Results and Perspectives in Particle Physics

Perspectives in Neutrino Physics

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An attempt of reviewing/drawing the emerging picture of neutrino properties (particularly, of neutrino masses) with emphasis on what we would like/hope to know in close future, and on the most puzzling neutrino features. In this view, we select and discuss a number of questions, with the guide of recent experimental achievements and a bit of theory/prejudice.

How well do we know neutrinos?

We know they have been always generous with surprises.
Perhaps the future reserves more surprises.
Perhaps we are turning to a less exciting era (measurements)[a]

We have strong hints of oscillations with

- $\Delta m^2 \sim 10^{-3}$ eV^2 $(\sim 15\sigma)$ •
- $\Delta m^2 \sim 10^{-4}$ eV^2 $(\sim 10\sigma)$ •
- $\Delta m^2 \sim 10^{0}$ eV^2 $(\sim 3 - 7\sigma)$ •

Many people believe that in the last 5 years, neutrinos led us beyond the frontiers of standard model.

(some other think that we passed from suspicion to triumphalism...)

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[a] I believe that, at least, we should be ready for this second possibility

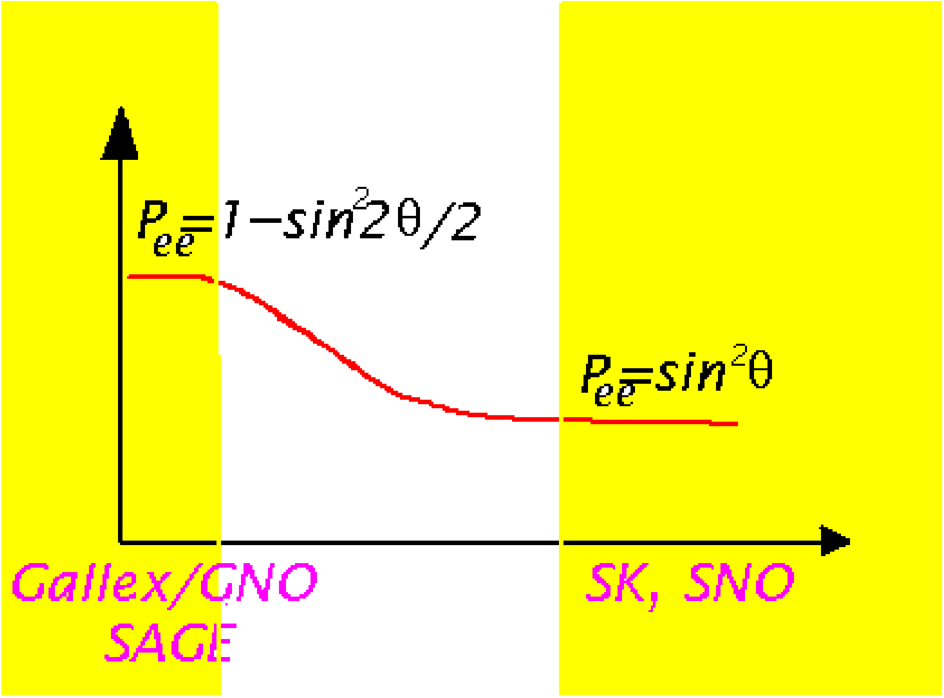
The oldest case: solar ν

With hindsight, solar neutrinos are also the most complicate case of oscillations, in the sense that the LMA solution is a transition regime.

Indeed, $\nu_e = \cos\theta\ \nu_1 + \sin\theta\ \nu_2$ in the sun converts into:

$$\begin{cases} \cos\theta\ \nu_1 + \sin\theta\ \nu_2\ e^{i\infty} & \text{at low } E \\ \nu_2 & \text{at high } E \end{cases}$$

The first case is the Gribov-Pontecorvo vacuum oscillation regime, the second one is the Mikheyev-Smirnov-Wolfestein regime, when *weak interaction* phases also affect the propagation.

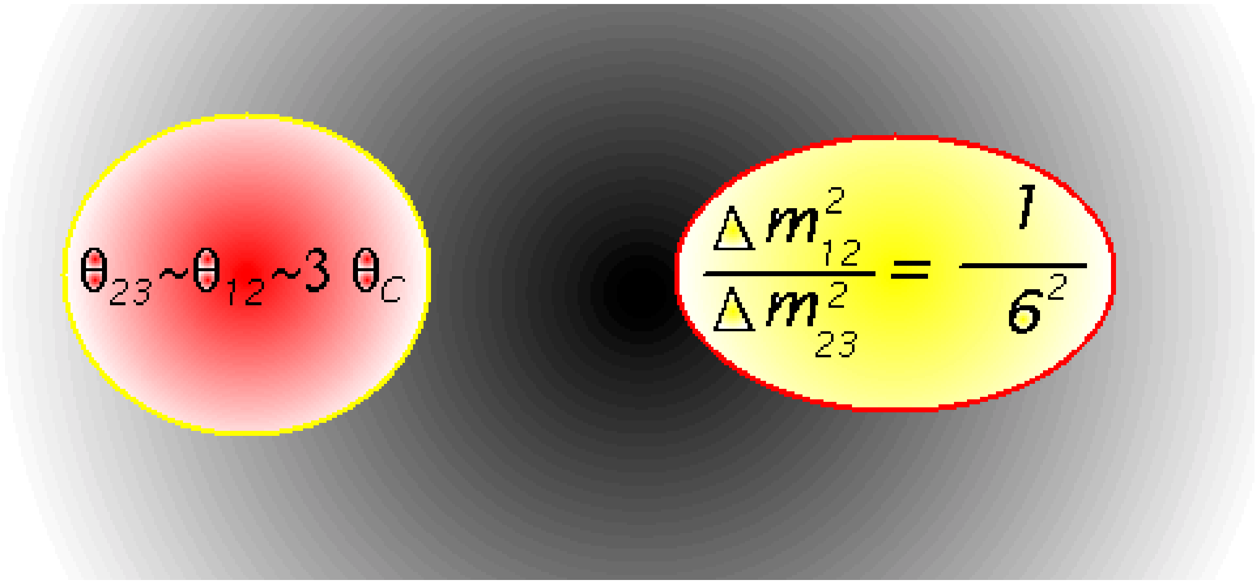


A “standard” 3ν interpretation

$$\nu_\ell = U_{\ell i} \cdot \nu_i \quad \text{with } \ell = e, \mu, \tau, \quad i = 1, 2, 3$$

$$\begin{aligned} U = \;& R_{23}(\theta_{23}) \cdot \mathrm{diag}(1, e^{i\phi}, 1) \\ & \cdot R_{13}(\theta_{13}) R_{12}(\theta_{12}) \cdot \mathrm{diag}(1, e^{i\alpha}, e^{i\beta}) \end{aligned}$$

$\theta_{23} = 45^\circ \pm 6^\circ$ $\Delta m^2_{23} =$ $2.7 \pm 0.4 \cdot 10^{-3}$	$\theta_{13} < 7^\circ$	$\theta_{12} = 34^\circ \pm 2^\circ$ $\Delta m^2_{12} =$ $7.1 \pm 0.6 \cdot 10^{-5}$
KAM, IMB, SK MACRO, Soudan K2K (Minos, ICARUS, OPERA)	CHOOZ, Palo Verde (ICARUS, Minos, Krasnoyarsk, JHF...)	Homestake, KAM, SK Gallex/GNO, SAGE, SNO, KamLAND (Borexino, ???)



Goals in oscillation

⋆ Priority is to get θ_{13}. There are a number of approved experiments that will reach few degrees sensitivity; future projects like JHF could go below 1 degree.

⋆ In the long run, we could use wrong sign muons from $\nu_e \to \nu_\mu$ oscillations (ν_e from $\mu^+ \to \nu_e \, e^+ \bar{\nu}_\mu$) to reveal leptonic $\not{C}\!P$

$$
\begin{aligned}
&P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu) \\
&\propto Im[U_{e1} U_{e3}^* U_{\mu 1}^* U_{\mu 3}] \propto \theta_{13} \sin\phi
\end{aligned}
$$

Essential to disentangle the MSW effect: opposite for ν_e and $\bar{\nu}_e$, mimickes fundamental $\not{C}\!P$

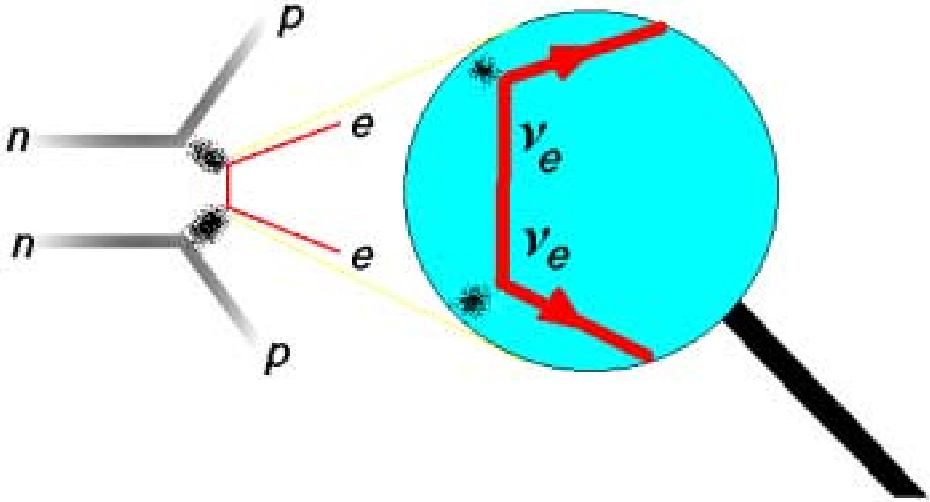
⋆ But, even in oscillations, surprises are not excluded (e.g., big oscillations into sterile neutrinos–I will not speak of that)

Non-oscillation techniques: $0\nu 2\beta$

The double beta decay processes ($N\nu 2\beta$) are:

$$(A,Z) \to (A,Z+2) + 2\, e^- + N\,\nu, \quad N = 0,2$$

Neutrino masses induce $0\nu 2\beta$:



(the arrows clash reveals Majorana character of mass)

We need a non-zero element of mass matrix:

$$M_{ee} \neq 0$$

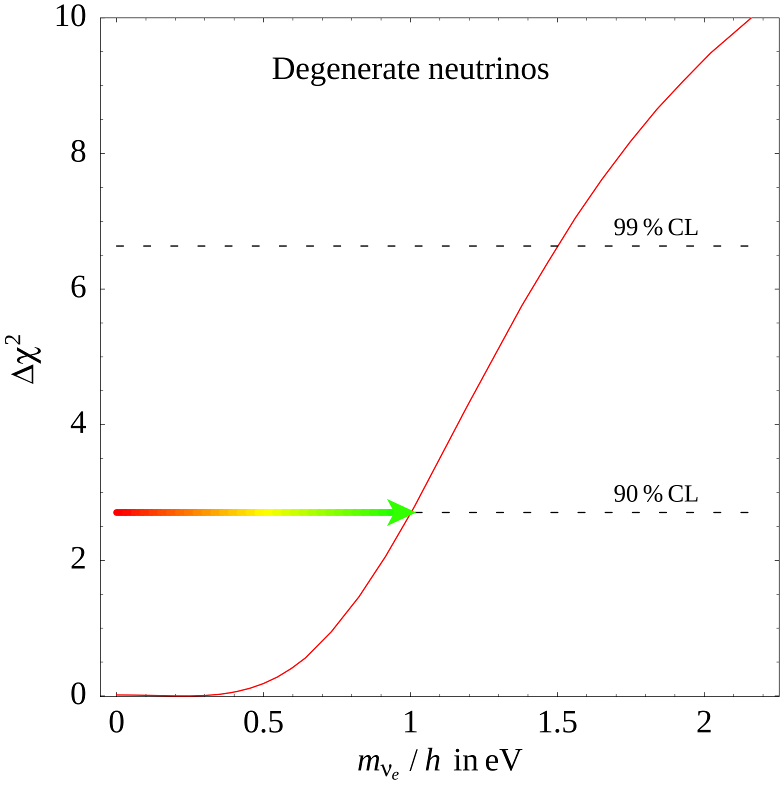
said otherwise, we probe just 1 element–not $M_{e\tau}$, $M_{\mu\mu}$...

Present best limit $350 \cdot h$ meV.

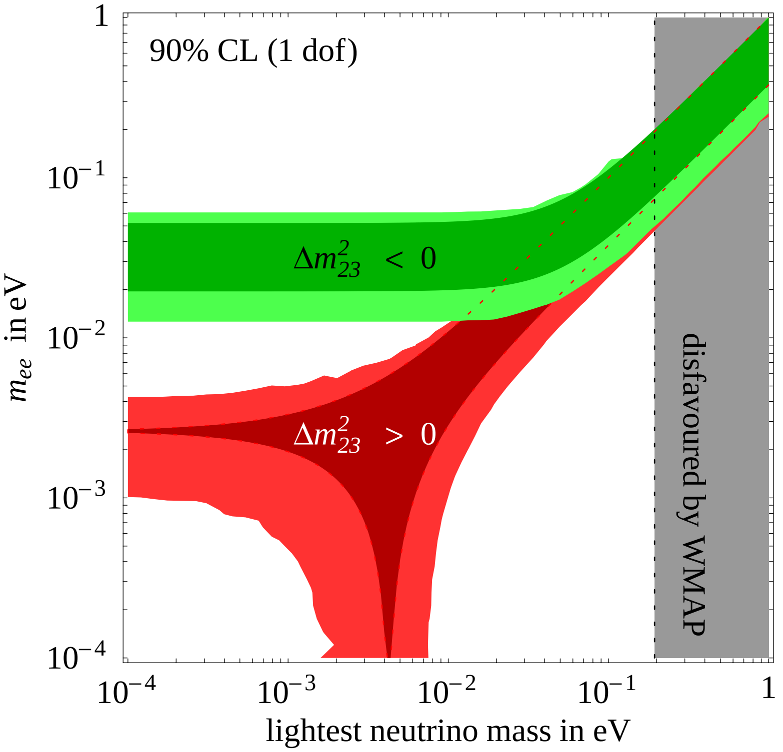
Plans to reach 10-20 meV sometimes in the future.

$0\nu2\beta$, ν-mass scale and oscillations

One can combine $0\nu2\beta$ and oscillation data learning on m_ν:



Alternatively, one gets the range of M_{ee} for any m_ν



(Too) many open questions!

Beside the crucial question of whether we have only 3 neutrinos that mix and oscillate among them, I list (roughly in my personal order of priority):

1. Why the mass hierarchy is so weak?
2. Why the leptonic mixing angles are large (when those of quarks are small)?
3. What is the absolute mass scale?
4. Is $\theta_{23} = 45^\circ$?
5. Is $\theta_{13} = 0$?
6. Is $\theta_{12} \neq 45^\circ$?

Today, the rough summary is:

$$|45^\circ - \theta_{23}| < \theta_C/2 \text{ (not so small)}$$

$$\theta_{13} < \theta_C/2 \text{ (not so small)}$$

$$\theta_{12} \neq 45^\circ \text{ at } \sim 4\sigma$$

Interlude: ν in astro-particle-physics

A partial list of cases when ν can be used as (astro)physical probes includes:

Site	Relevant process	Energy range	Experimental technique
Earth	fission	$\sim 10^6$ eV	undergr.detect.
Sun	fusion	$\sim 10^6$ eV	as above
Core-collapse supernova	non-equil. nucl.phys.(?)	$\sim 10^7$ eV	as above
AGN? GRB?	$p\gamma \to \Delta^+$	$\sim 10^{14}$ eV	large surface... km^3 detector
as above, ???	as above, ???	$\sim 10^{19}$ eV	inclined EAS, ...

We will spend few words on supernovae, since

⋆ Investigation relies on established techniques (it worked for SN1987A)

⋆ Has big payoff in astro- and particle physics (number of papers after SN1987A is very large)

⋆ It has enough question marks (at least for my taste)

Supernova 1–generalities

- Huge amount of gravitational energy of iron core, $E_b \sim 3 \cdot 10^{53}$ erg (~ 20 % $M_{core}c^2$) is released in ν during NS (BH?) formation

- Simulated explosions very difficult to obtain. Conservative attitude: need full 3D simulations. Perhaps, unexpected (astro)physics is involved. Perhaps, there is nothing like a "standard explosion"

- Agreement of expectations with SN1987A ν looks even too good. But there are just ~ 20 ν-events, and there is a number of strange features if one looks into the matter closely.

- Are we ready for next galactic supernova?[a]

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[a] An attempt of subliminal propaganda went here, since this is just the title of a workshop we are going to have at Gran Sasso on coming July 3-5.

Supernova 2–basics on ν

- A 0^{th}-order description of the energy distribution of the three ν types ($i = e, \bar{e}, \mu$) is the following:

$$F_i^0 = \frac{f_i E_b}{4\pi D^2} \cdot \frac{n(E/T_i)}{T_i^2} \text{ with } n(x) \approx \frac{0.18x^2}{1+\exp(x)}$$

General expectations:
$f_e \sim f_{\bar{e}} \sim f_\mu$, $T_e < T_{\bar{e}} < T_\mu$, $T_{\bar{e}} = 3 - 5$ MeV
(almost as imprecise as stated here).

- Oscillations in the star reshuffle the distributions. E.g., with 3 ν, 'normal' hierarchy, no MSW in Earth:

$$\bar{\nu}_e \to \quad \bar{\nu}_1 \Rightarrow F_{\bar{e}} = \cos^2\theta_{12}\ F_{\bar{e}}^0 + \sin^2\theta_{12}\ F_\mu^0$$

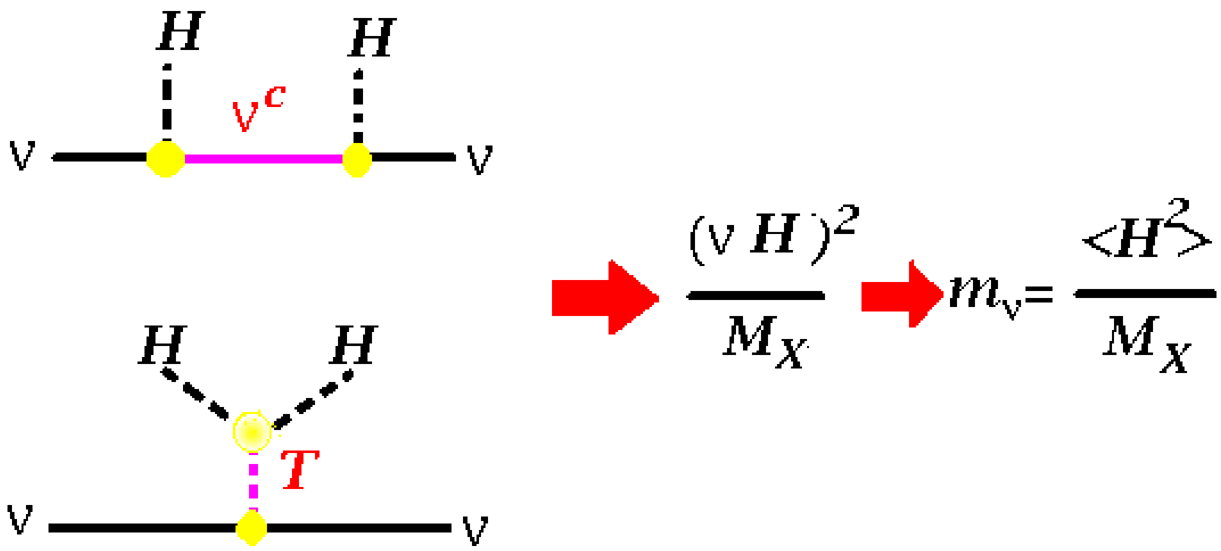
$$\nu_e \to \begin{cases} \nu_2 \Rightarrow F_e = \sin^2\theta_{12}\ F_e^0 + \cos^2\theta_{12}\ F_\mu^0 \\ \nu_3 \Rightarrow F_e = F_\mu^0 \end{cases}$$

- We should profit of three signals: ν_e, $\bar{\nu}_e$, $\nu_{NC} = \sum \nu_i$, (not only inverse beta decay $\bar{\nu}_e p \to n e^+$)

Possibly, we need several different reactions & detectors

Why ν masses are so small?

The famous seesaw mechanism is an answer
(ν^c is the heavy neutrino, T is a heavy higgs triplet):



⋆ A good chance for baryogenesis:
get $\Delta L \neq 0$ via ν^c decay, then convert to $\Delta B \neq 0$ by non-perturbative standard model effects (but I will not speak of this important issue further)

⋆ In SO(10), 126-dim. higgs gives big mass to ν^c.
But in this way, one gets also the triplet T!
Which is leading contribution to ν mass?

What is the structure of ν mass matrix?

When we consider $\nu_3 \approx (\nu_\mu + \nu_\tau)/\sqrt{2}$, the only non-zero contributions are $(M_\nu)_{\mu\mu} = (M_\nu)_{\mu\tau} = (M_\nu)_{\tau\tau}$.

We can imagine this is due to a "U(1) selection rule":

$$M_\nu \overset{\mathcal{O}(1)}{=} m_0 \begin{vmatrix} \varepsilon^2 & \varepsilon & \varepsilon \\ \varepsilon & 1 & 1 \\ \varepsilon & 1 & 1 \end{vmatrix}$$

Typically, $\mathcal{O}(1)$ coefficients yield two 'large' eigenvalues. Thus, assume a mild hierarchy $\sim 1/6$ and rotate basis:

$$M_\nu \to m_0 \begin{vmatrix} \varepsilon^2 & \varepsilon & 0 \\ \varepsilon & 1/3 & 0 \\ 0 & 0 & 2 \end{vmatrix}$$

If $\varepsilon \sim \theta_C$, we get LMA, and the expectations $\theta_{13} \sim \varepsilon$–fine for experiments–and $(M_\nu)_{ee} = (\Delta m^2_{atm})^{1/2}\varepsilon^2$–not that fine

- ⋆ $\mathcal{O}(1)$ coefficients can be taken at random –"statistics"
- ⋆ This framework can be reconciled with SU(5)

Do we have a theory of $\mathcal{O}(1)$ coefficients?

(An attempt with minimal SO(10))

Perhaps ν masses are different because the mass mechanism is special:

$$M_\nu \propto Y_{126} \text{ (the triplet option)}$$

This position is consistent with 2^{nd} and 3^{rd} family charged fermion masses–fine! Furthermore,

$$\begin{cases} M_E = vY_{10} - 3v'Y_{126} \\ M_D = vY_{10} + v'Y_{126} \end{cases} \Rightarrow M_\nu \propto \begin{vmatrix} 0 & 0 \\ 0 & m_b - m_\tau \end{vmatrix}$$

Thus, large mixing needs $b - \tau$ unification at GUT scale.

One gets $m_2/m_3 = 1/3 - 1/10$ in supersymmetric SO(10), as needed for LMA.

A full analysis including 1^{st} family should be soon available. I guess θ_{13} will come out large.

When an experimentalist...
instead, when a theorist...

I must admit that many theoretical proposals/guesses have been not *that* successful.[a] Still, I believe that:

- Already for ν masses, there are too many holes to be filled by experimental means only (e.g., $N_\nu = 3$ implies 9 parameters to be measured).
- At the same time, there are many important facts that we know on fermion masses, matter stability, cosmology... and they are most probably related each other.
- We should aim at theoretical schemes that are motivated, simple, and consistent with what we know.

I suspect we should consider grand unified ideas with renewed interest – perhaps, just more seriously.

That's it, thank you!

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[a] E.g.: 17 keV, SMA, hot dark matter, xdim-ν...

I thank the Organizers for kind invitation and support, the numerous persons from whom I learned on ν's (in particular R. Barbieri, S. Bertolini, A.Yu. Smirnov, T. Yanagida) and my collaborators with whom I share enjoyment for research (especially B. Bajc, F. Feruglio, A. Strumia, again G. Senjanovic, and all my friends and colleagues in the Gran Sasso national lab).

I include below a few theoretical references I used to prepare the talk and my email address as well: `vissani@lngs.infn.it`, in case you like to discuss some items better or just to send me a comment:

- F.Feruglio *et al*, hep-ph/0201291
- M.Fukugita, T.Yanagida, PLB 174,45 (1986)
- C.Froggatt, H.Nielsen, NPB 147, 277 (1979)
- F.V., hep-ph/0111373
- F.S.Ling, P.Ramond, hep-ph/0206004
- B.Bajc *et al*, hep-ph/0110310 and 0210207

Note that the abstract in the first page should be rather thought as a disclaimer: the task originally assigned by the Organizers, namely 'Perspectives in Neutrino Physics', is just mission impossible–too vast!