

Plasma induced neutrino spin-flip in a supernova and new bounds on the neutrino magnetic moment

A. Kuznetsov

Division of Theoretical Physics, Yaroslavl State University

XIV-th International Baksan School *Particles and Cosmology*,

Baksan Valley, Kabardino-Balkaria, Russia

April 21, 2007

In collaboration with N. Mikheev

Outline

- Neutrino spin-flip in the supernova core
- Cherenkov process $\nu_L \rightarrow \nu_R \gamma$ and its crossing $\nu_L \gamma \rightarrow \nu_R$
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- Conclusions

Neutrino spin-flip in the supernova core

Neutrino magnetic moment \Rightarrow spin-flipping processes
in the supernova core:

$$\nu_L \rightarrow \nu_R$$

ν_R 's being sterile fly away from the core \Rightarrow leaving no enough energy to explain the observed luminosity of the supernova \Rightarrow upper bound on the neutrino magnetic moment.

SN1987A, R. Barbieri and R. N. Mohapatra (1988): the neutrino spin-flip via both $\nu_L e^- \rightarrow \nu_R e^-$ and $\nu_L p \rightarrow \nu_R p$ scattering processes.

From the ν_R luminosity upper limit $Q_{\nu_R} < 10^{53}$ erg/s, the upper bound on the neutrino magnetic moment was established :

$$\mu_\nu < (0.2 - 0.8) \times 10^{-11} \mu_B .$$

However, the essential plasma polarization effects in the photon propagator were not considered comprehensively. An *ad hoc* photon thermal mass was inserted instead.

Neutrino spin-flip in the supernova core

Later on, A. Ayala, J. C. D'Olivo and M. Torres (1999) used the formalism of the **Thermal Field Theory** to take into account the influence of hot dense astrophysical plasma on the photon propagator.

The upper bound for the neutrino magnetic moment was improved by them in the factor of 2:

$$\mu_\nu < (0.1 - 0.4) \times 10^{-11} \mu_B .$$

However, looking at the intermediate analytical results by the authors, we conclude that only the contribution of plasma **electrons** was taken into account there, while the **proton** fraction was omitted.

Thus, the reason exists to reconsider the neutrino spin-flip processes in the supernova core more attentively.

We confirm in part, that the neutrino scattering on plasma **protons** is essential, as well as the scattering on plasma **electrons**.

Cherenkov process $\nu_L \rightarrow \nu_R \gamma$ and its crossing $\nu_L \gamma \rightarrow \nu_R$

Let us start from the Cherenkov process of the photon (plasmon) **creation** by neutrino, $\nu_L \rightarrow \nu_R \gamma$, which should be appended by the crossed process of the photon **absorption** $\nu_L \gamma \rightarrow \nu_R$.

The Lagrangian of the interaction of a neutrino with a magnetic moment μ_ν with photons is:

$$\mathcal{L} = -\frac{i}{2} \mu_\nu (\bar{\nu} \sigma_{\alpha\beta} \nu) F^{\alpha\beta},$$

where $\sigma_{\alpha\beta} = (1/2) (\gamma_\alpha \gamma_\beta - \gamma_\beta \gamma_\alpha)$, $F^{\alpha\beta}$ is the tensor of the photon electromagnetic field.

For the **creation** process amplitude one obtains

$$\mathcal{M}_{\nu_L \rightarrow \nu_R \gamma_\lambda} = j_\alpha \varepsilon_{(\lambda)}^{*\alpha},$$

where $\varepsilon_{(\lambda)}^{*\alpha}$ is the photon polarization vector, and

$$j_\alpha = \frac{1}{2} \mu_\nu [\bar{\nu}_R(p') (\hat{q} \gamma_\alpha - \gamma_\alpha \hat{q}) \nu_L(p)].$$

Cherenkov process $\nu_L \rightarrow \nu_R \gamma$ and its crossing $\nu_L \gamma \rightarrow \nu_R$

For the process width one obtains by the standard way:

$$\Gamma_{\nu_L \rightarrow \nu_R}^{\text{tot}} = \Gamma_{\nu_L \rightarrow \nu_R \gamma} + \Gamma_{\nu_L \gamma \rightarrow \nu_R} = \frac{1}{16 \pi^2 E} \int j_\alpha j_\beta^* \sum_{\lambda=t,\ell} \varepsilon_{(\lambda)}^{*\alpha} \varepsilon_{(\lambda)}^\beta Z_\gamma^{(\lambda)} \frac{d^3 p'}{E'} \\ \times \left\{ \frac{\delta(E - E' - \omega)}{2\omega} [1 + f_\gamma(\omega)] + \frac{\delta(E - E' + \omega)}{2\omega} f_\gamma(\omega) \right\},$$

where $f_\gamma(\omega) = (e^{\omega/T} - 1)^{-1}$ is the photon distribution function, $\lambda = t, \ell$ mean transversal and longitudinal photon polarizations, and $Z_\gamma^{(\lambda)} = (1 - \partial \Pi_{(\lambda)} / \partial \omega^2)^{-1}$ is the photon wave-function renormalization.

The functions $\Pi_{(\lambda)}$, defining the photon dispersion law:

$$\omega^2 - k^2 - \Pi_{(\lambda)}(\omega, k) = 0,$$

are the eigenvalues of the photon polarization tensor $\Pi_{\alpha\beta}$,

$$\Pi_{\alpha\beta} \varepsilon_{(\lambda)}^\beta = \Pi_{(\lambda)} \varepsilon_{(\lambda)\alpha}.$$

Cherenkov process $\nu_L \rightarrow \nu_R \gamma$ and its crossing $\nu_L \gamma \rightarrow \nu_R$

The value $\Gamma_{\nu_L \rightarrow \nu_R}^{\text{tot}}$ can be written in another form. Let us introduce the energy transferred from neutrino: $E - E' = q_0$, which is expressed via the photon energy $\omega(k)$ as $q_0 = \pm \omega(k)$, then δ -functions can be rewritten

$$\frac{\delta(q_0 - \omega(k))}{2\omega(k)} = \delta(q_0^2 - \omega^2(k)) \theta(q_0),$$

$$\frac{\delta(q_0 + \omega(k))}{2\omega(k)} = \delta(q_0^2 - \omega^2(k)) \theta(-q_0).$$

Transforming the δ -function to have the dispersion law in the argument:

$$\delta(q_0^2 - \omega^2(k)) = \left[Z_\gamma^{(\lambda)} \right]^{-1} \delta(q^2 - \Pi_{(\lambda)}(q)),$$

one can see that the renormalization factor $Z_\gamma^{(\lambda)}$ is cancelled in the process width.

Right-handed neutrino spectrum function

Instead of $\Gamma_{\nu_L \rightarrow \nu_R}^{\text{tot}}$, the physical value we should be more interested in, is e.g. the right-handed neutrino flux, integrated over the left-handed neutrino states, i.e. the number of right-handed neutrinos emitted per unit time:

$$N_{\nu_R} = \int dn_{\nu_L} \Gamma_{\nu_L \rightarrow \nu_R}^{\text{tot}} = \int \frac{d^3p V}{(2\pi)^3} f_{\nu_L}(E) \Gamma_{\nu_L \rightarrow \nu_R}^{\text{tot}},$$

where $f_{\nu_L}(E) = (e^{(E - \tilde{\mu}_\nu)/T} + 1)^{-1}$ is the left-handed neutrino distribution function with the chemical potential $\tilde{\mu}_\nu$. There exists even more convenient value, the right-handed neutrino spectrum function, $\Gamma_{\nu_R}(E')$, defining the width of the production of ν_R with the fixed energy E' by all the left-handed neutrinos:

$$\Gamma_{\nu_R}(E') = \frac{dN_{\nu_R}}{dn_{\nu_R}}, \quad dn_{\nu_R} = \frac{d^3p' V}{(2\pi)^3}.$$

Given $\Gamma_{\nu_R}(E')$, one can calculate both the right-handed neutrino flux and the right-handed neutrino luminosity.

Right-handed neutrino spectrum function

The function $\Gamma_{\nu_R}(E')$ takes the form:

$$\Gamma_{\nu_R}(E') = \frac{1}{16 \pi^2 E'} \int \frac{d^3 p}{E} f_{\nu_L}(E) j_\alpha j_\beta^* \sum_{\lambda=t,\ell} \varepsilon_{(\lambda)}^{*\alpha} \varepsilon_{(\lambda)}^\beta \delta(q^2 - \Pi_{(\lambda)}(q)) \\ \times \{ [1 + f_\gamma(q_0)] \theta(q_0) + f_\gamma(-q_0) \theta(-q_0) \},$$

and can be easily calculated *when the function $\Pi_{(\lambda)}(q)$ is real.*

However, it has, in general, an imaginary part.

It means, that the photon is unstable in plasma.

Right-handed neutrino spectrum function

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$$\times \{ [1 + f_\gamma(q_0)] \theta(q_0) + f_\gamma(-q_0) \theta(-q_0) \},$$

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However, it has, in general, an imaginary part.

It means, that the photon is unstable in plasma.

Instead of the δ -function one should use its generalization. We suppose the generalization of the Breit—Wigner type, with the retarded $\Pi_{(\lambda)}(q)$:

$$\delta(q^2 - \Pi_{(\lambda)}(q)) \Rightarrow \frac{1}{\pi} \frac{-\text{Im} \Pi_{(\lambda)} \text{sign}(q_0) \epsilon_\lambda}{(q^2 - \text{Re} \Pi_{(\lambda)})^2 + (\text{Im} \Pi_{(\lambda)})^2},$$

where $\epsilon_\lambda = +1$ for $\lambda = t$ and $\epsilon_\lambda = -1$ for $\lambda = \ell$.

The retarded function $\Pi_{(\lambda)}(q)$ means that the continuation is made:
 $q_0 \rightarrow q_0 + i\varepsilon, \quad \varepsilon > 0.$

Right-handed neutrino spectrum function

Taking into account that $f_\gamma(-q_0) = -[1 + f_\gamma(q_0)]$, one obtains

$$\text{sign}(q_0) \{ [1 + f_\gamma(q_0)] \theta(q_0) + f_\gamma(-q_0) \theta(-q_0) \} = 1 + f_\gamma(q_0),$$

and the right-handed neutrino spectrum function takes the form:

$$\Gamma_{\nu_R}(E') = \frac{1}{16 \pi^3 E'} \int \frac{d^3 p}{E} f_{\nu_L}(E) [1 + f_\gamma(q_0)] j_\alpha j_\beta^* \\ \times \sum_{\lambda=t,l} \frac{\varrho_{(\lambda)}^{\alpha\beta} (-\text{Im} \Pi_{(\lambda)}) \epsilon_\lambda}{(q^2 - \text{Re} \Pi_{(\lambda)})^2 + (\text{Im} \Pi_{(\lambda)})^2},$$

where the polarization density matrices for the transversal and longitudinal photons are introduced:

$$\varrho_{(t)}^{\alpha\beta} = \sum_{\lambda=t_1, t_2} \epsilon_{(\lambda)}^{*\alpha} \epsilon_{(\lambda)}^\beta = - \left(g^{\alpha\beta} - \frac{q^\alpha q^\beta}{q^2} - \frac{l^\alpha l^\beta}{l^2} \right),$$

$$\varrho_{(l)}^{\alpha\beta} = \epsilon_{(l)}^{*\alpha} \epsilon_{(l)}^\beta = - \frac{l^\alpha l^\beta}{l^2}, \quad l_\alpha = u_\alpha q^2 - q_\alpha (uq),$$

u_α is the four-vector of the plasma velocity.

Right-handed neutrino spectrum function

The structures appeared in the function $\Gamma_{\nu_R}(E')$ are called **the photon spectral density functions**:

$$\rho_{(\lambda)} = \frac{2 (-\text{Im } \Pi_{(\lambda)})}{(q^2 - \text{Re } \Pi_{(\lambda)})^2 + (\text{Im } \Pi_{(\lambda)})^2},$$

Changing the integration variables $d^3p \rightarrow dq_0 dk$, one obtains after calculation:

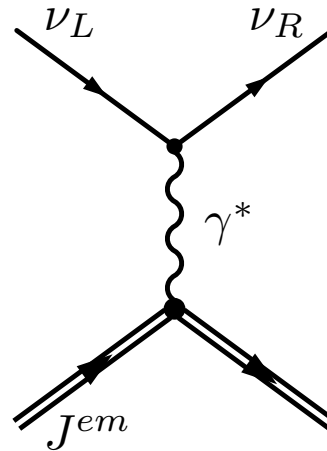
$$\Gamma_{\nu_R}(E') = \frac{\mu_\nu^2}{16 \pi^2 E'^2} \int_D dq_0 dk k^3 f_\nu(E' + q_0) [1 + f_\gamma(q_0)] (2E' + q_0)^2 \\ \times \left[1 - \left(\frac{q_0}{k} \right)^2 \right]^2 \left[\left(1 - \frac{k^2}{(2E' + q_0)^2} \right) \rho_{(t)}(q_0, k) - \rho_{(\ell)}(q_0, k) \right],$$

where D is the specific region of integration in the (q_0, k) plane.

Neutrino interaction with background

Thus, a “photon” considered in the neutrino chirality flip processes $\nu_L \rightarrow \nu_R \gamma$ and $\nu_L \gamma \rightarrow \nu_R$, obviously can not be treated as a real photon.

It would be more self-consistent to consider the vertex $\nu_L \nu_R \gamma^*$ in the neutrino scattering via the *intermediate virtual plasmon* γ^* on the plasma electromagnetic current presented by electrons, $\nu_L e^- \rightarrow \nu_R e^-$, protons, $\nu_L p \rightarrow \nu_R p$, etc., shown in the diagram:



Here, J^{em} is an electromagnetic current in the general sense, formed by different components of the medium, i.e. free electrons and positrons, free ions, neutral atoms, etc.

Neutrino interaction with background

The technics of calculations of the neutrino spin-flip rate is rather standard.

The only principal point is to use the photon propagator $G^{\alpha\beta}(q)$ with taking account of the plasma polarization effects. We take it in the form:

$$G^{\alpha\beta}(q) = \frac{-i \varrho_{(t)}^{\alpha\beta}}{q^2 - \Pi_{(t)}} + \frac{-i \varrho_{(\ell)}^{\alpha\beta}}{q^2 - \Pi_{(\ell)}},$$

which has no ambiguity when the functions $\Pi_{(t,\ell)}$ are *real*. Our generalization to the case of *complex* functions is based on using the same form of the propagator with the *retarded* functions $\Pi_{(t,\ell)}$.

Integrating the amplitude squared over the states of particles forming the electromagnetic current and over the states of the initial left-handed neutrinos, we obtain **just the same rate** $\Gamma_{\nu_R}(E')$ of creation of the right-handed neutrino with the fixed energy E' .

Right-handed neutrino spectrum function

There is also such a subtle effect as the additional energy W acquired by a left-handed neutrino in plasma. With this effect, the general expression for the right-handed neutrino spectrum function is:

$$\Gamma_{\nu_R}(E') = \frac{\mu_\nu^2}{16 \pi^2 E'^2} \int_D \frac{dq_0 dk}{k} f_\nu(E' + q_0) [1 + f_\gamma(q_0)] (2E' + q_0)^2 q^4$$

$$\times \left\{ \left(1 - \frac{k^2}{(2E' + q_0)^2} \right) \left[1 - \frac{2q_0 W}{q^2} + \frac{8E'(E' + q_0)W^2}{q^4 [(2E' + q_0)^2/k^2 - 1]} \right] \rho_{(t)}(q_0, k) \right.$$

$$\left. - \left(1 - \frac{2q_0 W}{q^2} \right) \rho_{(\ell)}(q_0, k) \right\},$$

where $q^2 = q_0^2 - k^2$.

We note that our result is in agreement with the rate obtained by P. Elmfors et al. (1997). However, extracting from our general expression *the electron contribution* only, we obtain the result which is **larger by the factor of 2** than the corresponding formula in the papers by A. Ayala et al. We believe that an error was made there.

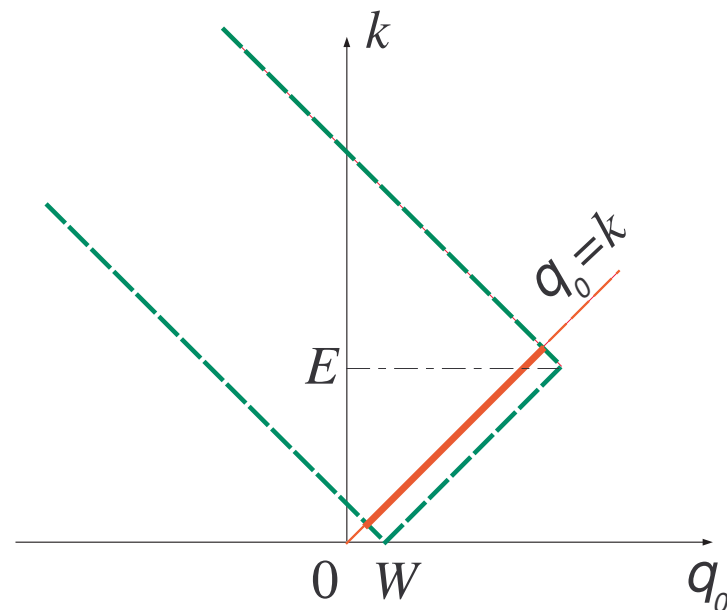
Right-handed neutrino spectrum function

Our formula having the most general form can be used for neutrino-photon processes in any optically active medium. We only need to identify the photon spectral density functions $\rho(\lambda)$. For example, in the medium where $\text{Im } \Pi_{(t)} \rightarrow 0$ in the space-like region $q^2 < 0$ corresponding to the refractive index values $n > 1$, the spectral density function is transformed to δ -function, and we reproduce the result of the paper by **W. Grimus and H. Neufeld (1993)** devoted to the study of the Cherenkov radiation of **transversal** photons by neutrinos.

If one **formally** takes the limit $\text{Im } \Pi_{(\ell)} \rightarrow 0$, the result obtained by **S. Mohanty and S. Sahu (1997)** can be reproduced, namely, the width of the Cherenkov radiation and absorption of **longitudinal** photons by neutrinos in the space-like region $q^2 < 0$. However, the limit $\text{Im } \Pi_{(\ell)} \rightarrow 0$ itself is **unphysical** in the plasma conditions considered by those authors and leads to the strong overestimation of a result.

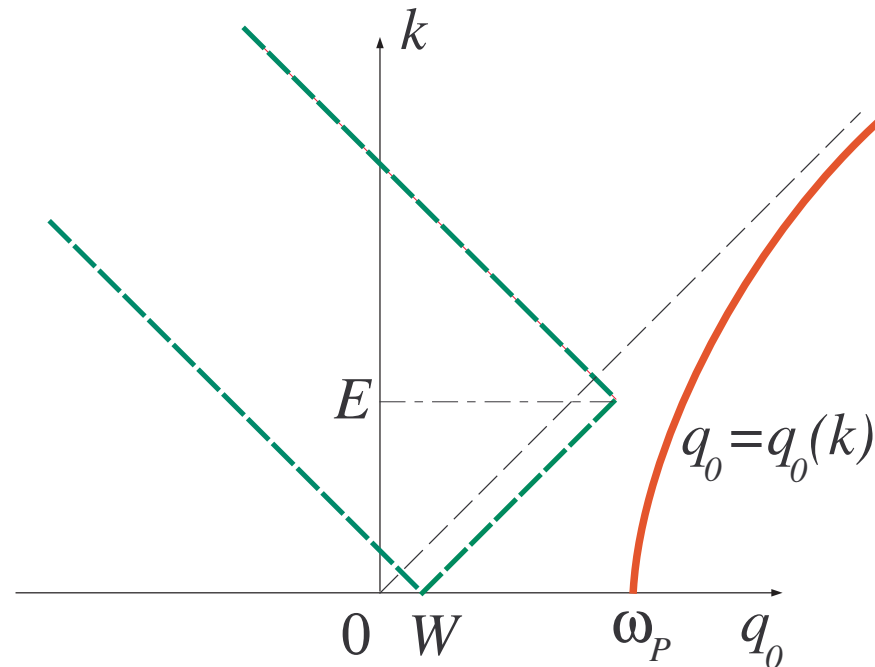
“Neutrino spin light”

One more **unphysical** case, the so-called “neutrino spin light”, was considered in the papers by A. Studenikin et al. (2003-2006), where **the photon dispersion in medium was ignored at all**. The region of integration for the width $\Gamma_{\nu_L \rightarrow \nu_R}^{\text{tot}}$ with the *fixed initial neutrino energy* E was the vacuum dispersion line $q_0 = k$ (the **red bold** line in the integration plot).



However, the photon dispersion in plasma is not the vacuum one!

“Neutrino spin light”



For the fixed plasma parameters, **the threshold** neutrino energy E_{\min} exists for coming of the dispersion curve into the allowed kinematical region.

It is useful to compare the numerical values in the figure.

“Neutrino spin light”

For the interior of a neutron star, the additional energy acquired by a left-handed neutrino in plasma (N_B is the barion density):

$$W \simeq 6 \text{ eV} \left(\frac{N_B}{10^{38} \text{ cm}^{-3}} \right),$$

while the plasmon frequency, defining the photon dispersion:

$$\omega_P \simeq 10^7 \text{ eV} \left(\frac{N_B}{10^{38} \text{ cm}^{-3}} \right)^{1/3}.$$

The threshold neutrino energy in this case:

$$E_{\min} \simeq \frac{\omega_P^2}{2W} \simeq 10 \text{ TeV}.$$

The details can be found in our papers:

- Mod. Phys. Lett. A **21**, 1769 (2006);
- Int. J. Mod. Phys. A (in press, e-print hep-ph/0701228).

Right-handed neutrino spectrum function

The right-handed neutrino spectrum function

$$\Gamma_{\nu_R}(E') = \frac{\mu_\nu^2}{16 \pi^2 E'^2} \int_D dq_0 dk k^3 f_\nu(E' + q_0) [1 + f_\gamma(q_0)] (2E' + q_0)^2$$
$$\times \left[1 - \left(\frac{q_0}{k} \right)^2 \right]^2 \left[\left(1 - \frac{k^2}{(2E' + q_0)^2} \right) \rho_{(t)}(q_0, k) - \rho_{(e)}(q_0, k) \right]$$

depends on the photon spectral density functions:

$$\rho_{(\lambda)} = \frac{2 (-\text{Im } \Pi_{(\lambda)})}{(q^2 - \text{Re } \Pi_{(\lambda)})^2 + (\text{Im } \Pi_{(\lambda)})^2}.$$

Let us compare the electron and proton contributions into them.

Polarization functions $\Pi_{(t,\ell)}$

The general expressions for the contributions of a charged fermion into the polarization functions $\Pi_{(t,\ell)}$ can be found e.g. in the paper by **E. Braaten and D. Segel (1993)**:

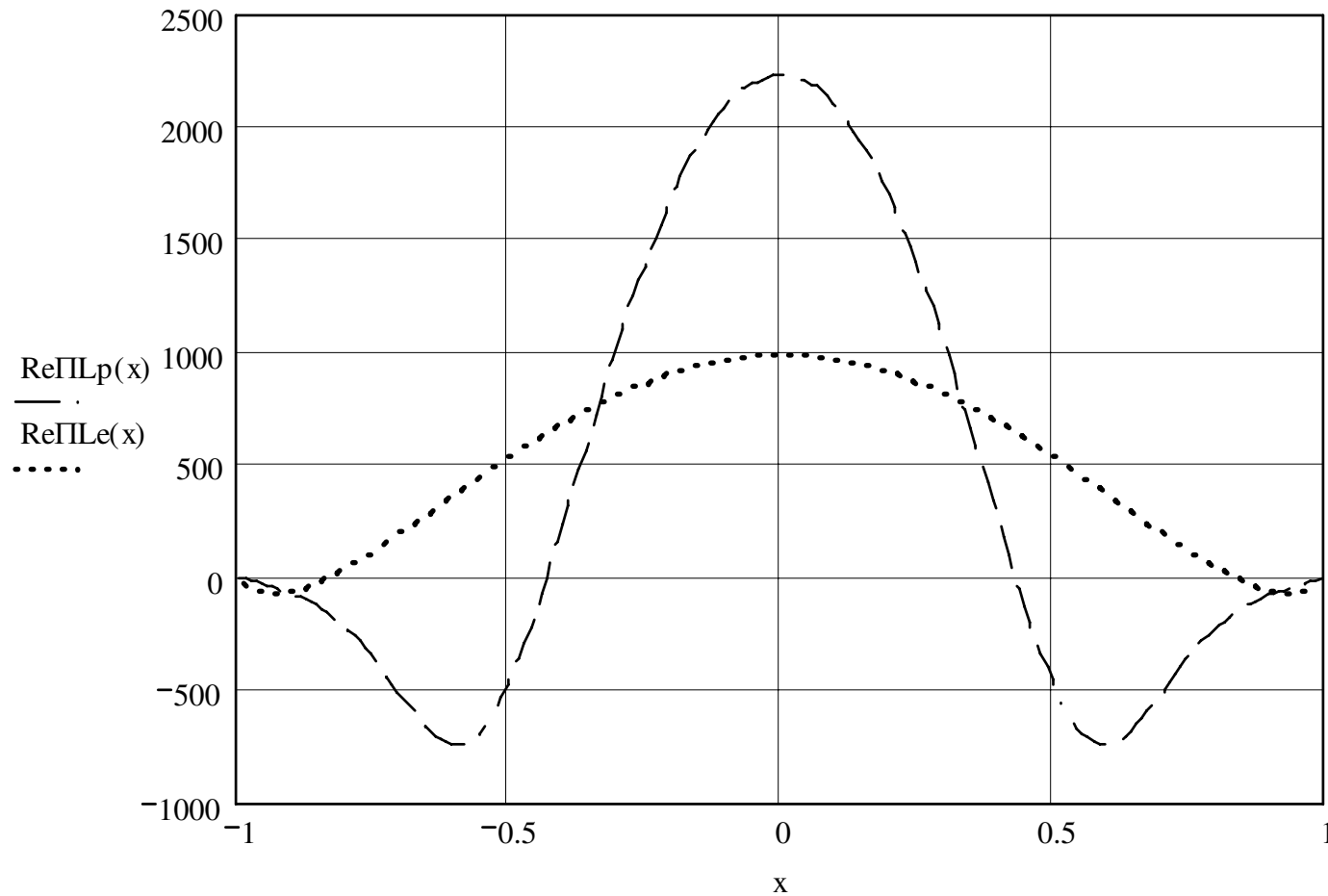
$$\Pi_{(t)}(\omega, k) = \frac{4\alpha}{\pi} \int_0^{\infty} \frac{dp p^2}{E} [f_F(E) + \bar{f}_F(E)] \\ \times \left(\frac{\omega^2}{k^2} - \frac{\omega^2 - k^2}{k^2} \frac{\omega}{2vk} \ln \frac{\omega + vk}{\omega - vk} \right),$$

$$\Pi_{(\ell)}(\omega, k) = \frac{4\alpha}{\pi} \frac{\omega^2 - k^2}{k^2} \int_0^{\infty} \frac{dp p^2}{E} [f_F(E) + \bar{f}_F(E)] \\ \times \left(\frac{\omega}{vk} \ln \frac{\omega + vk}{\omega - vk} - \frac{\omega^2 - k^2}{\omega^2 - v^2 k^2} - 1 \right),$$

where $v = p/E$.

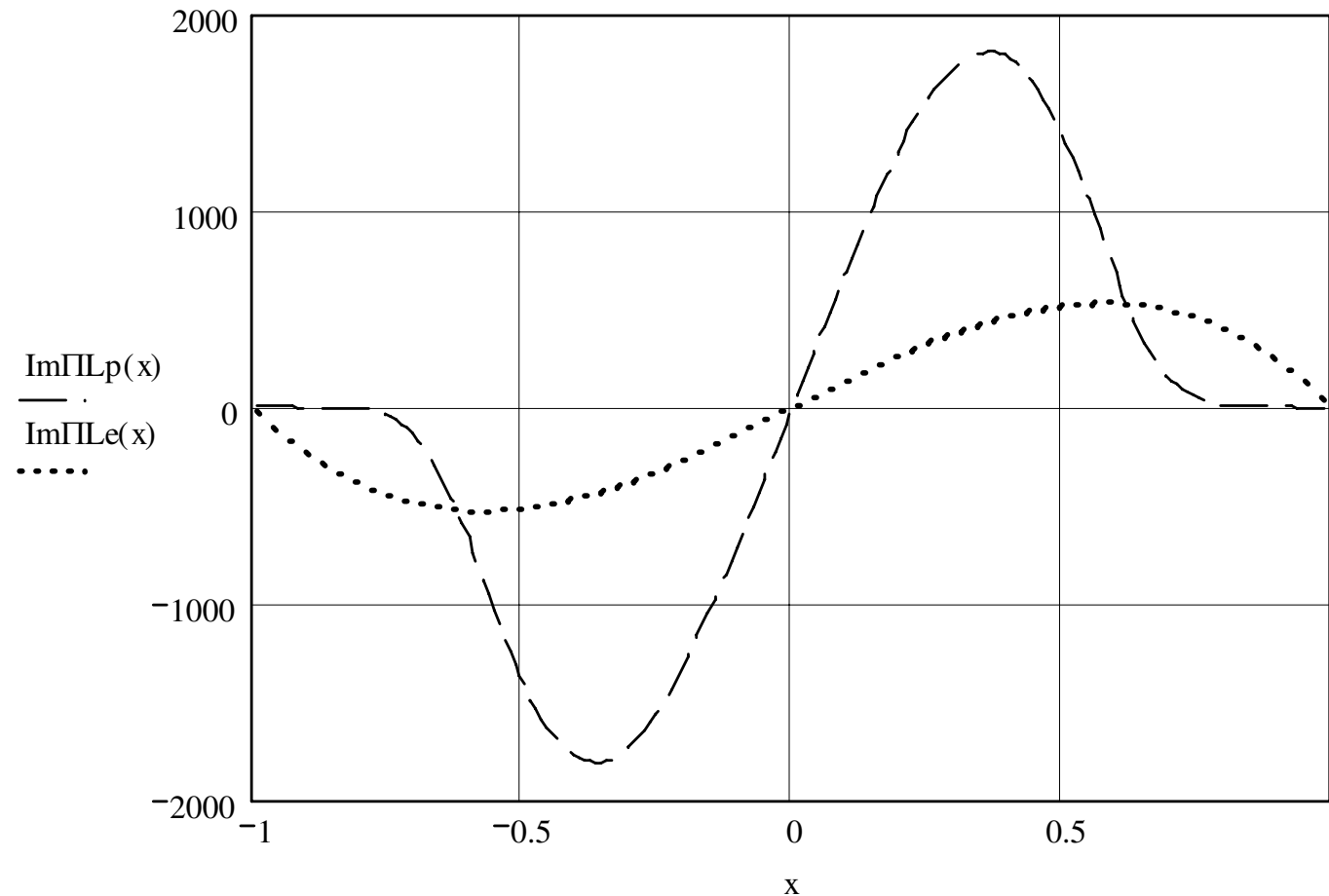
Electron and proton contributions into the real part of Π_ℓ

Electron contribution (dotted line) and proton contribution (dashed line) to the real part of Π_ℓ (hereafter $T = 60$ MeV).



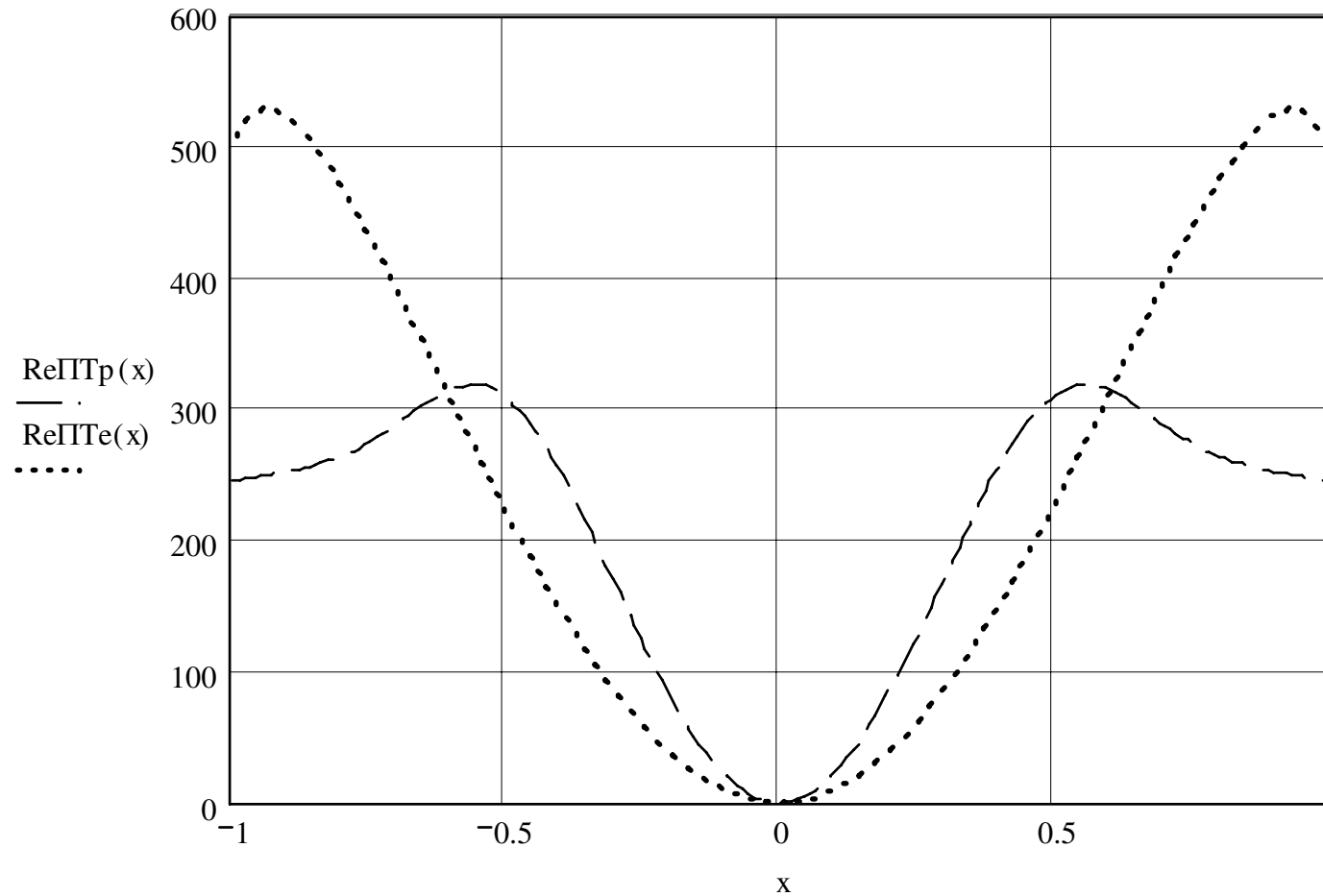
Electron and proton contributions into the imaginary part of Π_ℓ

Electron contribution (dotted line) and proton contribution (dashed line) to the imaginary part of Π_ℓ .



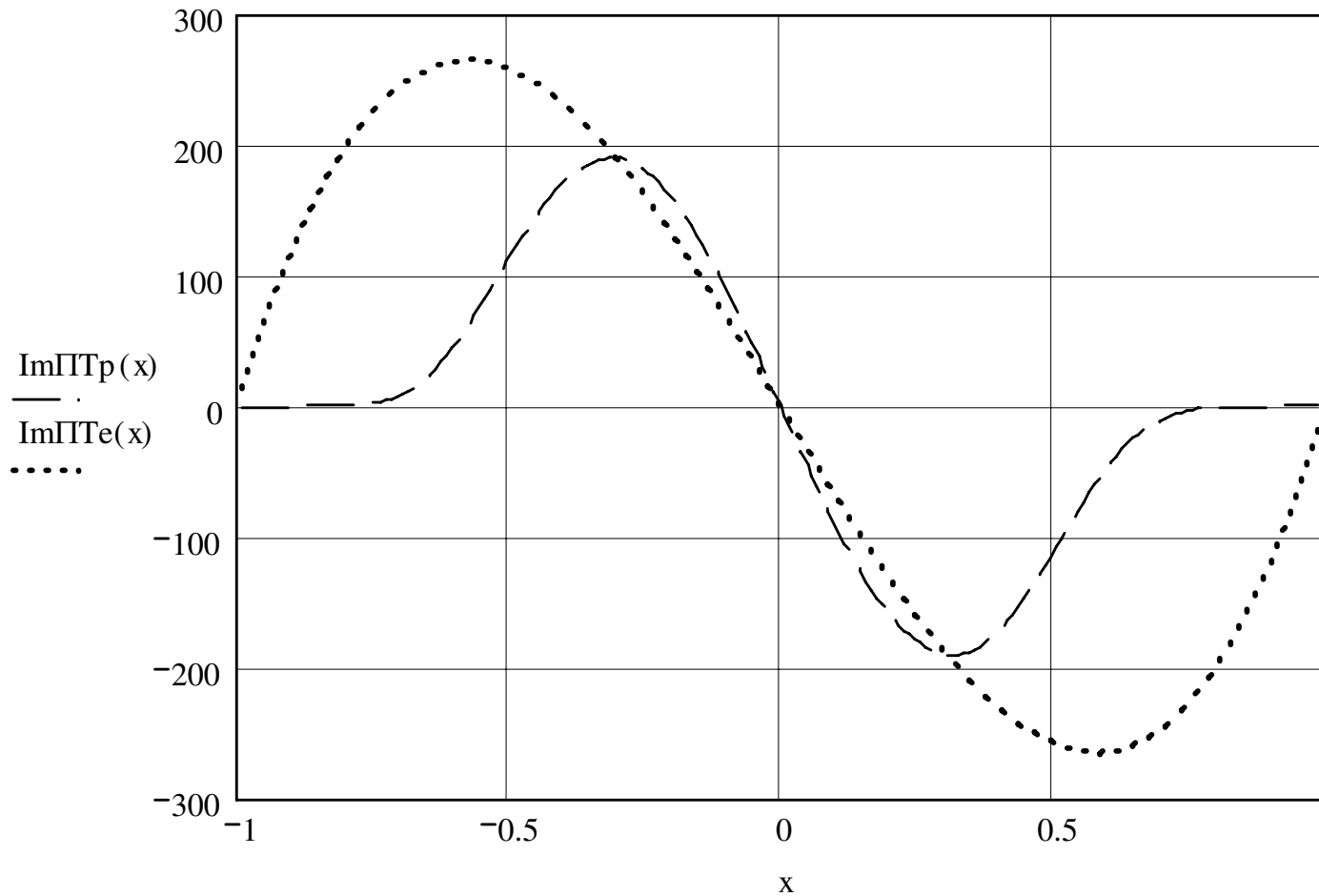
Electron and proton contributions into the real part of Π_t

Electron contribution (dotted line) and proton contribution (dashed line) to the real part of Π_t .



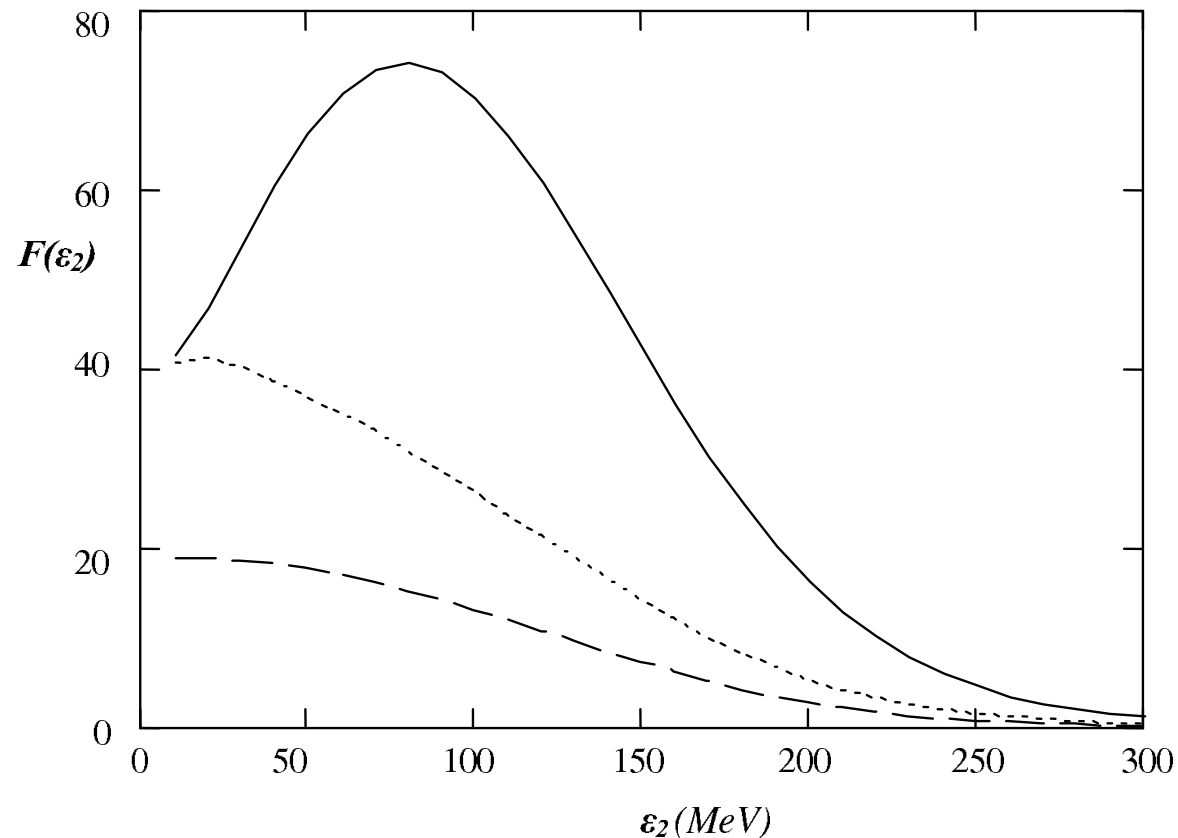
Electron and proton contributions into the imaginary part of Π_t

Electron contribution (dotted line) and proton contribution (dashed line) to the imaginary part of Π_t .



Neutrino chirality-flip rate

The production rate of ν_R with the proton contribution (solid line) and without it (dotted line). **The proton contribution is seen to be essential.**



The function $F(E')$ is defined by: $\Gamma_{\nu_R}(E') = (\mu_\nu^2 T^3 / (32 \pi)) F(E')$. The dashed line shows the result by **A. Ayala et al.**

Bound on μ_ν from the right-handed neutrino luminosity

The supernova core luminosity for ν_R emission can be computed as

$$Q_{\nu_R} = V \int \frac{d^3p'}{(2\pi)^3} E' \Gamma_{\nu_R}(E'),$$

where V is the plasma volume.

For the same supernova core conditions as in the paper by [Ayala et al.](#) (plasma volume $V \sim 8 \times 10^{18} \text{cm}^3$, temperature range $T = 30 - 60 \text{ MeV}$, electron chemical potential range $\mu_e = 280 - 307 \text{ MeV}$), we obtain

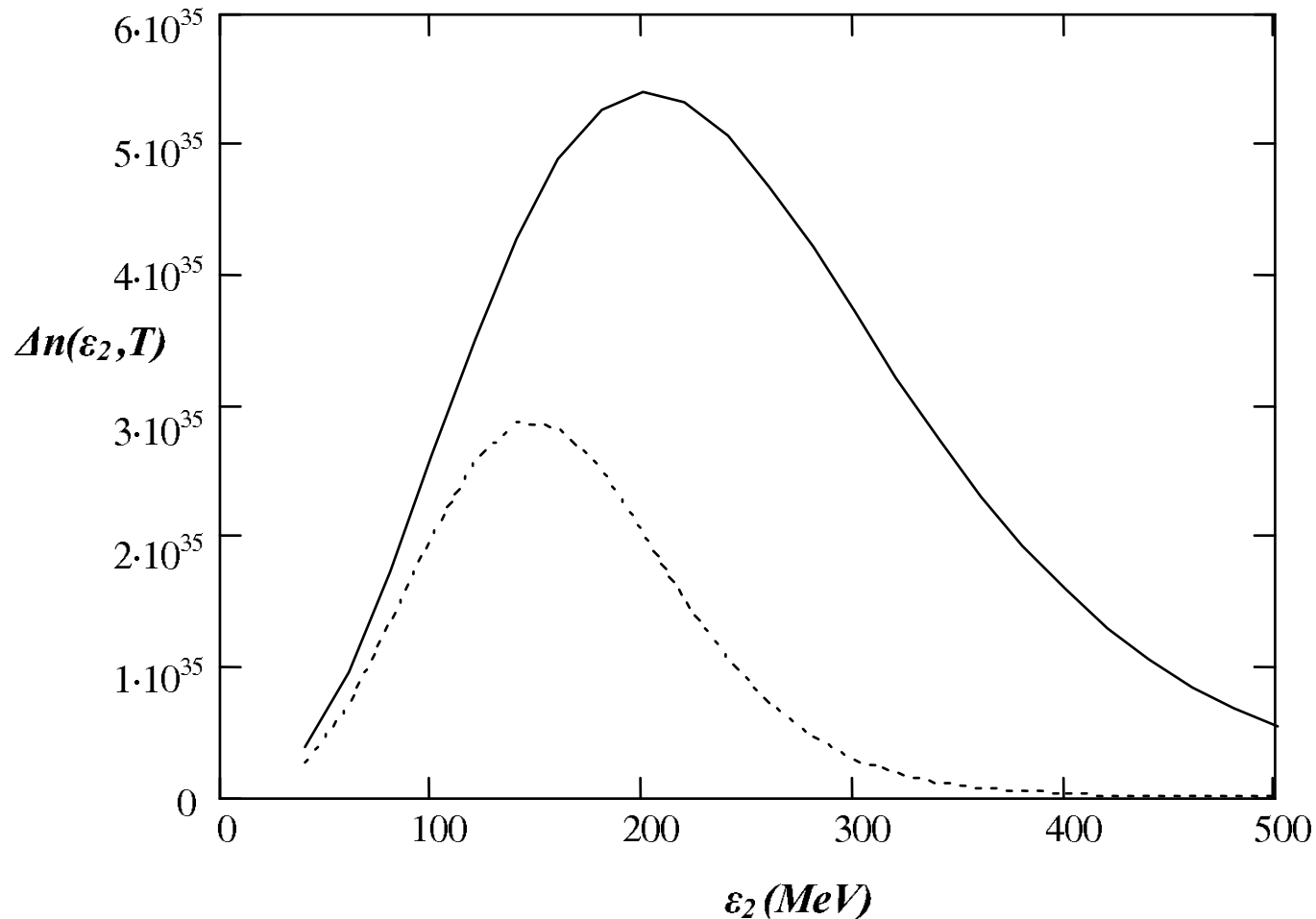
$$Q_{\nu_R} = \left(\frac{\mu_\nu}{\mu_B} \right)^2 (0.76 - 4.4) \times 10^{77} \text{ erg/s}.$$

Assuming that $Q_{\nu_R} < 10^{53} \text{ erg/s}$, we obtain the upper limit on the neutrino magnetic moment: $\mu_\nu < (0.5 - 1.1) \times 10^{-12} \mu_B$.

Remind that the result by [A. Ayala et al.](#) was: $\mu_\nu < (1 - 4) \times 10^{-12} \mu_B$.

Right-handed neutrino spectrum

The number of right-handed neutrinos (for $\mu_\nu = 10^{-12} \mu_B$) emitted per 1 cm^3 per 1 sec per 1 MeV of the energy spectrum for the plasma temperature $T = 60 \text{ MeV}$ (solid line) and for $T = 30 \text{ MeV}$ (dotted line).



Bound on μ_ν from the left-handed neutrino washing out

An additional method can be used to put a bound on the neutrino magnetic moment. Integrating the above-plotted value over all energies, one obtains the number of right-handed neutrinos emitted per 1 cm^3 per 1 sec . Dividing this to the initial left-handed neutrino number density, one can estimate the averaged time of the conversion of left-handed neutrinos to right-handed neutrinos. For the temperature range $T = 30 - 60 \text{ MeV}$, and for the electron chemical potential $\mu_e \sim 300 \text{ MeV}$, we obtain

$$\tau \simeq \left(\frac{\mu_\nu}{10^{-12} \mu_B} \right)^2 (0.14 - 0.36) \text{ sec}.$$

In order not to spoil the Kelvin—Helmholtz stage of the protoneutron star cooling ($\sim 10 \text{ sec}$), this time of the neutrino spin-flip should exceed a few seconds. Taking the conservative limit $\tau > 1 \text{ sec}$, we obtain the bound on the neutrino magnetic moment: $\mu_\nu < (0.4 - 0.6) \times 10^{-12} \mu_B$.

By this means, we improve the best astrophysical upper bound on the neutrino magnetic moment obtained by A. Ayala et al. (1999) by the factor of 3 to 7.

Conclusions

- We have investigated in detail the neutrino chirality-flip process under the conditions of the supernova core. The plasma polarization effects caused both by electrons and protons were taken into account in the photon propagator. The rate $\Gamma_{\nu_R}(E')$ of creation of the right-handed neutrino with the fixed energy E' , the energy spectrum, and the luminosity have been calculated.
- From the limit on the supernova core luminosity for ν_R emission, we have obtained the upper bound on the neutrino magnetic moment $\mu_\nu < (0.5 - 1.1) \times 10^{-12} \mu_B$.
- From the limit on the averaged time of the left-handed neutrino washing out, we have obtained the upper bound $\mu_\nu < (0.4 - 0.6) \times 10^{-12} \mu_B$.
- We have **improved** the best astrophysical upper bound on the neutrino magnetic moment by the factor of **3 to 7**.

The last slide

Thank you for your attention.

Many thanks to the Organizers for warm hospitality!

Slide for possible question on “Neutrino spin light”

At La Thuile Conference (March, 2007) **A. Studenikin** answered the question on our discussion: “They (A.K. and N.M.) simply confirmed our result at ultra-high neutrino energies.”

But at **ultra-high** neutrino energies **the local limit of the weak interaction does not describe comprehensively the additional neutrino energy** in plasma, and the **non-local** weak contribution must be taken into account.

In a general case, this non-local term *identical for both neutrinos and antineutrinos*, is

$$\Delta^{(\text{nloc})} W_i = -\frac{16 G_F E}{3 \sqrt{2}} \left[\frac{\langle E_{\nu_i} \rangle}{m_Z^2} (N_{\nu_i} + \bar{N}_{\nu_i}) + \delta_{ie} \frac{\langle E_e \rangle}{m_W^2} (N_e + \bar{N}_e) \right].$$

E is the energy of a neutrino with the flavor i , propagating through plasma, $\langle E_{\nu_i} \rangle$ and $\langle E_e \rangle$ are the averaged energies of plasma neutrinos and electrons.

There arises the window **(if exists)** in the neutrino energies for the process to be kinematically opened, $E_{\min} < E < E_{\max}$. For example, **in the solar interior there is no window for the process with electron neutrinos at all.**