Neutrino quantum decoherence due to radiative decay

Konstantin Stankevich
Department of Theoretical Physics
Moscow State University

K.Stankevich, A.Studenikin, Phys.Rev.D **101** (2020) 056004

при поддержке РФФИ, грант № 20-52-53022-ГФЕН

Сессия-конференция Секции ядерной физики ОФН РАН
«ФИЗИКА ФУНДАМЕНТАЛЬНЫХ ВЗАИМОДЕЙСТВИЙ"
10-12 марта, 2020 г.
Новосибирск, Россия

Based on

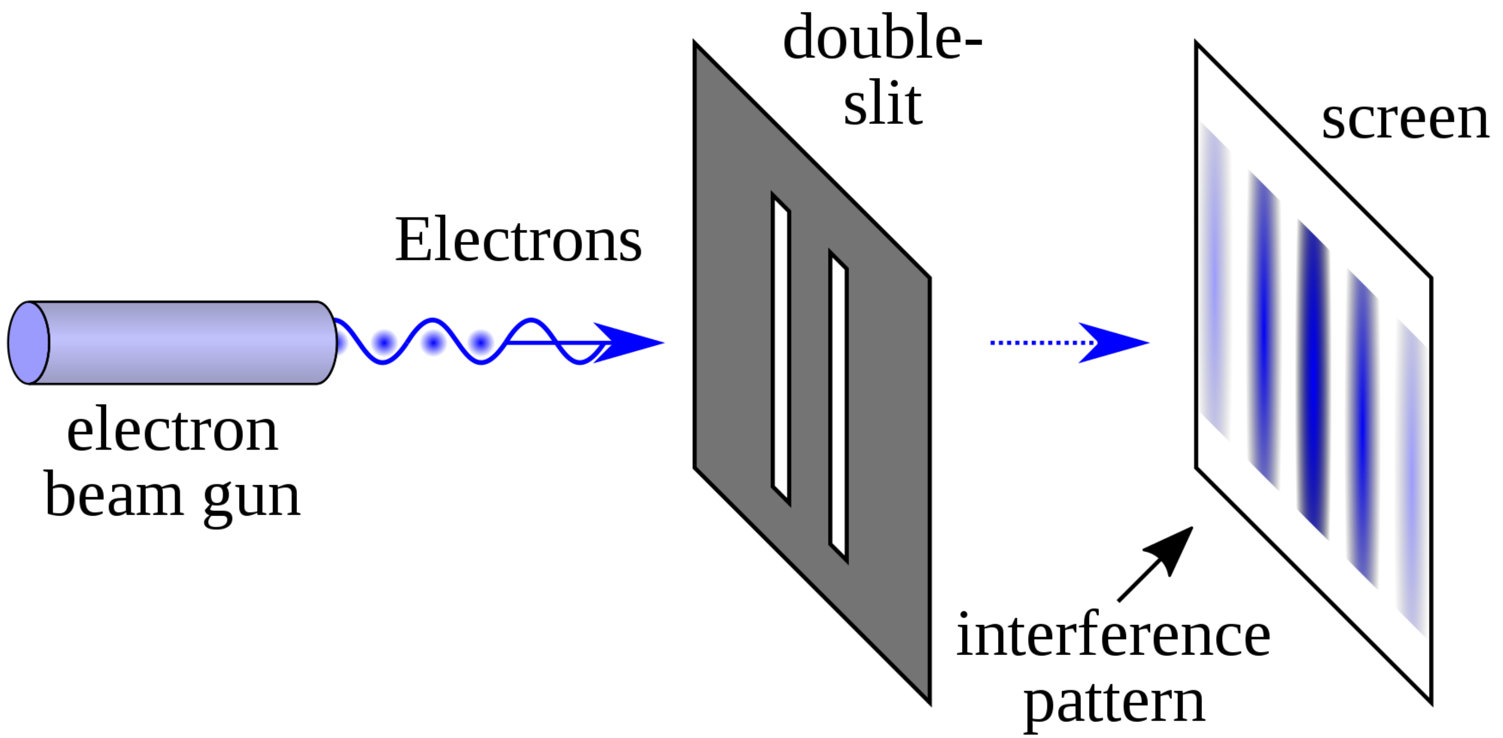
- *K.Stankevich, A.Studenikin,* PoS EPS-HEP2017 (2018) 645;
- *K.Stankevich, A.Studenikin,* PoS ICHEP2018 (2019) 925;
- *K.Stankevich, A.Studenikin,* J.Phys.Conf.Ser.1342 (2020);
- *K.Stankevich, A.Studenikin,* Phys.Rev. D **101** (2020) 056004.

Outline

- Introduction
- Lindblad equation
- New formalism for neutrino quantum decoherence
- Astrophysical environment
- Conclusion

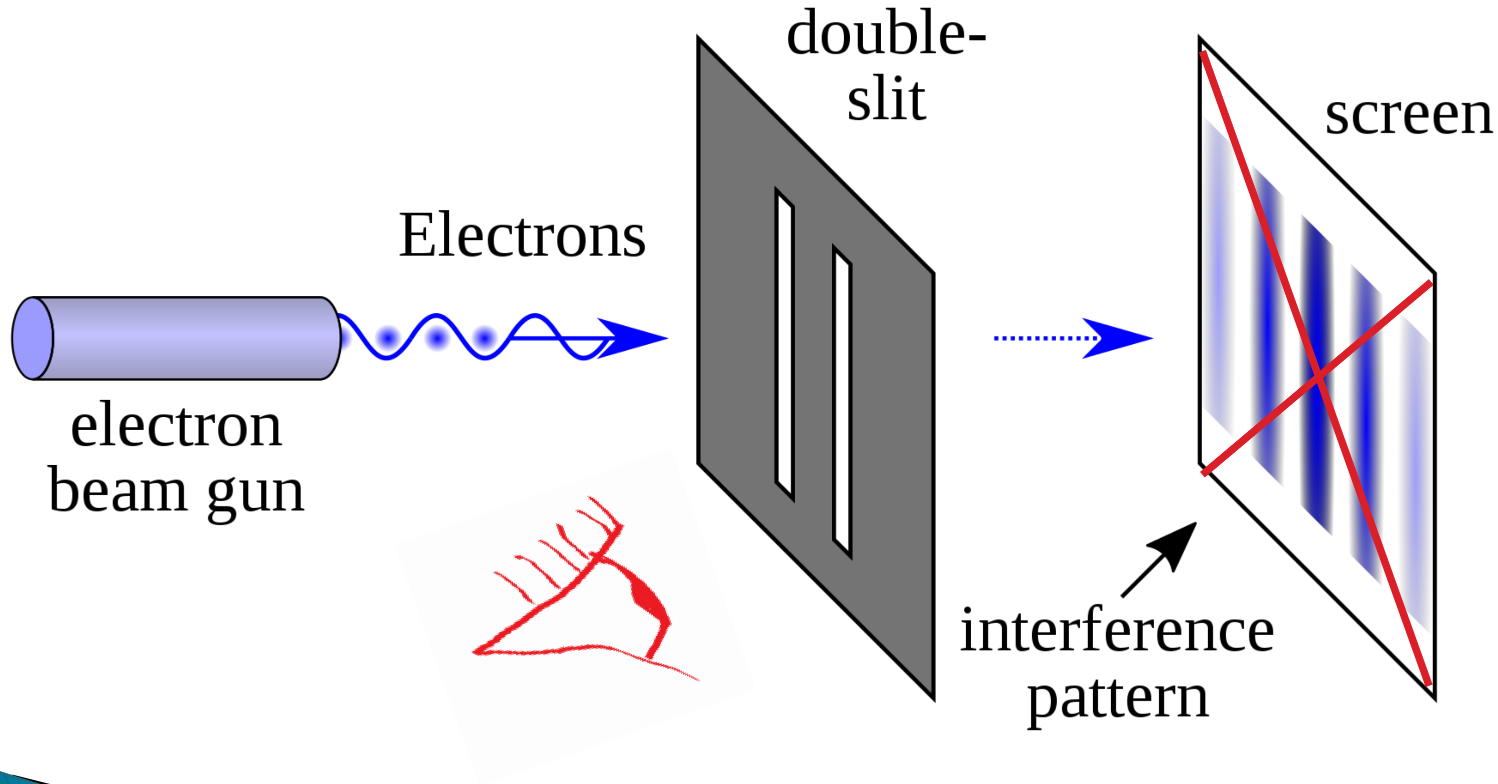
Introduction

- Quantum decoherence



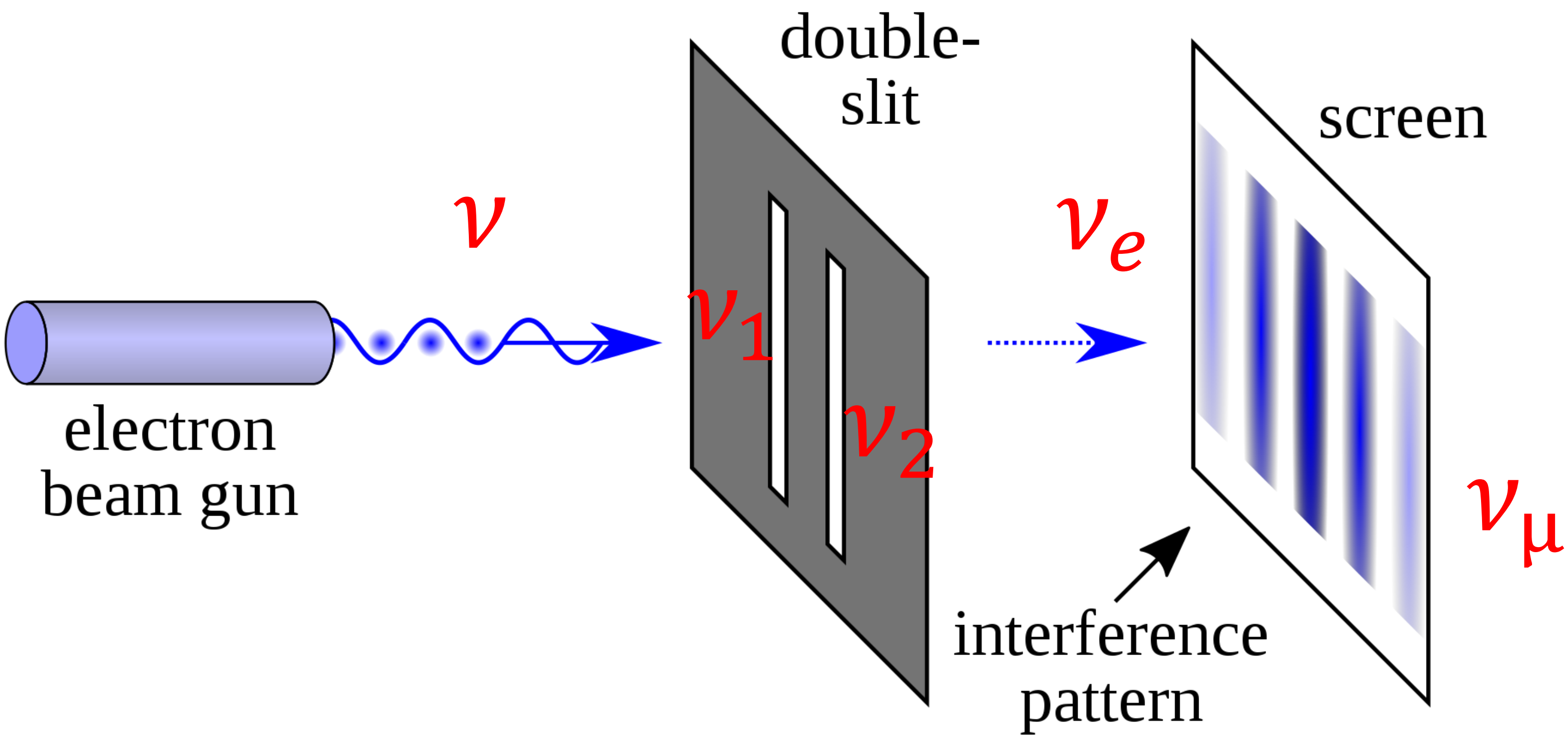
Introduction

- Quantum decoherence



Introduction

- Quantum decoherence



Lindblad equation (1976)

Lindblad equation

$$\frac{\partial \rho_\nu(t)}{\partial t} = -i\left[H_S, \rho_\nu(t)\right] + D\left[\rho_\nu\right]$$

$\rho_\nu(t)$ – neutrino density matrix

H_s – Hamiltonian of the neutrino system

$$D_{ll} = -diag\{\Gamma_1, \Gamma_1, \Gamma_2\}$$

Γ_1 decoherence parameter

Γ_2 relaxation parameter

Dissipative operators

$$D\left[\rho_\nu(t)\right] = \frac{1}{2}\sum_{k=1}^{N^2-1}\left[V_k, \rho_\nu V_k^\dagger\right] + \left[V_k\rho_\nu, V_k^\dagger\right]$$

Lindblad equation can be expanded by Pauli matrices σ_k :

$$\frac{\partial \rho_k(t)}{\partial t}\sigma_k = 2\epsilon_{ijk}H_i\rho_j(t)\sigma_k + D_{kl}\rho_l(t)\sigma_k$$

Lindblad equation (1976)

Lindblad equation

$$\frac{\partial \rho_\nu(t)}{\partial t} = -i\left[H_S, \rho_\nu(t)\right] + D\left[\rho_\nu\right]$$

$$D_{ll} = -diag\{\Gamma_1, \Gamma_1, \Gamma_2\}$$

Γ_1 decoherence parameter

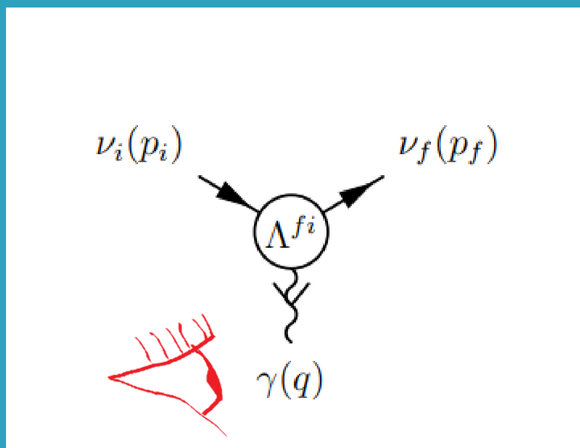
Γ_2 relaxation parameter

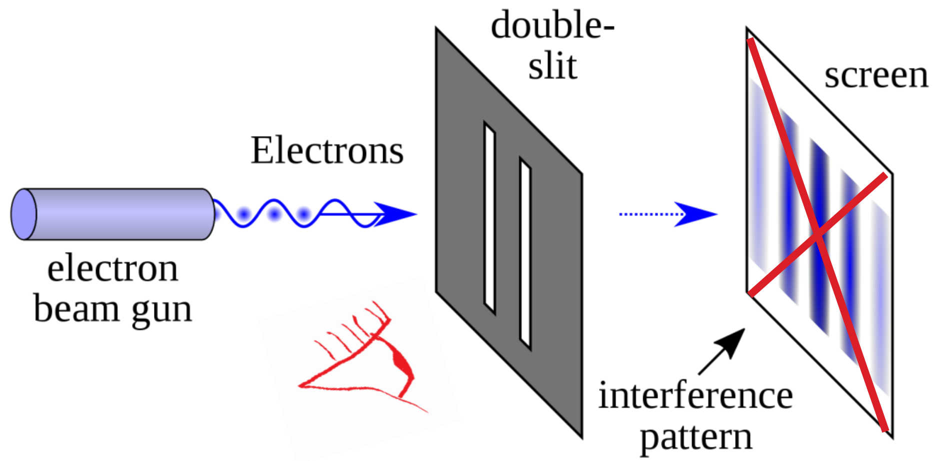
Neutrino flavour oscillation probability accounting for quantum decoherence of neutrino mass states

$$P_{\nu_\alpha \nu_\alpha} = \frac{1}{2}\left[1 + e^{-\Gamma_2 x}\cos^2 2\tilde{\theta} + e^{-\Gamma_1 x}\sin^2 2\tilde{\theta}\cos\left(\tilde{\Delta} x\right)\right]$$

Mechanism of neutrino quantum decoherence

Neutrino radiative decay





Formalism

Liouville equation for the density matrix of a system composed of neutrinos and an electromagnetic field

$$\frac{\partial}{\partial t}\rho = -i \int d^3x \, [H(x), \rho]$$

ρ – density matrix of the full system

H – Hamiltonian of the full system

$H = H_\nu + H_{int} + H_\gamma$

H_ν – neutrino system

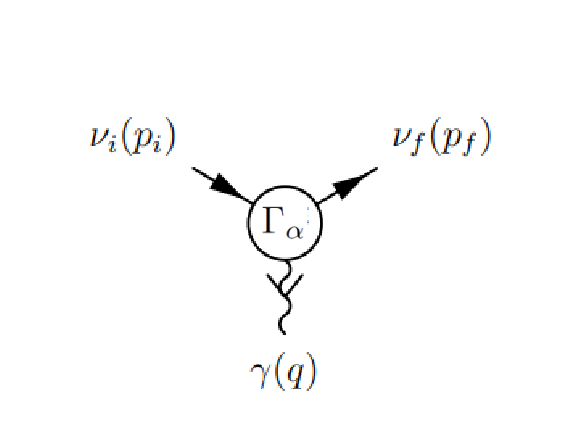
H_{int} – interaction

H_γ – electromagnetic field

Interaction is expressed as

$$H_{int}(x) = j_\alpha(x) A^\alpha(x)$$

$$j_\alpha(x) = \overline{\nu}_i(x) \Gamma_\alpha \nu_j(x)$$



Based on book H.P. Breuer, F. Petruccione "The theory of open quantum systems"

Formalism

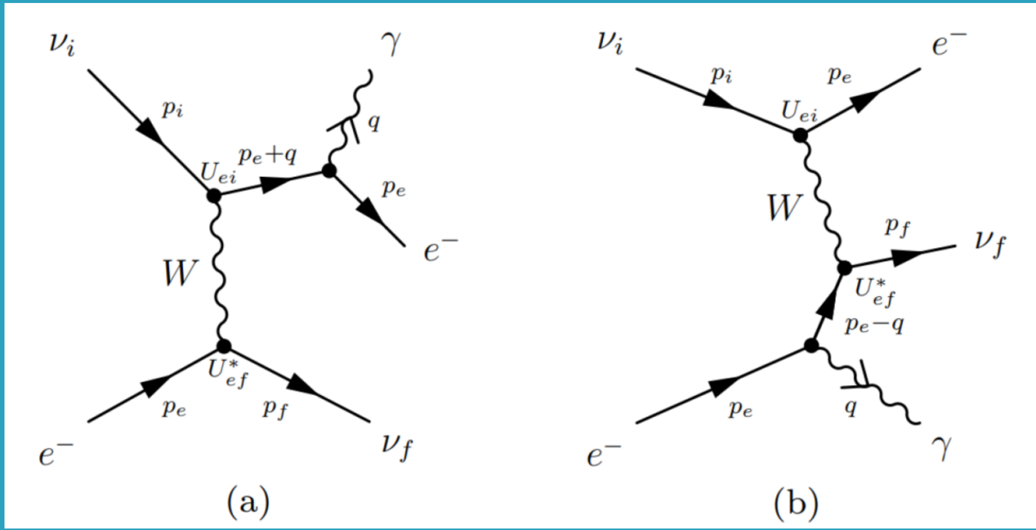
$$H_{int}(x) = j_\alpha(x) A^\alpha(x)$$

$$j_\alpha(x) = \overline{\nu}_i(x) \Gamma_\alpha \nu_j(x)$$

Electromagnetic vertex

$$\Gamma_\alpha = \sin 2\theta \, \tau \gamma_\alpha (1 - \gamma_5)$$

$$\tau = -\frac{e G_F T^2}{2\sqrt{2}}$$



J. C. D'Olivo, J. F. Nieves, P. B. Pal, Phys.Rev.Lett. 64 (1990) 1088.

Formalism

Liouville equation

$$\frac{\partial}{\partial t}\rho = -i\int d^3x\,[H(x),\rho]$$

After integrating

$$\rho_\nu(t_f) = tr_F\left(Texp\left[\int_{t_i}^{t_f} d^4x\,[H(x),\rho(t_i)]\right]\right)$$

$\rho_\nu(t) = tr_F\,\rho(t)$ – density matrix for neutrino

We rewrite equation using the decomposition of the chronological time-ordering operator T into time-ordering operator for a matter current T_j and for electromagnetic fields T_A as $T = T_j T_A$

$$\rho_\nu(t_f) = T^j\left(\exp\left[\int_{t_i}^{t_f} d^4x\,[H_\rho(x),\rho(t_i)]\right]\right.$$
$$\left. tr_F\left\{T^A\exp\left[\int_{t_i}^{t_f} d^4x\,[H_{int}(x),\rho(t_i)]\right]\right\}\right)$$

Formalism

$$\rho_\nu(t_f) = T^j \left(\exp\left[\int_{t_i}^{t_f} d^4x\, [H_\rho(x), \rho(t_i)]\right] \right.$$
$$\left. tr_F \left\{ T^A \exp\left[\int_{t_i}^{t_f} d^4x\, [H_{int}(x), \rho(t_i)]\right] \right\} \right)$$

Wick theorem

$$T^A \exp\left[\int_{t_i}^{t_f} d^4x\, [H_{int}(x), \rho(t)]\right] =$$
$$\exp\left[-\frac{1}{2}\int_{t_i}^{t_f} d^4x \int_{t_i}^{t_f} d^4x' [A_\mu(x), A_\nu(x')][j^\mu(x) j^\nu(x'), \rho(t_i)]\Theta(t-t')\right] \exp\left[\int_{t_i}^{t_f} d^4x [H_{int}(x), \rho(t_i)]\right]$$

$$\rho(t_i) = \rho_\nu(t_i) \otimes \rho_f$$

$$tr_f \left\{ \exp\left[\int_{t_i}^{t_f} d^4x [H_{int}(x), \rho(t_i)]\right] \right\} =$$
$$\exp\left[\frac{1}{2}\int_{t_i}^{t_f} d^4x \int_{t_i}^{t_f} d^4x' \{\langle A_\nu(x') A_\mu(x)\rangle_f j^\mu(x) j^\nu(x') \rho_\nu(t_i) + \langle A_\mu(x) A_\nu(x')\rangle_f \rho_\nu(t_i) j^\mu(x) j^\nu(x')\right.$$
$$\left. - \langle A_\nu(x') A_\mu(x)\rangle_f j^\mu(x) \rho_\nu(t_i) j^\nu(x') - \langle A_\mu(x) A_\nu(x')\rangle_f j^\nu(x') \rho_\nu(t_i) j^\mu(x)\}\right]$$

Formalism

Taking everything together one can get the following equation of evolution

$$\frac{\partial}{\partial t}\rho(t) = -i\left[H_\nu, \rho(t)\right] -$$
$$-\frac{i}{2}\int d^3x \int d^3x' \int_{t_i}^{t_f} dx_0' D(x-x')\left[\vec{j}(x), \{\vec{j}(x'), \rho(t)\}\right] -$$
$$-\frac{1}{2}\int d^3x \int d^3x' \int_{t_i}^{t_f} dx_0' D_1(x-x')\left[\vec{j}(x), \left[\vec{j}(x'), \rho(t)\right]\right],$$

$$D(x-x')_{ij} = i\left[A_i(x), A_j(x')\right],$$

– Pauli–Jordan commutator function

$$D_1(x-x')_{ij} = \langle\{A_i(x), A_j(x')\}\rangle_f$$

– Anticommutator function

$$\langle O\rangle_f = tr_f\left(O\frac{1}{Z}\exp[-H_f/k_B T_\gamma]\right)$$

– averaging with respect to the radiation field

Results

Neutrino evolution equation has the form of Lindblad equation

$$\frac{\partial}{\partial t}\rho_{\tilde{\nu}}(t) = -i\left[H_{\tilde{\nu}}, \rho_{\tilde{\nu}}(t)\right] +$$
$$+\kappa_1\left(\sigma_-\rho_{\tilde{\nu}}(t)\sigma_+ - \frac{1}{2}\sigma_+\sigma_-\rho_{\tilde{\nu}}(t) - \frac{1}{2}\rho_{\tilde{\nu}}(t)\sigma_+\sigma_-\right) +$$
$$+\kappa_2\left(\sigma_+\rho_{\tilde{\nu}}(t)\sigma_- - \frac{1}{2}\sigma_-\sigma_+\rho_{\tilde{\nu}}(t) - \frac{1}{2}\rho_{\tilde{\nu}}(t)\sigma_-\sigma_+\right)$$

where

$$f(E) = \frac{1}{e^{E/kT_\gamma} - 1}$$

$$\sigma_+ = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, \quad \sigma_- = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$$

$$\Delta_{ij} = \frac{\sqrt{(\Delta m_{ij}\cos 2\theta_{ij} - A)^2 + \Delta m_{ij}^2 \sin^2 2\theta_{ij}}}{2E}$$

$$\sin^2 2\tilde{\theta}_{ij} = \frac{\Delta m_{ij}^2 \sin^2 2\theta_{ij}}{(\Delta m_{ij}\cos 2\theta_{ij} - A)^2 + \Delta m_{ij}^2 \sin^2 2\theta_{ij}}$$

$$\kappa_1 = \frac{\Delta_{ij}}{\pi^2}\sin^2 2\tilde{\theta}_{ij}\tau^2(f(2\Delta_{ij}) + 1),$$

$$\kappa_2 = \frac{\Delta_{ij}}{\pi^2}\sin^2 2\tilde{\theta}_{ij}\tau^2 f(2\Delta_{ij})$$

$$\tau = -\frac{eG_F T^2}{2\sqrt{2}}$$

$$\kappa_1 \approx \kappa_2 = \kappa$$

Decoherence and relaxation parameters are expressed as

$$\Gamma_1 = \frac{\kappa}{2}, \qquad \Gamma_2 = \kappa.$$

Results

Neutrino evolution equation accounting for massless dark photons

$$\frac{\partial}{\partial t}\rho_{\tilde{\nu}}(t) = -i\left[H_{\tilde{\nu}}, \rho_{\tilde{\nu}}(t)\right] + \\ + \kappa_1\left(\sigma_-\rho_{\tilde{\nu}}(t)\sigma_+ - \frac{1}{2}\sigma_+\sigma_-\rho_{\tilde{\nu}}(t) - \frac{1}{2}\rho_{\tilde{\nu}}(t)\sigma_+\sigma_-\right) + \\ + \kappa_2\left(\sigma_+\rho_{\tilde{\nu}}(t)\sigma_- - \frac{1}{2}\sigma_-\sigma_+\rho_{\tilde{\nu}}(t) - \frac{1}{2}\rho_{\tilde{\nu}}(t)\sigma_-\sigma_+\right),$$

$$\kappa_X = \frac{\Delta_{ij}}{\pi^2}\sin^2 2\tilde{\theta}_{ij}\tau_X f_X(2\Delta_{ij})$$

$$\tau = -\frac{c_W}{\sqrt{1-\sigma^2 c_W^2}}\frac{eG_F T^2}{2\sqrt{2}}$$

$$\kappa_1 \approx \kappa_2 = \kappa_X$$

where

$$f_X(E) = \frac{1}{e^{E/kT_X} - 1}$$

$$\sigma_+ = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, \quad \sigma_- = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$$

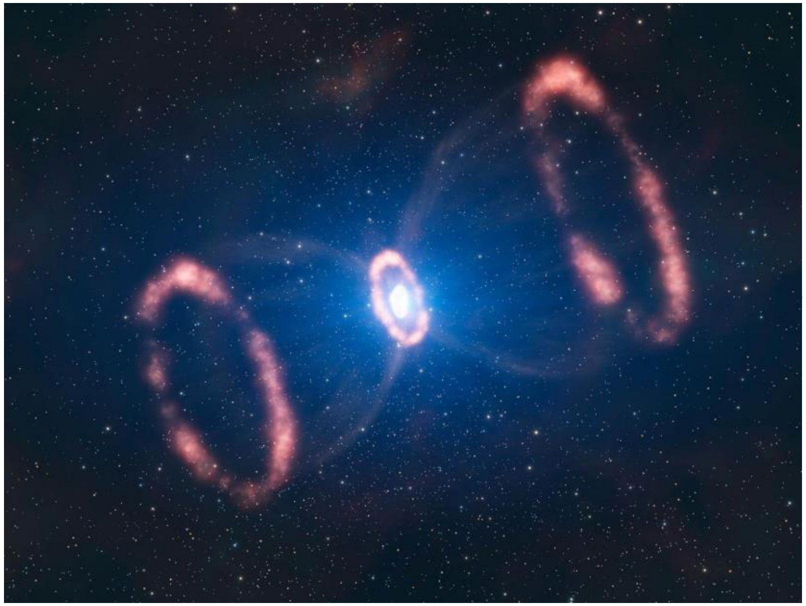
$$\Delta_{ij} = \frac{\sqrt{(\Delta m_{ij}\cos 2\theta_{ij} - A)^2 + \Delta m_{ij}^2 \sin^2 2\theta_{ij}}}{2E}$$

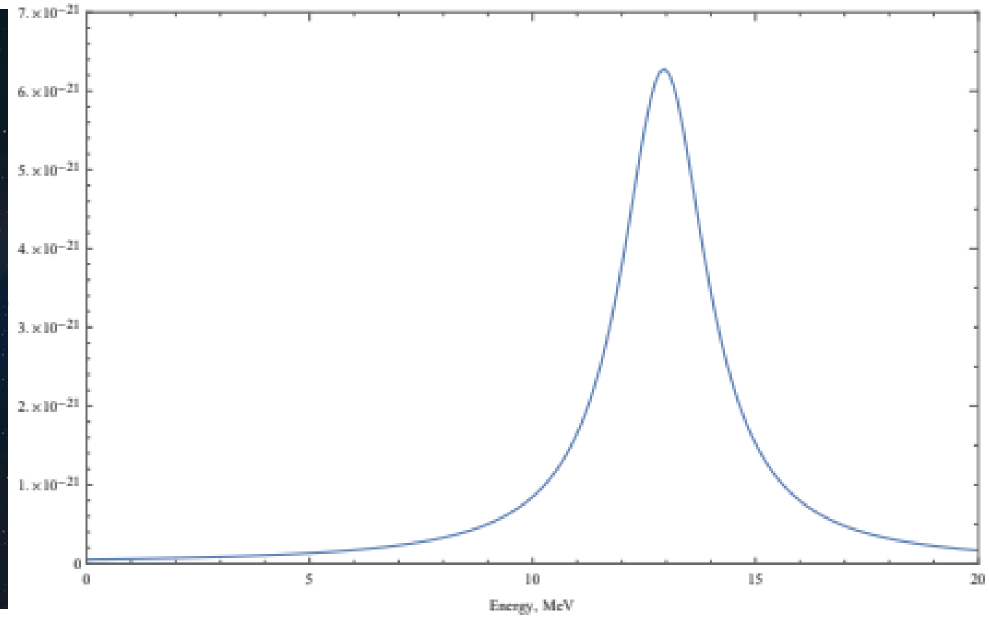
$$\sin^2 2\tilde{\theta}_{ij} = \frac{\Delta m_{ij}^2 \sin^2 2\theta_{ij}}{(\Delta m_{ij}\cos 2\theta_{ij} - A)^2 + \Delta m_{ij}^2 \sin^2 2\theta_{ij}}$$

$c_W = \cos\Theta_W$ is the cosine of the weak mixing angle

σ – characterises the mixing between dark photons and photons of the standard model

Results





Supernovae parameters

$T = 30\ MeV$

$T_\gamma = 100\ MeV$

$n = 10^{29} \frac{1}{cm^3}$

R. Bollig, H.-Th. Janka, et. al. Phys.Rev.Lett. 119 (2017)

Obtained values of decoherence parameters

$\Gamma_1 \approx 10^{-21} GeV$ for $\nu_e \nu_s$ oscillations

$\Gamma_1 \approx 10^{-31} GeV$ for $\nu_e \nu_\tau$ oscillations

Experimental constraints

$\Gamma_1 < 10^{-24} GeV$ for reactor neutrino fluxes

$\Gamma_1 < 10^{-28} GeV$ for solar neutrino fluxes

Заключение

- Предложен новый подход к описанию квантовой декогеренции нейтрино

- На основе разработанного подхода изучен новый механизм квантовой декогеренции за счет радиационного распада нейтрино

- Впервые были получены аналитические выражения для параметров декогеренции Г_1 и релаксации Г_2

- Результаты важны для исследования потоков нейтрино от сверхновых
(JUNO, Hyper-Kamiokande)

Спасибо за внимание