D Naumov & V.Naumov

NEUTRINO VELOCITY ANOMALIES

A resolution without a revolution

JINR, Dubna, October 2011

Accelerator measurements of neutrino velocity.

Relation $v = p/\sqrt{p^2 + m^2}$ is confirmed for electrons for $1 - v$ down to 2×10^{-7} .

[Z. G. T. Guiragossian *et al.*, Phys. Rev. Lett. 34 (1975) 335]

In all ν experiments it is assumed that this relation holds for muons, pions, and kaons.

- FNAL 1976 [345 m (decay pipe) + 550 m (shield), $\langle E_\nu^{(\pi)} \rangle = 25$ GeV, $\langle E_\nu^{(K)} \rangle = 75$ GeV]:

$$|v_\nu - v_\mu| < 4 \times 10^{-4} \ (99\% \text{ C.L.})$$

  [J. Alspector *et al.*, Phys. Rev. Lett. 36 (1976) 837]

- FNAL 1979 [345 m (decay pipe) + 550 m (shield), $E_\nu^{(\pi,K)} = 30$ to 200 GeV]:

$$|v_\nu - \overline{v}_\nu| < 7 \times 10^{-5}, \quad |v_\nu^{(K)} - v_\nu^{(\pi)}| < 5 \times 10^{-5}, \quad |v_{\nu,\overline{\nu}} - 1| < 4 \times 10^{-5} \ (95\% \text{ C.L.}).$$

  [G. R. Kalbfleisch *et al.*, Phys. Rev. Lett. 43 (1979) 1361]

- FMMF 1995

  [E. Gallas *et al.*, Phys. Rev. Lett. 52 (1995) 6]

- FNAL-SOUDAN (MINOS experiment) 2007 [734 km, $\langle E_\nu \rangle \sim 3$ GeV, $E_\nu \lesssim 120$ GeV]:

$$\delta \mathrm{t} = (126 \pm 32_{\mathsf{stat}} \pm 64_{\mathsf{sys}})\ \mathsf{ns}\ (68\%\ \text{C.L.}),$$
$$\Downarrow (?)$$
$$(v_\nu - 1) = (5.1 \pm 2.8_{\mathsf{stat}} \pm 0.30_{\mathsf{sys}}) \times 10^{-5}\ (68\%\ \text{C.L.}).$$

The measurement is consistent with the speed of light to less than 1.8σ.
The corresponding 99% confidence limit on the speed of the neutrino is

$$-2.4 \times 10^{-5} < (v_\nu - 1) < 12.6 \times 10^{-5}\ (99\%\ \text{C.L.}).$$

This measurement has implicitly assumed that the m_2 and m_3 neutrino mass eigenstates that comprise the beam are traveling at the same velocity. This assumption is borne out in observing that the arrival times at the far detector match the expectation distribution. Indeed, if the two eigenstates were to travel at velocities differing by as little as $\delta v/v \gtrsim 4 \times 10^{-7}$, the short ~ 1 ns [~ 29.4 cm, VN] bunches would separate in transit and thus decohere, changing or destroying oscillation effects at the far detector.

[P. Adamson *et al.* (MINOS Collaboration) Phys. Rev. D 76 (2007) 072005]

A few details:

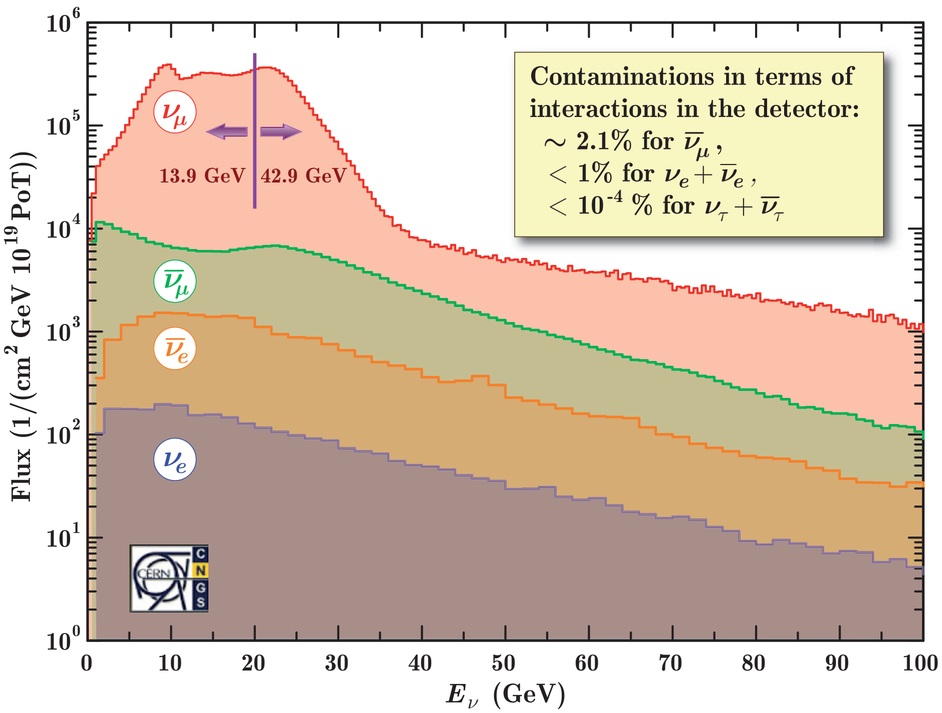
⋆ MINOS measures the absolute transit time of an ensemble of neutrinos, to < 100 ns accuracy, by comparing ν arrival times at the near detector (ND) and far detector (FD). The distance between front face of the ND and the center of the FD is 734298.6 ± 0.7 m.

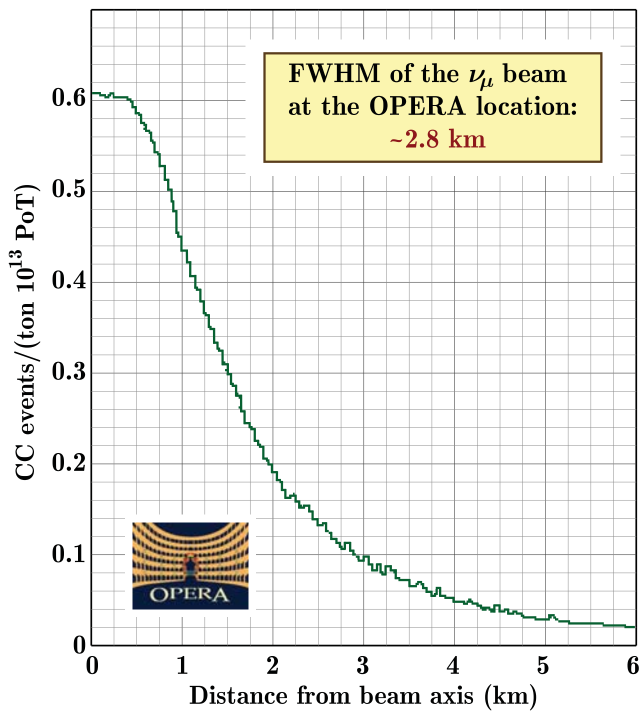
⋆ The beam flavor content: 93% ν_μ, 6% $\overline{\nu}_\mu$, 1% $\nu_e + \overline{\nu}_e$ at ND. After oscillating, the beam at FD is approximately 60% ν_μ.

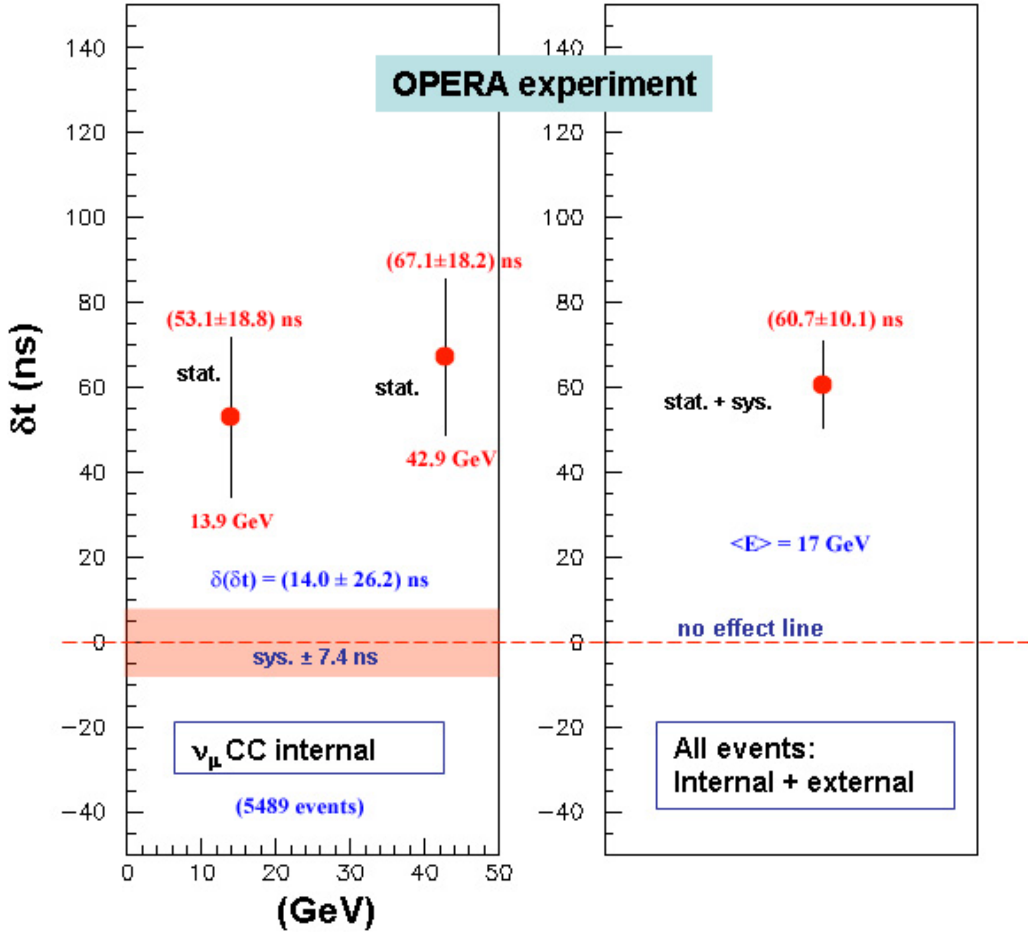
- CERN-LNGS (OPERA experiment) 2011 [730 km, $\langle E_\nu \rangle \sim 17$ GeV, $E_\nu \lesssim 350$ GeV]:

$$\delta t = (60.7 \pm 6.9_{\text{stat}} \pm 7.4_{\text{sys}}) \text{ ns},$$
$$\Downarrow (?)$$
$$(v_\nu - 1) = (2.48 \pm 0.28_{\text{stat}} \pm 0.30_{\text{sys}}) \times 10^{-5}.$$

[T. Adam *et al.* (OPERA Collaboration) arXiv:1109.4897 [hep-ex] (September 23, 2011)]







◁ Summary of the results for the measurement of δt.

The left plot shows δt vs. neutrino energy for ν_μ CC internal events. The errors attributed to the two points are just statistical in order to make their relative comparison easier since the systematic error (represented by a band around the no-effect line) cancels out.

The right plot shows the global result of the analysis including both internal and external events (for the latter the neutrino energy cannot be measured).

The error bar in the right plot includes statistical and systematic errors added in quadrature.

The result provides no clues on a possible energy dependence of δt in the domain explored by the OPERA, within the statistical accuracy of the measurement.

Astrophysical constraint.

ν burst from SN 1987A (Kamiokande-II, IMB, BUST)
[≈ 51 kps, $\langle E_{\overline{\nu}} \rangle \sim 15$ MeV, $E_{\overline{\nu}} \lesssim 40$ MeV]:

$$|v_\nu - 1| < 2 \times 10^{-9}.$$

[K. Hirata *et al.* (Kamiokande- Collaboration) Phys. Rev. Lett. 58 (1987) 1490;
R. M. Bionta *et al.* (IMB Collaboration) Phys. Rev. Lett. 58 (1987) 1494;
E. N. Alekseev *et al.* J. Exp. Theor. Phys. Lett. 45 (1987) 589]

Arguments: **[M. J. Longo Phys. Rev. D 36 (1987) 3276]**

The arrival time of the antineutrinos is known to be within a few seconds of 7:35:40 UT on February 23, 1987. The arrival time of the first light from SN is less well known. The last confirmed evidence of no optical brightening was at approximately 2:20 UT[a]. The earliest observations of optical brightening were at 10:38 UT by Garrad and by McNaught[b].

Standard SN theory expects that the neutrinos and antineutrinos are emitted in the first few second of the collapse, while the optical outburst begins ~ 1 h later, when the cooler envelope is blown away.

Altogether this leads to an uncertainty of about 3 h. Hence

$$|v_\nu - 1|_{\max} \sim 3\ \mathrm{h}/(1.6 \times 10^5 \times 365 \times 24\mathrm{h}) \approx 2 \times 10^{-9}.$$

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[a] I. Shelton, IUA Circular No. 4330,1987.
[b] G. Garradd, IUA Circular No. 4316, 1987; R. H. McNaught, *ibid.*

BUT!

- Remember about the first low-energy ($E_{\overline{\nu}} = 7 - 11$ MeV) pulse detected by LSD[a] at 2:52:36 UT that is $4^{\text{h}}44^{\text{m}}$ earlier the second (Kamiokande-II-IMB-BUST) pulse. This fact is usually ignored by the community.
- Nonstandard models of the stellar collapse predict the neutrino time advance to be much larger than 1 h (from a few hours to a few days).
- The second pulse signal shows a number of "anomalies", for instance,
  * the average $\overline{\nu}_e$ energies inferred from the IMB and Kamiokande observations are quite different;
  * the large time gap between the first 8 and the last 3 Kamiokande events looks worrisome;
  * the distribution of the positrons should be isotropic, but is found to be significantly peaked away from the direction of the SN.

  In the absence of other explanations, these features are blamed on statistical fluctuations in the sparse data.

Due to these doubts Longo's limit is generally not robust.

Naive estimations:

Assuming that δv is energy independent and $\delta \mathrm{t}_{L=730\,\mathrm{km}} = 60.7$ ns (OPERA) we obtain

$$\delta \mathrm{t}_{\mathrm{SN1987A}} \approx 4 \text{ yr}.$$

So it seems that any case there is a huge contradiction between the MINOS/OPERA result and astrophysics.

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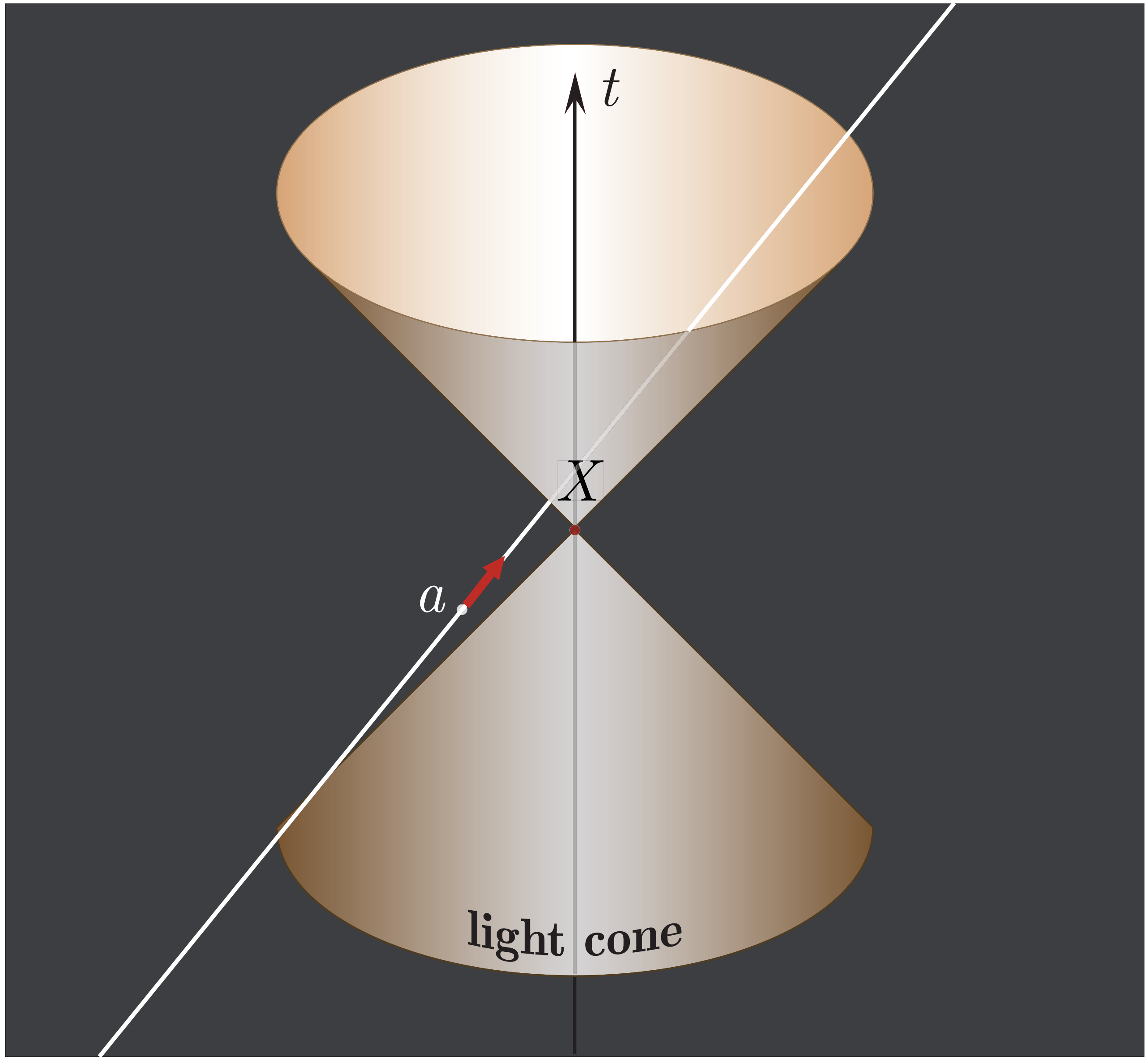
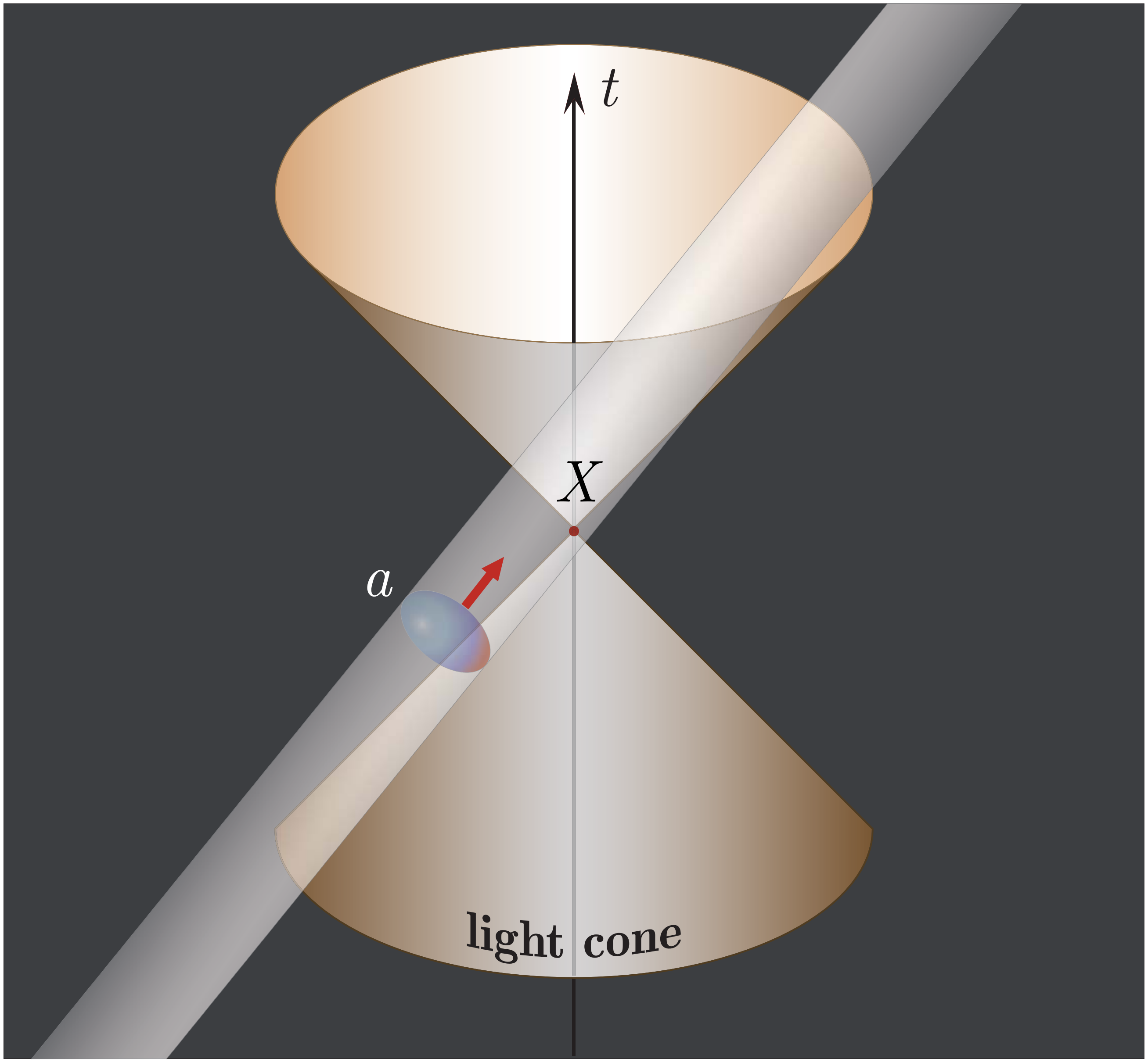
[a] V. L. Dadykin *et al.*, Pisma v Zh. Eksp. Teor. Fiz. **45** (1987) 464.

A point particle a cannot affect the space-time point X.



A finite size body a (or a wavepacket) whose center moves along the same world line as the particle a can affect the space-time point X.



Neutrino wavepacket

In our previous papers we developed a covariant field-theoretical approach to neutrino oscillations which operates with the relativistic wavepackets describing initial and final states of particles involved into the production and detection of neutrino. The neutrino in this approach is described as a virtual mass eigenfield travelling between the macroscopically separated production and detection vertices of Feynman graphs. Thus we make no any assumption about its wavefunction. Instead, within our formalism we compute the neutrino wavefunction which turns out to be a wavepacket with spatial and momentum widths defined and functionally dependent on those of the particles involved into the neutrino production and detection subprocesses. Explicitly, up to a coordinate independent spinor factor, the effective (outgoing) neutrino wavefunction reads

$$\psi_\nu^* = e^{iE_\nu(x_0-\mathbf{v}_\nu\mathbf{x})-\sigma_\nu^2\Gamma_\nu^2\left(\mathbf{x}_\parallel-\mathbf{v}_\nu x_0\right)^2-\sigma_\nu^2\mathbf{x}_\perp^2}. \tag{1}$$

It is shown that the center of any external wavepacket moves *in the mean* along the classical trajectory

$$\langle\mathbf{x}_\varkappa\rangle = \widetilde{\mathbf{x}}_\varkappa + \mathbf{v}_\varkappa x_\varkappa^0$$

conserving energy, momentum and effective volume ($\propto 1/\sigma_\varkappa^3$); under certain conditions the packets remain stable (nondiffluent) during the times much longer than their mean lifetimes (in case of unstable particles) or the mean time between the two successive collisions in the relevant ensemble (in case of stable particles).

Neutrino wavepacket for a two-body decay

$$\sigma_\nu^2 \approx m_\nu^2 \left(\frac{m_a^2}{\sigma_a^2} + \frac{m_\mu^2}{\sigma_\mu^2} \right)^{-1}, \quad a = \pi \text{ or } K.$$

Then from the above-mentioned conditions of stability for the meson and muon wavepackets it follows that σ_ν must satisfy the following conditions

$$\sigma_\nu^2 \ll m_\nu^2 \left(\frac{m_\mu}{\Gamma_\mu} + \frac{m_a}{\Gamma_a} \right)^{-1},$$

where $\Gamma_a = 1/\tau_a$ and $\Gamma_\mu = 1/\tau_\mu$ are the full decay widths of the meson a and muon. Considering that for *any* know meson $m_\mu/\Gamma_\mu \gg m_a/\Gamma_a$, we conclude that

$$\sigma_\nu^2/m_\nu^2 \ll \Gamma_\mu/m_\mu \approx 2.8 \times 10^{-18}. \tag{2}$$

Therefore the neutrino momentum uncertainty is fantastically small. From (2) one can immediately derive the lower bounds for the effective spatial dimensions of the neutrino wavepacket:

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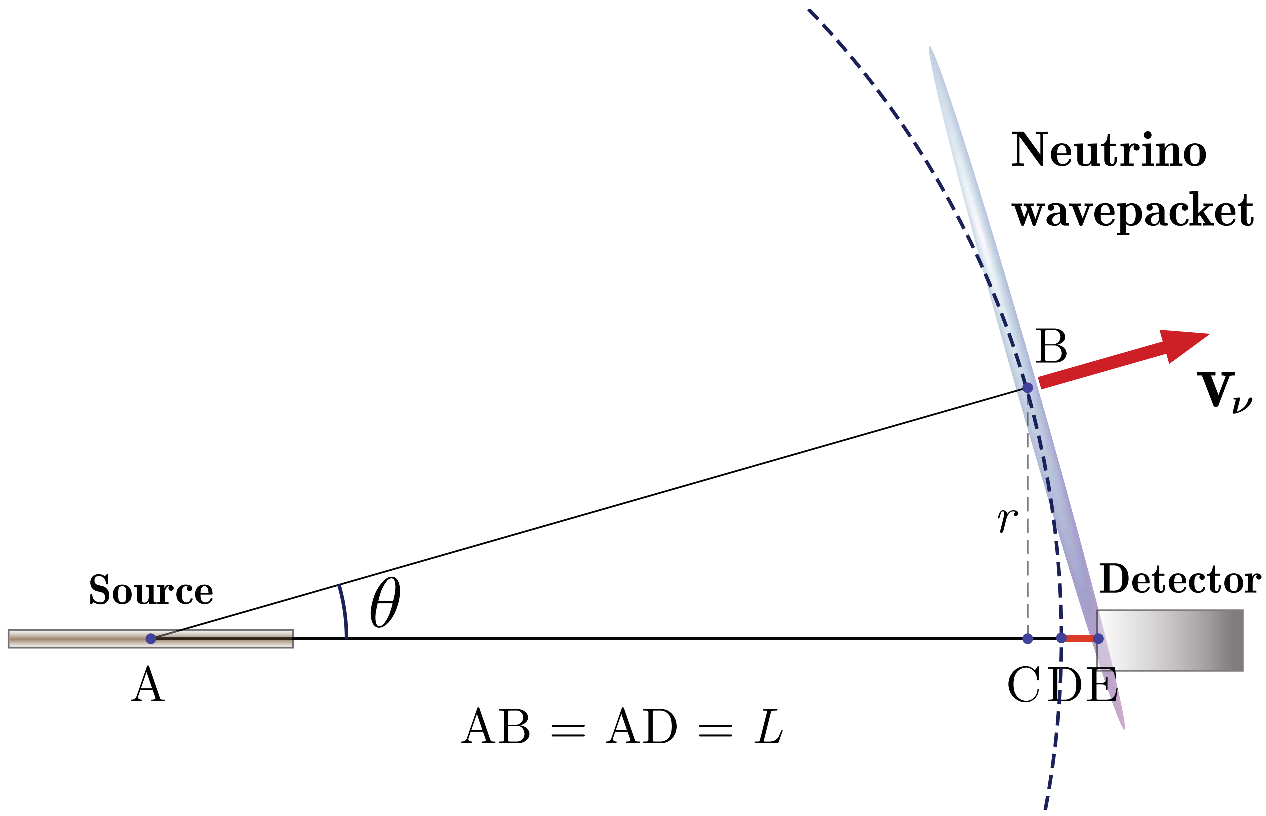
$$d_\perp \gg \left(\frac{0.1\ \text{eV}}{m_\nu}\right)\ \text{km},$$

$$d_\parallel = \frac{d_\perp}{\Gamma_\nu} \gg 10^{-2}\left(\frac{10\ \text{GeV}}{E_\nu}\right)\left(\frac{0.1\ \text{eV}}{m_\nu}\right)\ \mu\text{m},$$

So the neutrino wavepacket appears as a huge but superfine disk of microscopic (energy dependent) thickness in longitudinal direction, comparable with the thickness of a soap-bubble skin, and macroscopically large (energy independent) diameter in the transverse plane .

Qualitative estimations



Neutrinos are emitted from the "Source" and are registered in the "Detector". The centers of the neutrino wavepackets will arrive at the points B and D simultaneously, while the signal from the neutrino wavepacket (shown as an extremely oblate spheroid) which moves under the angle $\theta = \angle$BAC to the beam axis will arrive earlier since DE > 0. Neutrino velocity vector $\mathbf{v}_\nu$ lies in the plane of the figure. Proportions do not conform to reality.

The school-level planimetry suggests that the advancing time is given by

$$\delta t = L\,(1/\cos\theta - 1) \approx r^2/(2L). \tag{3}$$

Here we assume that

(i) $1 - v_\nu \lll 1$,

(ii) the neutrino wavepacket effective width is much larger than the detector dimensions, and

(iii) $\theta \ll 1$.

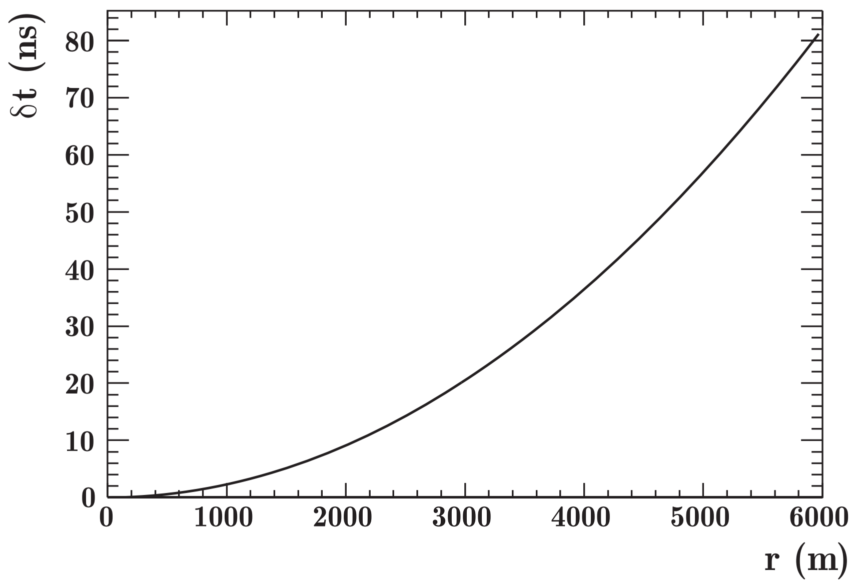


Рис. 1: Advance δt as a function of r.

What is the probability to find a neutrino at a distance r from the beam axis? This could be estimated taking into account that neutrino production is dominated by two-particle decays of pions and kaons. The angular distribution of massless neutrinos from these decays is

$$\frac{dI}{d\Omega} = \frac{1 - v_a^2}{4\pi(1 - v_a \cos\theta)^2} \approx \frac{1}{\pi(1 + \mathit{\Gamma}_a^2 \theta^2)^2}. \tag{4}$$

Here θ is the angle between the momenta of the meson a and neutrino ($0 \leq \theta \leq \pi$), v_a is the meson velocity, and $\mathit{\Gamma}_a = (1 - v_a^2)^{-1/2} = E_a/m_a$. The second approximate equality in Eq. (4) holds for small angles and relativistic meson energies ($\theta \ll 1$, $4\mathit{\Gamma}_a^2 \gg 1$). In the latter case, the main contribution to the neutrino event rate comes from the narrow cone $\theta \lesssim 1/\mathit{\Gamma}_a$. Considering that the mean neutrino energy, $\overline{E}_\nu$, from the muonic decay of a meson with energy E_a is $\overline{E}_\nu = \mathit{\Gamma}_a E_\nu^{(a)}$, where $E_\nu^{(a)} = (m_a^2 - m_\mu^2)/(2m_a)$ is the neutrino energy in the rest frame of the particle a, the characteristic angle can be defined as $\theta_{(a)} = E_\nu^{(a)}/\overline{E}_\nu$.

In the case of OPERA, one can (very) roughly estimate the characteristic angles for the “low-energy” (LE) range ($E_\nu < 20$ GeV, $\overline{E}_\nu \approx 13.9$ GeV) and “high-energy” (HE) range ($E_\nu > 20$ GeV, $\overline{E}_\nu \approx 42.9$ GeV), assuming that the main neutrino sources in these ranges are, respectively, $\pi_{\mu 2}$ and $K_{\mu 2}$ decays:

$$\theta_{\mathsf{LE}} \gtrsim \theta_{(\pi)} = 2.1 \times 10^{-3}, \quad \theta_{\mathsf{HE}} \lesssim \theta_{(K)} = 5.5 \times 10^{-3}.$$

This provides us with an order-of-magnitude estimate of the mean values of r and advancing times δt:

$$r_{\mathsf{LE}} \gtrsim 1.7 \text{ km}, \quad r_{\mathsf{HE}} \lesssim 11 \text{ km};$$
$$\delta t_{\mathsf{LE}} \gtrsim 5.6 \text{ ns}, \quad \delta t_{\mathsf{HE}} \lesssim 36.7 \text{ ns}.$$

Since the LE and HE ranges contribute almost equally to the CNGS ν_μ beam, there must be a definite trend towards earlier neutrino arrival to OPERA with approximately 21 ns mean time-shift and a "tail" or, better to say, "fore" of the same order coming from the "edges" of the CNGS beam.

Similar estimation for the low-energy NuMI beam at Fermilab producing neutrinos for the MINOS experiment can be done with a better accuracy, since the $\pi_{\mu 2}$ decay is here the dominant source of neutrinos and the radial distribution of the beam is expected to be very flat. So, by using $\overline{E}_\nu = 3$ GeV we obtain

$$r \approx 36.2 \text{ km}, \quad \delta t \approx 120.7 \text{ ns}. \tag{5}$$

The latter number is in surprisingly good agreement with the MINOS observation. Obviously, MINOS should observe at the average a much earlier arrival of neutrinos, in comparison with OPERA, because of the lower mean neutrino energy which corresponds to a wider transverse beam distribution and hence to a larger input from the misaligned neutrinos.

Numerical estimations

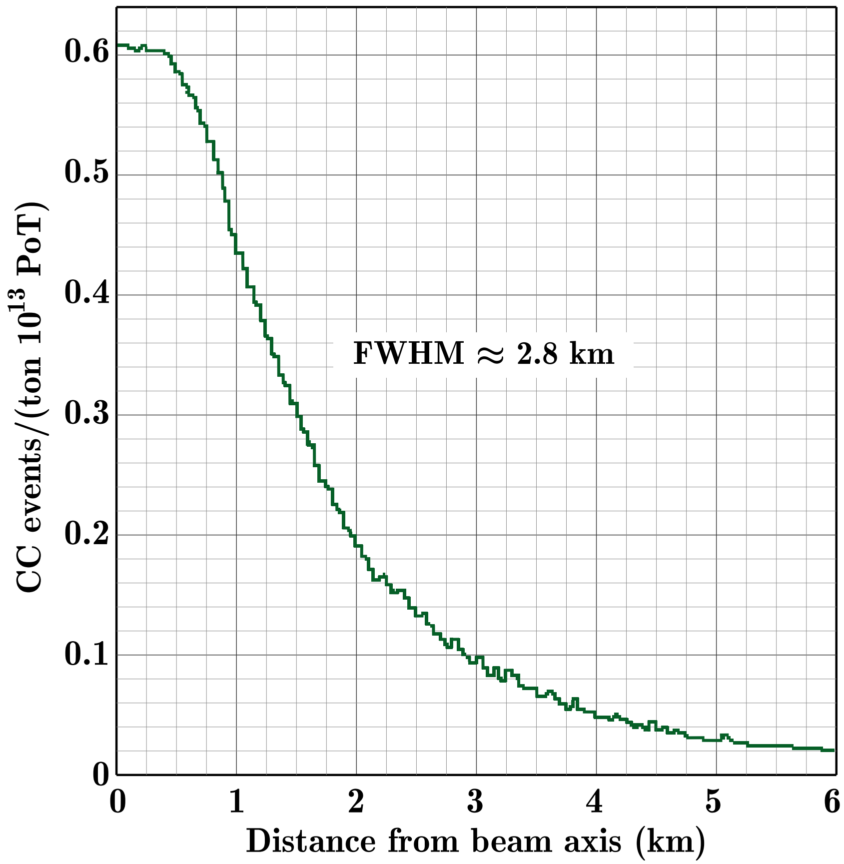


Рис. 2: Probability of neutrino charged current interactions expected in OPERA as function of r.

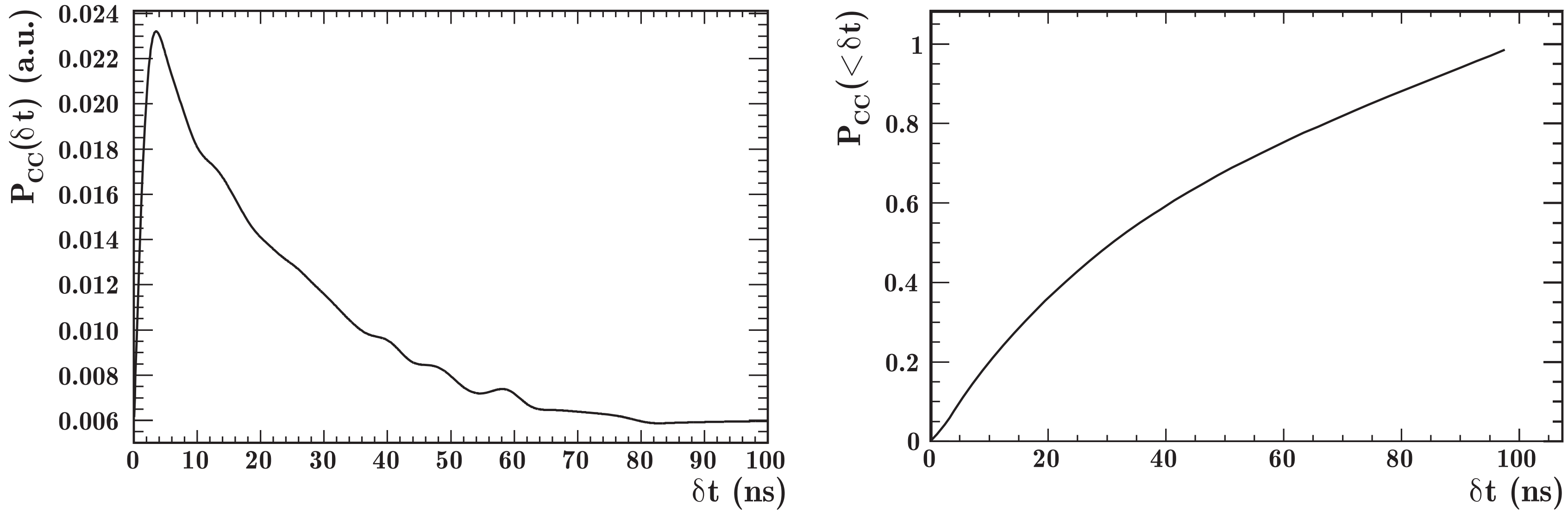


Рис. 3: Left panel: Advance δt distribution expected in OPERA. Right panel: $P_{\mathsf{CC}}(< \delta t)$ distribution expected in OPERA.

$\langle \delta t \rangle$ is about 20 ns with similar variance and with the tail extending up to about 100 ns.

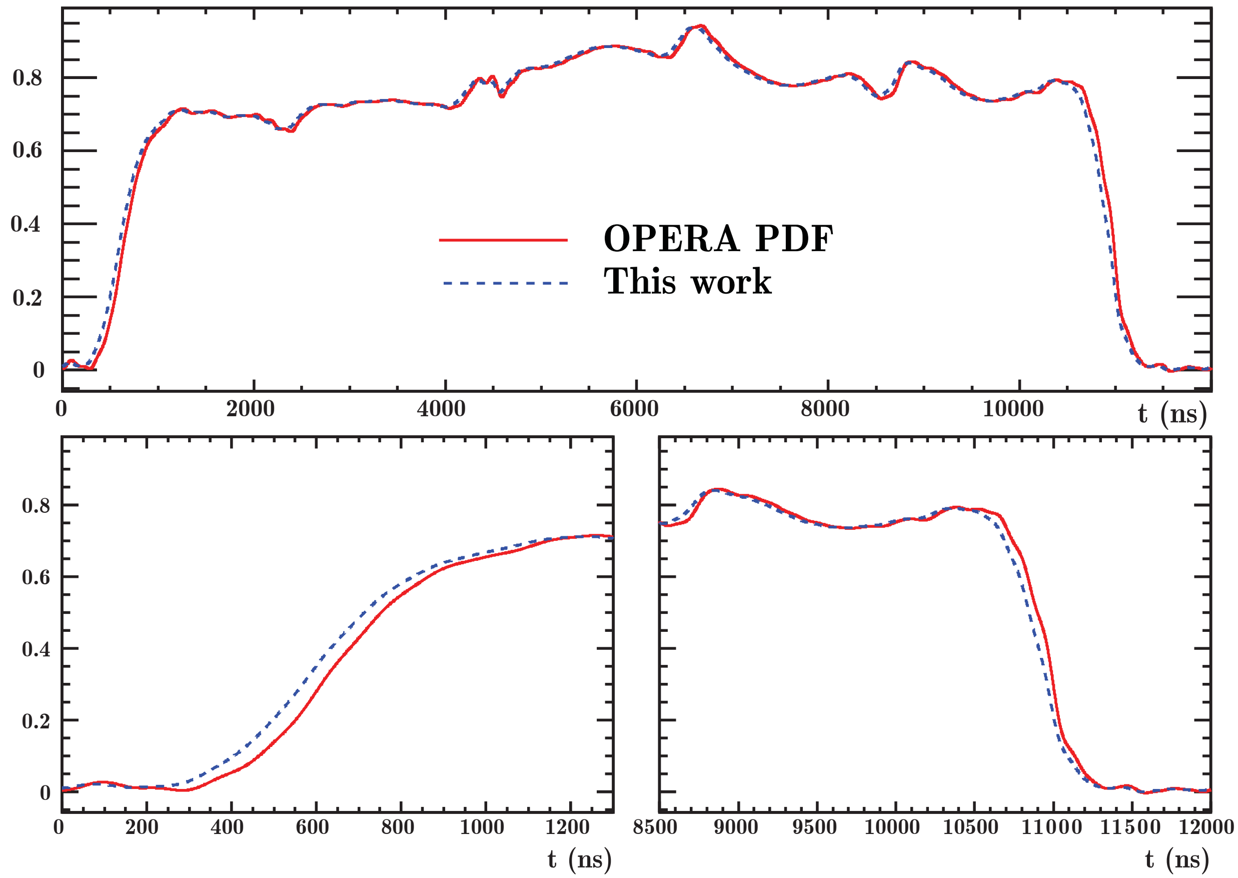


Рис. 4: Top panel: time probability density function for the first beam extraction taken as an example, expected by the OPERA Collaboration and our calculation. In both cases, the systematic “instrumental” shift is not shown since it does not change the shape of the curves. Bottom left and right panels: zooms of the top panel for the left and right fronts of the signal, respectively.

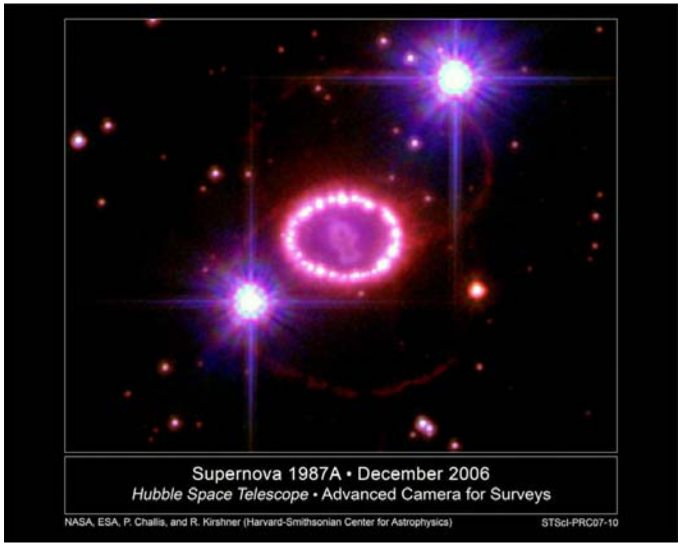
Conclusions

Large transverse size of the neutrino wavepacket and uncollimated beam of neutrinos seem to explain the earlier arrival of the neutrino signal in OPERA and MINOS. The neutrino signal is estimated to arrive in advance by about 20 ns in the mean (with a similar variance) for OPERA and by about 120 ns for MINOS. In the case of the OPERA experiment only this effect essentially reduces the statistical significance of its observation. Moreover, we have evaluated the expected time distribution of the neutrino arrival in OPERA and obtained that the left and right fronts are shifted to the left by about 50–60 ns and 20–25 ns, respectively. This probably explains the observed anomaly all-in-all without any exotic hypothesis, like Lorentz violation and so on. Let us underline that in our calculations we do not use any adjustable parameter. In the case of the MINOS experiment there is also a surprisingly good agreement between our expectation (5) and experimental result. Therefore, we argue that observations of superluminal neutrinos by the OPERA and MINOS experiments can be treated as a manifestation of the huge transverse size of the neutrino wavefunction. This kind of effects could be investigated in the future experiments (in particular, in the off-axis neutrino experiments) with more details in order to prove or disprove our explanation.

Let us note that one should not expect an increase in the number of neutrino induced events due to the misaligned neutrino interactions because this effect will be compensated by the corresponding decrease of the number of aligned neutrinos.

What about SN1987A?

Let us briefly discuss the situation with the observed (anti)neutrino signal from SN1987A. A proper treatment of these neutrinos should take care about the dispersion of the neutrino wavepackets at astronomical distances. Deliberately neglecting the dispersion, it appears that any terrestrial detector is sensitive only to the aligned neutrinos, since the misaligned neutrinos will have negligible impact due to the smallness of their wavepacket transverse size relative to the astrophysical scale of about 50 kps. Therefore, no advance signal should be expected. However this problem is not so simple and needs in a more detailed theoretical analysis.



Thank you for attention!