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A critical appraisal of some concepts used in neutrino physics

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Summary. — Some concepts used in neutrino physics, and highly considered in the past decade, are examined. They regard neutrino propagation, models for leptonic mixing, the interpretations of neutrinoless double beta decay and of the observations of SN1987A. On the basis of this examination, we argue that it would be useful to strengthen the role of the discussions among experts in neutrino physics, to assess the motivations and the value of the assumptions that underly the investigations.

PACS 01.70.+w – Scientific method.

1. – Superluminal neutrinos

Superluminal neutrinos are no more needed [1]; our goal, though, is to make a step back and examine how this concept arose. The ground was prepared by speculations on non-Einsteinian dispersion relations, as the velocity is $\vec{v} = \partial E/\partial \vec{p}$. Gonzalez-Mestres '97 proposed $E^2 = m^2 + [\sin(p\,a)/a]^2$ for hadrons, with $a \sim 1/M_{\text{Planck}} \equiv \sqrt{G_N}$, arguing that the new kinematics can wipe out the GZK cutoff; the 3-4σ indication from AGASA is contradicted by AUGER. Amelino-Camelia, Ellis, Mavromatos, Nanopoulos, Sarkar '97 proposed $p^2 = E^2(1 + \xi E/E_{\text{QG}})$ for the photons, of which "quantum gravity" was alleged. It implies $v = 1 - \xi E/E_{\text{QG}}$ and thus a delay that depends on the energy; the 2.5σ hint from MAGIC is excluded from HESS. Coleman and Glashow '98 proposed $E_a = c_a\sqrt{p^2 + (m_a c_a)^2}$, where $c_a \neq 1$ is a particle-depending constant; the interpretation along these lines of OPERA 2011 findings [2] was criticized by many theorists.

MINOS begun the recent campaign of measurement of neutrino velocity (see fig. 1) with these motivations [3] "...theories have been proposed to allow some or all neutrinos to travel along "shorcuts" off the brane through large extra dimensions (5), and thus have apparent velocities different than the speed of light. Some of these theories (6-8) allow $|v - c|/c \sim 10^{-4}$ at neutrino energies of a few GeV." Reference (6) is *Ann. Fond. Broglie* **31** (2006) 227 of Volkov, refs. (7,8) are unpublished. Reference (5) by Mohapatra and Smirnov discusses "branes" and "extra dimensions" but does not mention "shortcuts" while curiously, the paper *Sterile-active neutrino oscillations and shortcuts in the extra dimension* by Päs, Pakvasa, Weiler, is not quoted in any of these works. The word
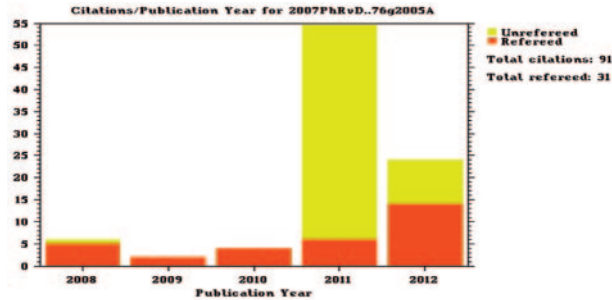
Fig. 1. – Citations received by the study of neutrino velocity performed by MINOS 2007. It shows that the upper bound that they obtained was considered of limited interest, till the analysis of OPERA appeared. Note also the relatively large number of papers published recently (orange). From the NASA/ESO database, March 2012.

"theories" used to introduce refs. (5-8) denotes respect, but does not mean that they have the status, say, of QED, of relativity or of quantum theory; note that we call "models" and not "theories" the standard description of the Sun by Bahcall and the one of elementary particles by Glashow, Weinberg, Salam.

The concept of superluminal neutrinos became appealing in the past decade. Various supporting arguments have contributed to the positive attitudes toward OPERA 2011 findings [2]. *E.g.*, the declarations of Petronzio on the Italian newspaper *Il Messaggero* (Sept. 23, 2011) allude to the "extra dimensions" often mentioned in the past *Piano Triennale* of INFN. Evidently theorists are not to be blamed for mistakes in experimental analyses, moreover unpublished; the issue is however that they have the responsibility of what is considered interesting and what it is being discussed.

2. – Leptonic mixing angles

In the nineties, the solution of the solar neutrino anomaly preferred by many theorists was the small angle solution, now gone. Something similar happened with θ_{13}. *E.g.*, Harrison, Perkins, Scott '02 have posited a mixing matrix with $\theta_{13} = 0$, termed "tri-bimaximal", that has had a significant impact on the general scientific discussion[1].

The measurements do not corroborate similar positions and rule out many proposals, see fig. 2. The remaining proposals should be examined to assess their value. *E.g.*, ref. [5] guessed the gross structure of the neutrino mass matrix M_ν by one key parameter and describing the residual uncertainty with a matrix of random numbers of $\mathcal{O}(1)$, namely $M_\nu \propto \mathrm{diag}(\varepsilon, 1, 1) \cdot \mathtt{random} \cdot \mathrm{diag}(\varepsilon, 1, 1)$. The best value – much better than $\epsilon = 1$ called "anarchy" – was found to be $\varepsilon = \theta_C = 13° \sim \sqrt{m_\mu/m_\tau} = 14°$. This value supported the large-angle solution of the solar-neutrino anomaly before it was confirmed, suggested a deviation of θ_{23} from the maximal value of similar size, and yielded $\theta_{13} = 12° \pm 6°$ in agreement with the recent θ_{13} measurements (or $6° \pm 3°$ with diagonal charged leptons).

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[1] This paper received more than 10 citations by many prominent colleagues, including S. King (50), Z.-Z. Xing (39), E. Ma (35), W. Rodejohann (29), S. Morisi (28), G. Altarelli (27), L. Merlo (23), S. Antusch (22), J. Valle (21), F. Feruglio (20), Y. Koide (20), C. Hagedorn (18), M. Hirsch (18), X.-G. He (18), M. Tanimoto (17), R. Mohapatra (15), A. Zee (14), F. Bazzocchi (13), M.-C. Chen (13), A. Smirnov (13), D. Meloni (13), W. Scott & P. Harrison (12), W. Grimus (12), S. Petcov (11) and P. Frampton (11). From inSPIRE database.
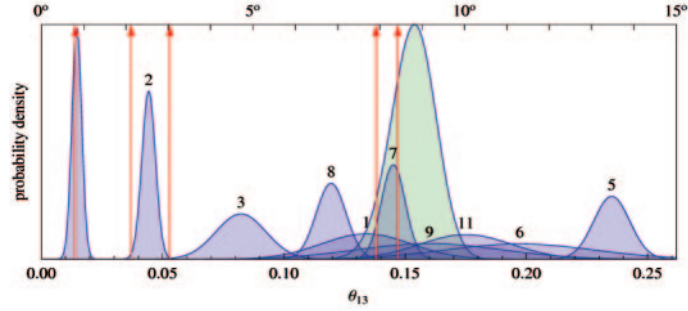
Fig. 2. – The area in lighter color is the distribution probability of the θ_{13} as found from the experimental analyses; the blue curves and the arrows, instead, indicate various theoretical predictions. From [4], where references can be found.

Let us emphasize the peculiarities of this approach. Reference [5] aims at an understanding of the mass matrix, rather than immediately postulating or discussing the mixing matrix. This seems a methodological merit, for the mixing matrix is derived by the mass matrix in gauge theories. However, approaches as ref. [5] concern a *class* of mass matrices: this calls for a more complete setup and, in fact, for a theory of the $\mathcal{O}(1)$ coefficients.

The speculations starting from $\theta_{13} = 0$, including most variants of tribimaximal mixings, have suggested that the conventional beams were not as appealing as the neutrino factories or beta beams; after [6] the value of this opinion is being reconsidered.

3. – Neutrinoless double-beta decay

Various higher-dimensional operators, that respect the $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge symmetry, however violate the baryon and lepton numbers, as noted in [7] and [8];

$$\delta\mathcal{L} = \frac{(\ell H)^2}{M} + \frac{\ell qqq}{M'^2} + \frac{(\ell qd^c)^2}{M''^5} \qquad \text{with} \qquad \begin{cases} M < 10^{11}\,\text{TeV}, & \text{for dim.5,} \\ M' > 10^{12}\,\text{TeV}, & \text{for dim.6,} \\ M'' > 5\,\text{TeV}, & \text{for dim.9.} \end{cases}$$

The bounds on dim.5 comes from neutrino masses $m_\nu < 0.1\,\text{eV}$, the one on dim.6 from matter stability, and the one on dim.9 is from the test of lepton number violation that we discuss here[2]. The transition $(A, Z) \rightarrow (A, Z+2) + 2e^-$, named neutrinoless double-beta decay, can be induced by the operators of dim.5, the one of dim.9, and other ones. Which is the leading source of this process? If the dim.5 operator, that provides us with Majorana neutrino mass terms, accounts for the observed three flavor oscillations and also dominates the transition, the key quantity is the $e - e$ element of the neutrino mass matrix m_{ee}. It can be calculated and displayed [9] as shown in fig. 3, for the two types of mass hierarchies allowed by the data and as a function of the lightest neutrino mass.

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[2] Here we show just some representative operators. Note that if there are light sterile neutrinos, dark matter—or generally additional light states—more operators may be required, and that a large effective mass could stem from small adimentional couplings y, *e.g.*, $1/M = y^2/\mu$.
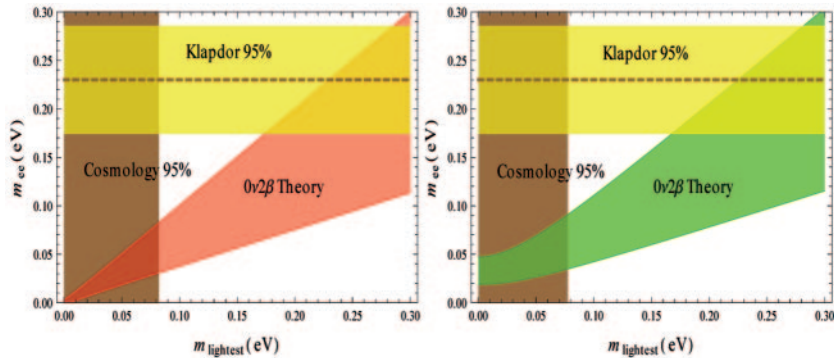
Fig. 3. – Value of m_{ee} from Klapdor results [12]; bound on m_{lightest} from cosmology [13]; expectations from `dim.5` operators and 3 flavor oscillations. Left, normal hierarchy; right, inverted hierarchy. Note the disagreement with the expectations.

The previous assumption is reasonable but does not apply in general. When the scale of lepton number violation is low, the higher dimension operator can play a main role, and the connection with Majorana neutrino masses (*i.e.*, with the `dim.5` operators) is quite loose or just absent. *E.g.*, neutrinoless double-beta decay process can be due to sterile neutrinos below 10 GeV that explain neutrino masses [10]. Also in left-right extensions of the standard model that can be probed at the LHC, the `dim.9` operators are relevant [11]. Therefore, we cannot conclude on logical grounds that we have a "black-box theorem", namely a necessary connection between the observation of neutrinoless double-beta decay and a Majorana nature of the ordinary neutrinos. Rather, we can say that under reasonable conditions (if the higher order operators play no role, in the absence of other light neutrinos, etc.) we expect quantitative correlations as the one in fig. 3.

Similar reluctance to analyze critically the views to which we are accustomed can be perceived also from the language. When we speak of neutrino*less* double-*beta* decay, we use a terminology for initiates and define a reaction for the *absence* of neutrinos, which is quite repulsive to common sense—even if it draws an analogy with the double-beta decay and it recalls us the absence of "missing energy". Another useful description of the same is *creation of electrons in a nuclear transition*, that emphasizes the violation of the lepton number, rather than alluding to a theoretical interpretation in terms of virtual Majorana neutrinos–or in modern terms, the dominance of `dim.5` operators. Moreover, such an alternative description can be explained also to laymen, it shows that the process is as important as proton decay and suggests connections with leptogenesis.

4. – Interpretations of SN1987A observations

The observations of SN1987A by Kamiokande-II, IMB and Baksan have begun a new chapter of astronomy. The main discussion of the astrophysical aspects lasted few years; the subsequent discussion of supernova neutrinos has proceeded, quite irrespectively of the interpretation of the SN1987A observations. The discussions in particle physics instead lasted much longer, and concerned mostly neutrino properties (initially, neutrino masses; later, neutrino mixings; more recently, exotic aspects). Based on [14], we would like to emphasize some attitudes of the discussion, that illustrate its limitations:
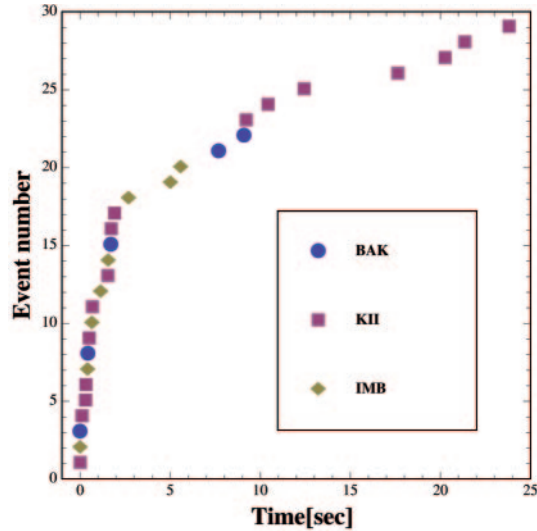
Fig. 4. – Temporal distribution of the events of Kamiokande-II (KII), Baksan (BAK) and IMB. Compatibly with the errors on the absolute time of Kamiokande-II and Baksan, the time of the first event (beginning of data taking) has been set to be the same. The rapid accumulation of events in the first second is evident already from the data: 6 events in KII, 3 in IMB, 2 in BAK. From [14].

i) A diffused opinion has been—and it is—that SN1987A was "non-standard". *E.g.*, it has been repeated that the average energy of the events observed from SN1987A is *too* low. However, the most recent simulations support lower energies—which suggests that the uncertainties are not understood. ii) Smirnov, Spergel and Bahcall have discussed in *Phys. Rev. D*, **49** (1994) 1389 whether SN1987A excludes large lepton mixing. *A posteriori*, the answer is evident, but the point to reiterate is that questions like these cannot be addressed before knowing the astrophysical uncertainties. iii) The previous two issues regard the energy distribution of the events; curiously, the meaning of the temporal distribution of the events, shown in fig. 4, has been discussed thoroughly only quite recently. iv) The observations of Baksan have been often ignored. Similarly, it is not clear whether the discussion of LSD findings was as complete as possible. v) Important pending questions, such as the existence of a compact remnant (neutron star?), or of multiple neutrino emissions, have received—and receive—only a marginal attention.

Perhaps, now that we know a lot on neutrino properties, the scope of the discussion of SN1987A events will widen.

5. – Discussion

We considered from various points of view certain theoretical concepts pertinent to superluminal neutrinos; models for θ_{13}; neutrinoless double-beta decay; SN1987A. We realized that in several cases, ideas that became popular and attracted consensus (as measured by conferences, publications, citations) do not correspond to valid concepts. A natural question is whether we can avoid this type of polarizations.

Let us examine the issue in general terms. Physics requires an extensive use of deductive (or analytical) methods—here is where mathematics acts as a very effective tool—but

it needs also to apply inductive procedures. The assumptions, the concepts, or the attitudes of the scientific discussions, belong mostly to inductive aspects of the method, and they should be subjected to critical attention in order to function properly(^{3}). This corresponds to the *pars destruens* of Bacon's inductive method and can be summarized with Newton's words *hypotheses non fingo*.

The shortage of fresh data is not the only problem that should worry us. The concepts and the assumptions we adopt should undergo critical examinations, and in our humble opinion we are called to make more efforts in this sense. In the same spirit, we think that open and frank scientific discussions among experts ought to play a more important role in neutrino physics. Activities like these are worthwhile even if (or just because) they may lead to opinions in partial contrast with current trends/hot topics.

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Two months after – note added. The healthy state of experimental neutrino physics is unquestionable: RENO collaboration has released data that corroborate Daya Bay results on θ_{13}; also, a null result from EXO-200 excludes the largest values of m_{ee} compatible with Klapdor's findings.

REFERENCES

[1] http://agenda.infn.it/materialDisplay.py?materialId=slides&confId=4896.
[2] ADAM T. *et al.*, arXiv:1109.4897 V2.
[3] ADAMSON P. *et al.*, *Phys. Rev. D*, **76** (2007) 072005.
[4] STRUMIA A. and VISSANI F., *Neutrino masses and mixings and...*, hep-ph/0606054 V3.
[5] VISSANI F., *JHEP*, **11** (1998) 025, eq. (5); *Phys. Lett. B*, **508** (2001) 79; hep-ph/0111373.
[6] AN F. P. *et al.*, arXiv:1203.1669.
[7] WEINBERG S., *Phys. Rev. Lett.*, **43** (1979) 1566 and *Phys. Rev. D*, **22** (1980) 1694.
[8] WILCZEK F. and ZEE A., *Phys. Rev. Lett.*, **43** (1979) 1571.
[9] VISSANI F., *JHEP*, **06** (1999) 022, fig. 4.
[10] MITRA M. *et al.*, *Nucl. Phys. B*, **856** (2012) 26; arXiv:1205.3867.
[11] TELLO V. *et al.*, *Phys. Rev. Lett.*, **106** (2011) 151801.
[12] KLAPDOR H. *et al.*, *Phys. Lett. B*, **586** (2004) 198, *Mod. Phys. Lett. A*, **21** (2006) 1547.
[13] DE PUTTER R. *et al.*, arXiv:1201.1909.
[14] VISSANI F. *et al.*, arXiv:1008.4726, *Frontiers Objects in Astrophysics and Particle Physics*, edited by F. GIOVANNELLI and G. MANNOCCHI, *Proc. SIF*, Vol. **103** (SIF, Bologna) 2011, p. 611.

(^{3}) Surely, these considerations should not overrule Popper's falsifiability criterion, but we need them anyway, since not all falsifiable statements have some scientific interest.