) are connected with the parameters by

$$\tan 2\theta = \frac{2m_{e\bar{\mu}}}{m_{\mu\bar{\mu}} - m_{e\bar{e}}}$$

$$m_{1,2} = \frac{1}{2}\left(m_{\mu\bar{\mu}} + m_{e\bar{e}} \mp \sqrt{(m_{\mu\bar{\mu}} - m_{e\bar{e}})^2 + 4\,m_{e\bar{\mu}}^2}\right)$$

- Mixing is maximal If there is μ-e symmetry

$$m_{\mu\bar{\mu}} = m_{e\bar{e}};\; m_{e\bar{\mu}} \neq 0$$

- Vacuum oscillations were considered for maximal mixing

The full phenomenological theory of neutrino mixing and the theory of neutrino oscillations in vacuum was developed in the '70s

S.B. and *B.Pontecorvo (1975)*

- **Neutrino mixing was introduced in analogy with Cabibbo-GIM mixing of quarks (lepton-quark analogy)**
- **The main idea : neutrinos like all other fundamental fermions (leptons and quarks) are massive particles**
- **A mixing of massive fermions is a general feature of gauge theories with spontaneous violation of a symmetry**

Thus, it looked quite natural to us that phenomenon of mixing is common for quarks and neutrinos

For the mixing

$$\nu_{eL} = \cos\theta \;\; \nu_{1L} + \sin\theta \;\; \nu_{2L}$$

$$\nu_{\mu L} = -\sin\theta \;\; \nu_{1L} + \cos\theta \;\; \nu_{2L}$$

$\nu_{1,2}$ are **4-component fields of Dirac particles** with masses $m_{1,2}$

Possible values of the neutrino mixing angle were discussed . We have concluded that

"... it seems to us that the special values of the mixing angle $\theta = 0$ (the usual scheme in which muonic charge is strictly conserved) and $\theta = \pi/4$ (maximal mixing) are of the greatest interest. "

The scheme proposed was based on Dirac mass term:

$$\mathcal{L}^{\mathrm{D}} = -\sum_{l l'} \bar{\nu}_{l' R} \, M^{\mathrm{D}}_{l' l} \, \nu_{l L} + \mathrm{h.c.}$$

- **The total lepton number *L* is conserved**
- **The possible oscillations are the same as in Majorana case $\nu_e \leftrightarrow \nu_\mu$**
- **In spite ν_{lR} in the mass term there are no transitions into sterile states (conservation of *L*)**

Our next step was the most general mass term

S.B. and *B. Pontecorvo (1976)*

- ν_{lL} in the interaction
- ν_{lL} and ν_{lR} in the mass term
- no conservation of *L*

$$\mathcal{L}^{\mathrm{D+M}} = -\frac{1}{2}\sum_{l,l'}\overline{(\nu_L)^c}\, M^{\mathrm{L}}_{l'l}\nu_{lL} - \sum_{l'l'}\bar{\nu}_{l'R}\, M^{\mathrm{D}}_{ll'}\,\nu_{lL}$$
$$-\frac{1}{2}\sum_{l,l'}\bar{\nu}_{l'R}\, M^{\mathrm{R}}_{l'l}(\nu_{lR})^c + \mathrm{h.c.}$$

M^L, M^R are complex symmetrical matrices, and M^D is a complex matrix

L $^{D+M}$ is called Dirac and Majorana mass term

$$\nu_{lL} = \sum_{i=1}^{2n} U_{li}\nu_{iL}; \quad (\nu_{lR})^c = \sum_{i=1}^{2n} U_{\bar{l}i}\nu_{iL},$$

U is the unitary 2n x 2n mixing matrix, ν_i is the field of the Majorana neutrino with mass m_i

If m_i are small, transitions

- $\nu_l \longrightarrow \nu_{l'}$ ***(flavor - flavor)***
- $\nu_l \longrightarrow \nu_{sL}$ ***(flavor - sterile)***

are possible.

The Dirac and Majorana mass term is the framework for the see-saw mechanism of neutrino mass generation.

The theory of neutrino oscillations

During ‘70s the theory of neutrino oscillations in vacuum, which is used today for analysis of the neutrino oscillation data was developed.

In the case of neutrino mixing the lepton numbers L_e, L_μ and L_τ are not conserved.

What are flavor neutrinos ν_e , ν_μ and ν_τ?

From the very beginning we define flavor neutrinos as particles, which take part in the standard CC weak processes with corresponding leptons.

For example:

- neutrino produced together with μ^+ in the decay $\pi^+ \to \mu^+ + \nu_\mu$ is ν_μ
- ν_e produces electron in the process $\nu_e + n \to e^- + p$
- etc.

States of flavor neutrinos

$$|\nu_l\rangle = \sum_i U_{li}^* \; |\nu_i\rangle$$

$|\nu_l\rangle$ is the state of neutrino with mass m_i and momentum p

- Thus, flavor neutrinos are described by *mixed coherent states*
- Based on assumption that neutrino mass-squared differences are so small that *due to uncertainty relation* it is impossible to distinguish production (detection) of neutrinos with different masses

$$L_{osc} >> d$$

d is quantum mechanical dimension of neutrino source

Decay probabilities and neutrino cross sections are given by the Standard Model

We applied to the flavor state the evolution equation of the field theory

$$i\frac{\partial|\Psi(t)\rangle}{\partial t} = \mathrm{H}\,|\Psi(t)\rangle$$

and came to the standard expression to the transition probability

$$\mathrm{P}(\nu_l \to \nu_{l'}) = |\delta_{ll'} + \sum_{i\geq 2} U_{l'i}U^*_{li}\ (e^{-i\Delta m^2_{i1}\frac{L}{2E}} - 1)|^2$$

L is the source-detector distance, *E* is neutrino energy, and $\Delta m^2_{i1} = m_i^2 - m_1^2$.

Necessary condition for the observation of neutrino oscillation

$$\Delta m_{i1}^2 \frac{L}{E} \geq 1$$

demonstrates ***enormous sensitivity of experiments*** on the search for neutrino oscillations to small neutrino mass squared differences

This was from our point of view the main reason to perform oscillations experiments

- **Due to interference nature of the phenomenon of neutrino oscillations and possibility to have very large values of *L/E* the investigation of neutrino oscillations is the most sensitive way *to search for small Δm^2***
- **This strategy brought success**
- **We summarized it in the first review on neutrino oscillations**

  (S.B.* and *B.Pontecorvo, 1977)

- **Except papers of B.Pontecorvo, MNS and B.P. and collaborators at that time it was published the papers by**

  J.Bahcall and S.Frautschi *(1969)*
  H.Fritzsch and P.Minkowsky *(1976)*
  S.Elizer and A.Swift *(1976)*

- **At the end of ’70s a common interest to the problem of the neutrino mass**
- **It was connected with the development of the GUT models and the invention of the see-saw mechanism of the neutrino mass generation.**
- **Neutrino masses started to be considered as a signature of new, beyond the Standard Model physics**

Today in the framework of the three neutrino mixing

$$\Delta m^2_{21} = (8.2^{+0.6}_{-0.5}) \cdot 10^{-5}\mathrm{eV}^2$$

$$\tan^2\theta_{12} = (0.40^{+0.09}_{-0.07})$$

$$1.9 \cdot 10^{-3} \le \Delta m^2_{32} \le 3.0 \cdot 10^{-3}\mathrm{eV}^2$$

$$\sin^2 2\theta_{23} \ge 0.90$$

$$\sin^2\theta_{13} \le 5 \cdot 10^{-2}$$

Because of $\Delta m^2_{21} \ll \Delta m^2_{32}$ and $\sin^2\theta_{13} \ll 1$ the dominant transitions

- **governed by Δm^2_{32} is $\nu_\mu \rightarrow \nu_\tau$**
- **governed by Δm^2_{21} are $\nu_e \rightarrow \nu_\mu$ and $\nu_e \rightarrow \nu_\tau$**

What physics was discovered?

What are implications?

- **Are massive neutrinos ν_l Majorana or Dirac particles?**
- **Type of neutrino mass spectrum: hierarchy, inverted hierarchy, degenerate,…?**
- **The lightest neutrino mass?**
- **How many massive neutrinos, sterile neutrinos?**
- **The value of $sin^2\theta_{13}$?**
- **CP phase?**
- **What are precise values of oscillation parameters?**

Conclusions

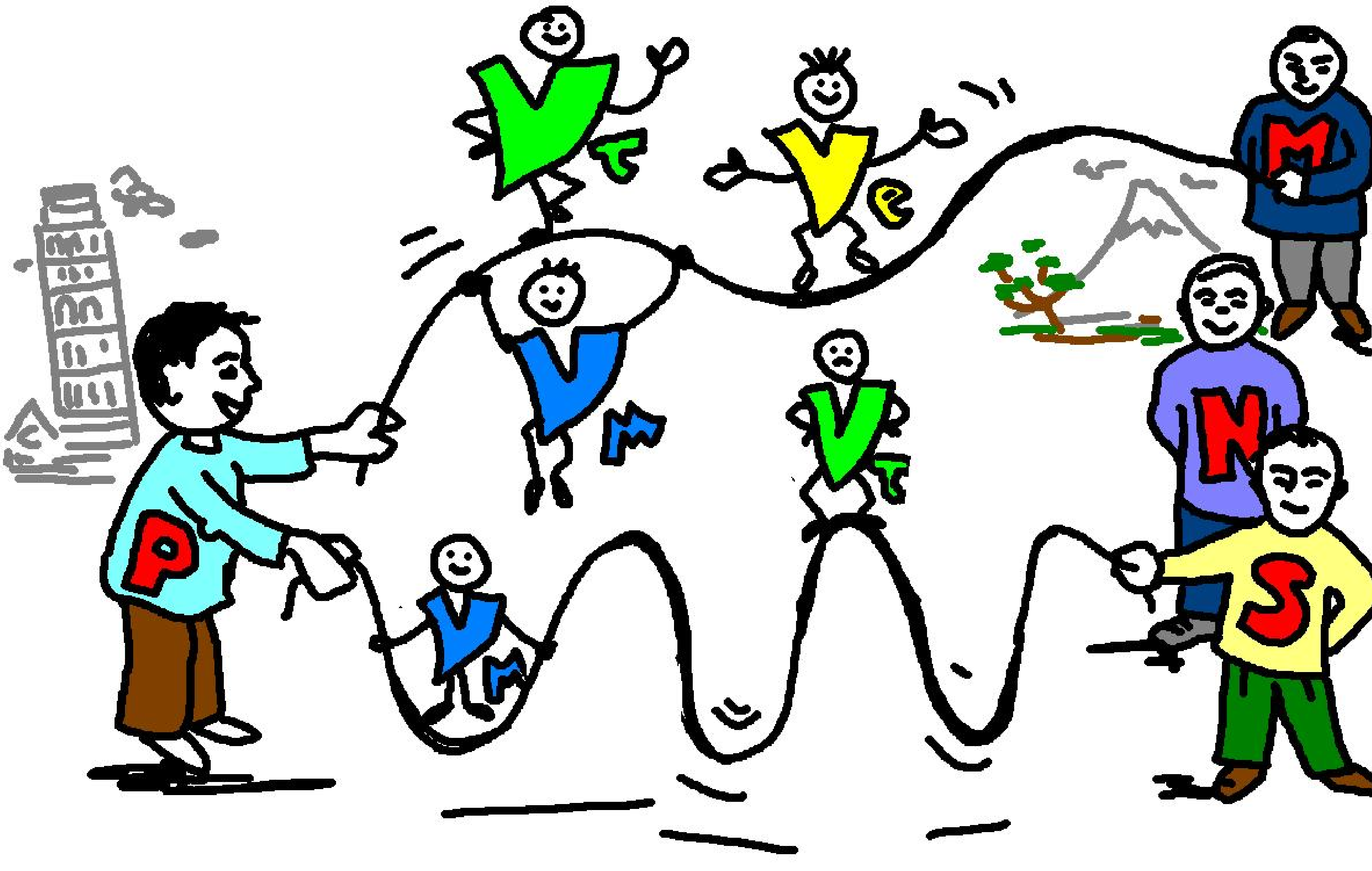
- The history of neutrino oscillations is an illustration of a complicated and thorny way of science: correct pioneer ideas are often have wrong basis or are accompanied by wrong one.

- Analogy is still an important guiding principle

- Courageous general ideas (no symmetries which forbid neutrino masses, oscillations is the most sensitive method to look for...) inspite contradiction with general opinion, have good chances to be correct

From *S.L.Glashow* talk
at the Venice "Neutrino Telescope Workshop" *(March 2003)*

"...if only Bruno Pontecorvo could have seen how far we have come towards understanding the pattern of neutrino masses and mixing! Way back in 1963 he was among the first have envisaged the possibility of neutrino flavor oscillations. For that reason the analog to the Cabibbo-Kobayashi-Maskawa matrix pertinent to neutrino oscillations should be known as the PMNS matrix to honour four neutrino visionaries: Pontecorvo, Maki, Nakagawa, and Sakata. "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