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Neutrino Decoherence in Normal Matter

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Based on PRD 102, 056007 (2020) and PRD 100, 115049 (2019)

- Introduction to Neutrino Physics
- Decoherence in Quantum Mechanical systems (open system)
- Neutrino Interaction: Notation and conventions
- Finite Temperature Field Theory
- Neutrino Self-Energy (2 Loops)
- Connection of nonforward scattering with the Lindblad Equation (Master Equation)
- Calculation of Jump Operator
- Two-generation neutrinos (An Example)
- Summary

Neutrino Physics

Neutrino Properties

- Spin ½, Massive, 3 Flavors, corresponding to 3 lepton families
- Dirac Majorana !!
- We observe flavor states
- Superposition of mass eigenstates ⟹Neutrino Oscillation
- Do we know the neutrino oscillation angles ?
- Dirac and Majorana Phases (!)

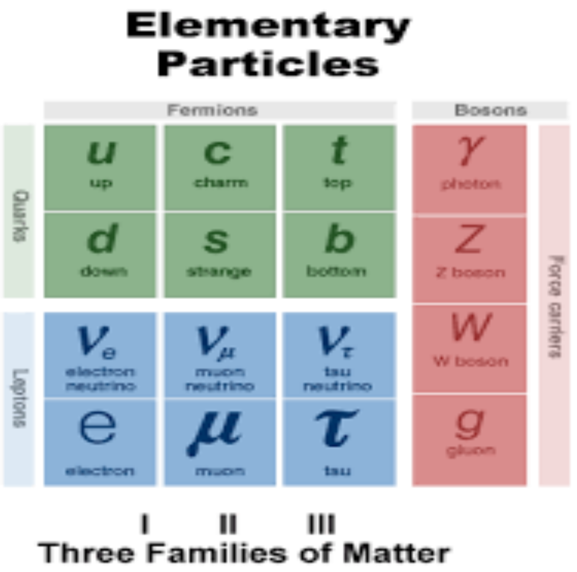
Neutrino Astronomy

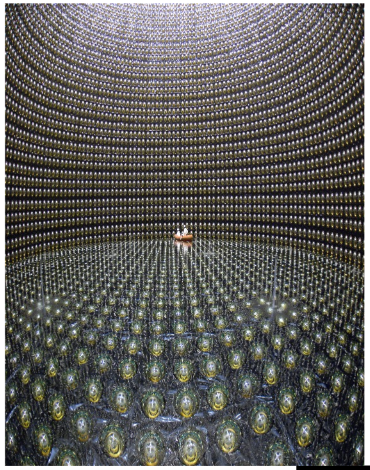
- Solar neutrino problem and its solution
- Atmospheric neutrino anomaly

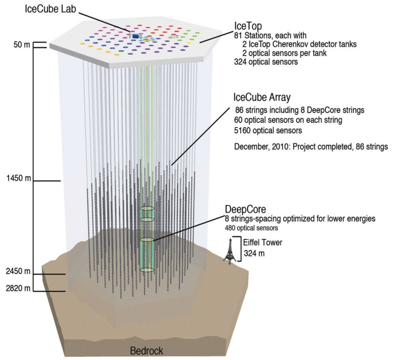
High Energy Astrophysical Neutrinos

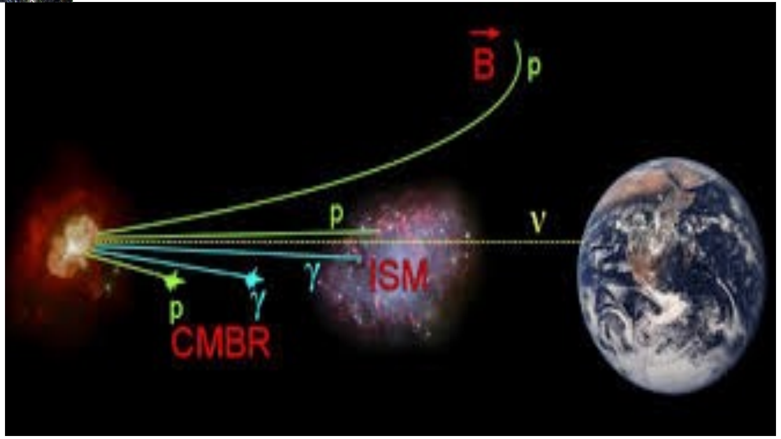
- Production Mechanism(s) pp/pγ
- Detection by Neutrino detector (IceCube)

  Charged Current and Neutral Current processes
- Current Status of neutrino Physics
- **Non-standard neutrinos (Sterile, Heavy, Dark Matter !!!!)**



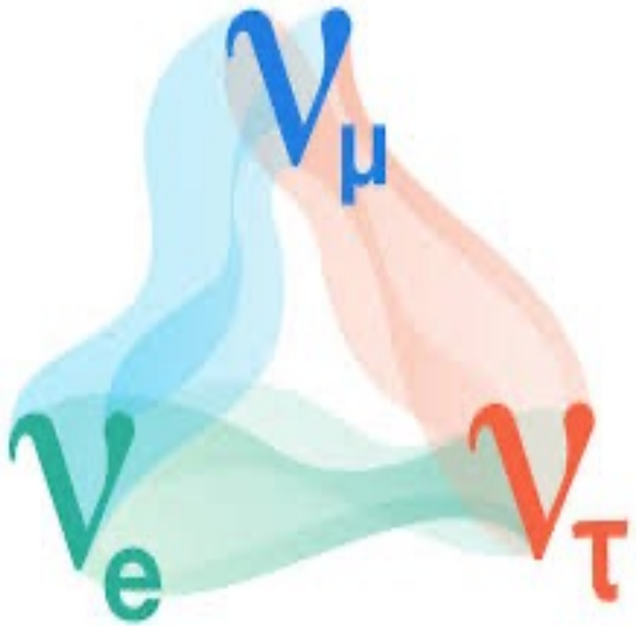


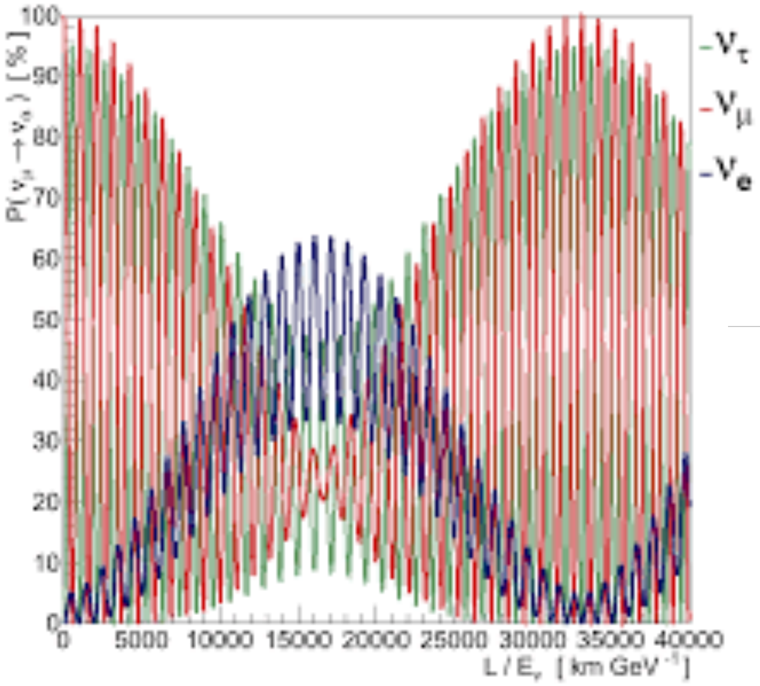




Neutrino Mixing and Oscillation

The quarks in the matter are not independent from each other, a Quantum mixing exist among them. In the same way, all the three neutrinos, if they were massive could be mixed by quantum mechanics: A neutrino traveling in space would then be a mixture of all three.





$$|\nu_\alpha >= \sum_i U^*_{\alpha,i}|\nu_i >$$

$$|\nu_i >= \sum_\alpha U_{\alpha i}|\nu\alpha >$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P_{\alpha\rightarrow\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Neutrino Oscillation in Matter

Consider the Normal Matter (charged neutral) e, p and n

$$i\frac{d}{dt}\begin{bmatrix}\nu_e \\ \nu_\mu\end{bmatrix} = \begin{bmatrix} V - \Delta\cos2\theta & \frac{\Delta}{2}\sin2\theta \\ \frac{\Delta}{2}\sin2\theta & 0 \end{bmatrix}\begin{bmatrix}\nu_e \\ \nu_\mu\end{bmatrix}$$

$$\Delta = \Delta m^2 / 2 E_\nu$$

$$V = \sqrt{2}G_F N_e$$

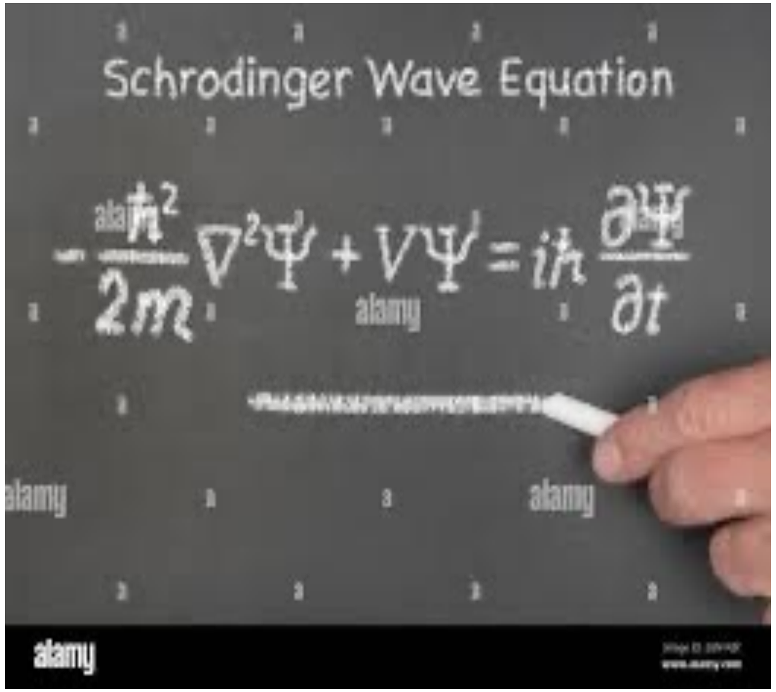
matter effect on the propagation of neutrino

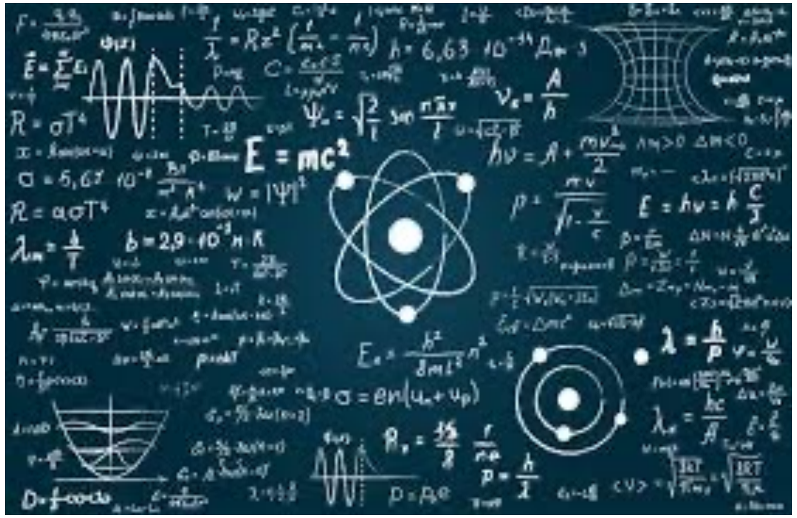
$$P_{\nu_e \to \nu_\mu}(l) = \frac{\Delta^2 \sin^2 2\theta}{\omega^2} \sin^2\left(\frac{\omega l}{2}\right)$$

$$\omega = \left[(V - \Delta\cos2\theta)^2 + \Delta^2 \sin^2 2\theta\right]^{1/2}$$

Quantum Mechanics

- In Quantum Mechanics, particles (say Electrons) are described by a Wave function through Schrödinger Equation
- $i\,\hbar\,\partial_t \psi(t) = \hat{H}\psi(t)$
- A mathematical representation of the quantum state of a system.
- A probabilistic interpretation of the wave function is used to explain various quantum effects. As long as there exists a definite phase relation between different states, the system is said to be coherent. Coherence is preserved under the laws of quantum physics.





Quantum Decoherence !!!!!

Decoherence was first introduced in 1970 by the German physicist H. Dieter Zeh[1] and has been a subject of active research since the 1980s.[2] Decoherence has been developed into a complete framework, but there is controversy as to whether it solves the measurement problem, as the founders of decoherence theory admit in their seminal papers.

When the concept of decoherence was first introduced to the broader scientific community by Zurek's (1991) article in *Physics Today*, it elicited a series of contentious comments from the readership (see the April 1993 issue of *Physics Today*). In response to his critics, Zurek (2003b, p. 718) states

> In a field where controversy has reigned for so long this resistance to a new paradigm [namely, to decoherence] is no surprise.

Decoherence, the measurement problem, and interpretations of quantum mechanics , arXiv:0312059
Maximilian Schlosshauer

Omnès (2002, p. 2) had this assessment:

> The discovery of decoherence has already much improved our understanding of quantum mechanics. (...) [B]ut its foundation, the range of its validity and its full meaning are still rather obscure. This is due most probably to the fact that it deals with deep aspects of physics, not yet fully investigated.

- Decoherence can be viewed as the loss of information from a system into the environment **(or heat bath)**.
- Decoherence is a consequence of the unavoidable interaction of virtually all physical systems with their environment.

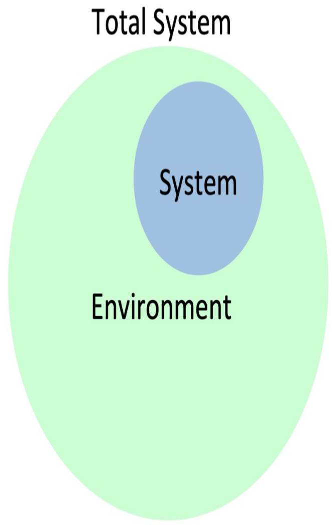


FIG. 1: A total system divided into the system of interest, "System", and the environment.

- Every system is coupled with its surroundings. Viewed in isolation, the system's dynamics are non-unitary (although the combined system plus environment evolves in a unitary fashion). The dynamics of the system alone are irreversible. As with any coupling, **entanglements** are generated between the system and environment.
- These have the effect of sharing quantum information with its surroundings.

- The term *decoherence* is used in many fields of (quantum) physics to describe the disappearance or absence of certain superpositions of quantum states.
- Decoherence has been used to understand the possibility of the collapse of the wave function in quantum mechanics.
- Decoherence does not generate actual wave-function collapse. It only provides a framework for apparent wave-function collapse, as the quantum nature of the system "leaks" into the environment. That is, components of the wave function are decoupled from a coherent system and acquire phases from their immediate surroundings. A total superposition of the global or universal wavefunction still exists (and remains coherent at the global level), but its ultimate fate remains an interpretational issue.

Type of a Quantum state

- The state vector ψ contains all information about a quantum system. But in many cases detail information of a system are not known. (In many cases there are interactions between a system and its environment, decoherence. For example, this may lead to spontaneous emission in the atom or to a loss of radiation in a cavity.)
- If we want to describe a quantum system that is not isolated from its environment, we have to replace the description by the state vector ψ by a new concept - this will be the Density Matrix formalism.

Neutrino Interaction: Notation and conventions

The neutral-current couplings of the interaction Lagrangian that are relevant to our calculation are given by

$$L_Z = -g_Z Z^\mu \left[\sum_a \overline{\nu}_{La}\gamma_\mu \nu_{La} + \overline{e}\gamma_\mu(a_e + b_e\gamma_5)e + J_\mu^{(Z)} \right] ,$$

$$a_e = -\frac{1}{2} + 2\sin^2\theta_W ,$$
$$b_e = \frac{1}{2} .$$

$J^Z{}_\mu$ Nucleon neutral-current, interms of the quark fields

$$q = \begin{pmatrix} u \\ d \end{pmatrix} ,$$

g_z=g/(2cosθw)

$$J_\mu^{(Z)} = \overline{q}\gamma_\mu \frac{\tau_3}{2} q - \overline{q}\gamma_\mu\gamma_5 \frac{\tau_3}{2} q - 2\sin^2\theta_W J_\mu^{(em)} ,$$

$$J_\mu^{(em)} = \overline{q}\gamma_\mu \frac{\tau_3}{2} q + \frac{1}{6}\overline{q}\gamma_\mu q ,$$

EM current

$$\langle f(p')|J_\mu^{(Z)}(0)|f(p)\rangle = \overline{u}(p')j_{f\mu}^{(Z)}(p-p')u(p)$$

$$j_{f\mu}^{(Z)}(q) = a_f\gamma_\mu + b_f\gamma_\mu\gamma_5 - i\frac{c_f}{2m_N}\sigma_{\mu\nu}q^\nu$$

their $q^2 = 0$ limiting value

$$a_f = I_{3f} - 2\sin^2\theta_W Q_f ,$$
$$b_f = -I_{3f}g_A ,$$
$$c_f = I_{3f}[F_{2p}^{(em)}(0) - F_{2n}^{(em)}(0)] - 2\sin^2\theta_W F_{2f}^{(em)}(0)$$

Notation and conventions

where $Q_p = 1, Q_n = 0,\ I_{3p} = -I_{3n} = 1/2$ and

$$F_{2p}^{(em)}(0) = 1.79\,,$$

$$F_{2n}^{(em)}(0) = -1.71\,.$$

Charged-Current part of the Lagrangian

$$L_W = -\left(\frac{g}{\sqrt{2}}\right) W^{\mu} \nu_L \gamma_{\mu} e_L + h.c.$$

Finite Temperature Field Theory

- the velocity four-vector of the background medium u^μ and k^μ the momentum of the propagating neutrino. In the background medium's own rest frame u^μ=(1,0), $k_\mu = (\omega, \vec{\kappa})$.
- Let us consider first the case of one neutrino propagating in the medium, ignoring flavor mixing. The dispersion relation $\omega(\vec{\kappa})$ and the spinor of the propagating mode are determined by solving the equation

$$(k_\mu \gamma^\mu - \Sigma_{eff})\psi L(k) = 0$$

- where Σ_{eff} is the neutrino thermal self-energy, which can be decomposed in the form

$$\Sigma_{eff} = \Sigma_r + i\Sigma_i, \quad \Sigma_{eff} = V^\mu \gamma_\mu L, \quad \Sigma_{r,i} = V^\mu \gamma_\mu L, \quad V^\mu = V^\mu + iV^\mu$$

$$\Sigma_r = \Sigma_{11r} \equiv \frac{1}{2}(\Sigma_{11} + \overline{\Sigma}_{11}),$$

Finite Temperature Field Theory

Real and Imaginary parts of neutrino energy

$$\omega^{(\nu,\bar{\nu})} = \omega_r^{(\nu,\bar{\nu})} - \frac{i\gamma^{(\nu,\bar{\nu})}}{2}$$

$$\omega_r^{(\nu,\bar{\nu})} = \kappa + V_{eff}^{(\nu,\bar{\nu})}$$

$$-\frac{\gamma^{(\nu)}(\vec{\kappa})}{2} = n \cdot V_i(\kappa, \vec{\kappa}) \,,$$

$$-\frac{\gamma^{(\bar{\nu})}(\vec{\kappa})}{2} = n \cdot V_i(-\kappa, -\vec{\kappa}) \,.$$

$$-\frac{1}{2}\Gamma^{(\nu)} = n \cdot V_i^{(W)}(\kappa, \vec{\kappa}) + \sum_{f=e,n,p} n \cdot V_i^{(Z,f)}(\kappa, \vec{\kappa}) \,,$$

$$V_{eff}^{(\nu)} = n \cdot V_r(\kappa, \vec{\kappa}) = V_r^0(\kappa, \vec{\kappa}) - \hat{\kappa} \cdot \vec{V}_r(\kappa, \vec{\kappa}) \,,$$

$$n^\mu = (1, \hat{\kappa}) \,.$$

$$V_{eff}^{(\bar{\nu})} = -n \cdot V_r(-\kappa, -\vec{\kappa}) = -V_r^0(-\kappa, -\vec{\kappa}) + \hat{\kappa} \cdot \vec{V}_r(-\kappa, -\vec{\kappa})$$

$$\Sigma_i = \frac{\Sigma_{12}}{2in_F(x_\nu)} \,,$$

$$V_i^\mu = \frac{1}{2} \mathrm{Tr}\, \gamma^\mu \Sigma_i \,,$$

$$V_i^{(Z,f)\alpha} = \frac{1}{2} \mathrm{Tr}\, \gamma^\alpha \Sigma_i^{(Z,f)} \,,$$

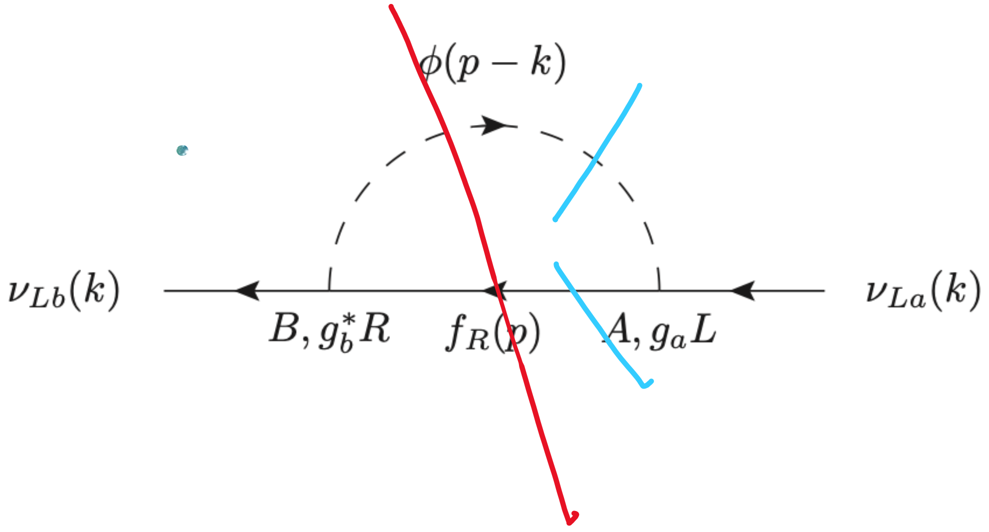
$$V_i^{(W)\alpha} = \frac{1}{2} \mathrm{Tr}\, \gamma^\alpha \Sigma_i^{(W)} \,,$$

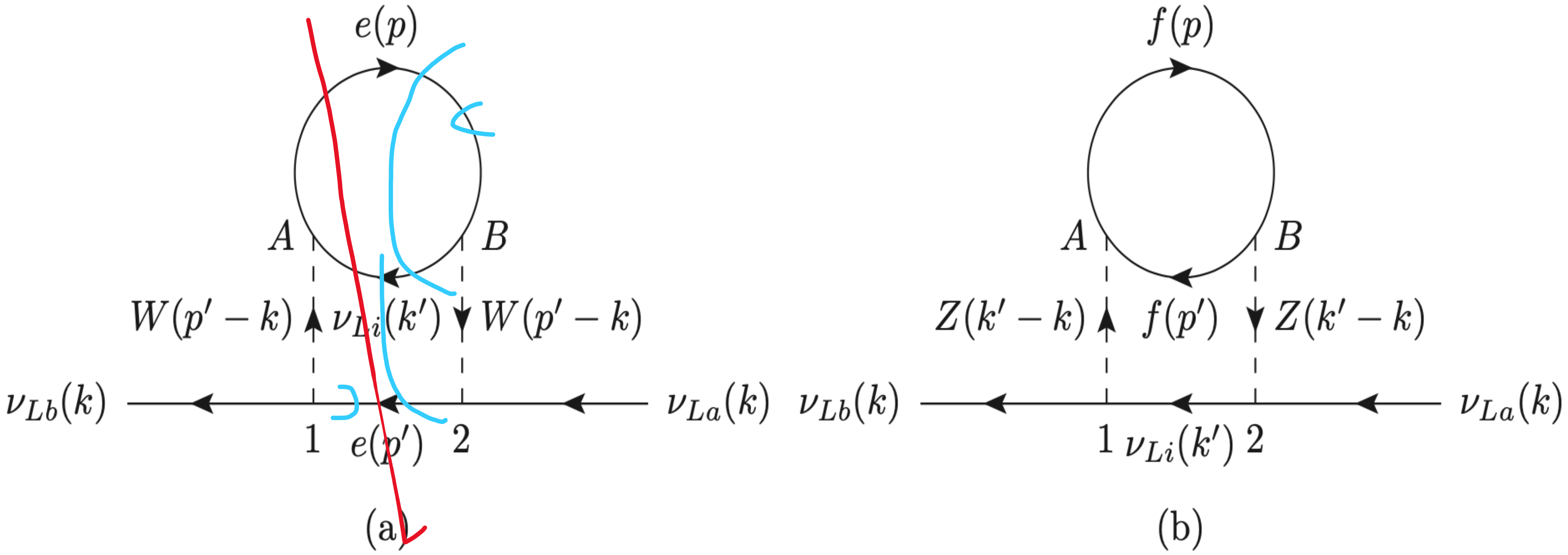
$$\Sigma_i = \Sigma_i^{(W)} + \sum_{f=e,n,p} \Sigma_i^{(Z,f)} \,.$$

Neutrino Self-Energy (2-Loop

Real Part Σ_r

Imaginary Part Σ_i



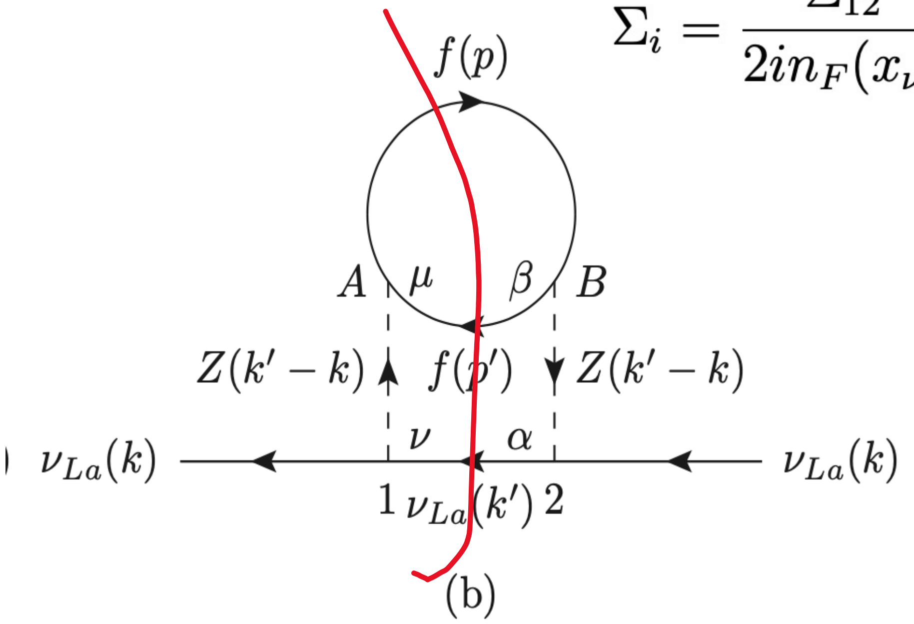


Feynman Diagram Calculation (Imaginary part)

$$S_{21}^{(f)}(p) = -2\pi i \delta(p^2 - m_f^2)\sigma^{(f)}(p) e^{x_f} n_F(x_f)\epsilon(p\cdot u)\,,$$

$$S_{12}^{(f)}(p') = 2\pi i \delta(p'^2 - m_f^2)\sigma^{(f)}(p') n_F(x'_f)\epsilon(p'\cdot u)\,,$$

$$(S_{12}^{(\nu_{La})}(k')) = 2\pi i \delta(k'^2)\sigma^{(\nu)}(k') n_F(x'_\nu)\epsilon(k'\cdot u)\,,$$



$$\Sigma_i = \frac{\Sigma_{12}}{2in_F(x_\nu)}\,,$$

$$-i\left(\Sigma_{12}^{(Z,f)}(k)\right)_{ba} = -2K_{ba}^{(Z)}\int \frac{d^4p'}{(2\pi)^4}\frac{d^4p}{(2\pi)^4}\gamma^\mu L i S_{12}^{(\nu_{La})}(k')\gamma^\nu L$$
$$\times\,\mathrm{Tr}\left(\gamma_\mu(a_f + b_f\gamma_5) i S_{12}^{(f)}(p')\gamma_\nu(a_f + b_f\gamma_5) i S_{21}^{(f)}(p)\right)\,,$$

$$K_{ba}^{(Z)} = \left(\frac{g_Z^4}{2m_Z^4}\right)\delta_{ab} = \left(\frac{g^4}{32m_W^4}\right)\delta_{ab}\,,$$

$$\left(\Sigma_i^{(Z,f)}(k)\right)_{ba} = -K_{ba}^{(Z)} \int \frac{d^3p'}{(2\pi)^3 2E_{p'}} \frac{d^3p}{(2\pi)^3 2E_p} \frac{d^3\kappa'}{(2\pi)^3 2\omega_{\kappa'}}$$

$$\times (2\pi)^4 \left\{ \delta^{(4)}(k+p-k'-p') N_{\mu\nu}(p,p') M^{\mu\nu}(k') E_{\nu,++} \right.$$

$$- \delta^{(4)}(k-p-k'-p') N_{\mu\nu}(-p,p') M^{\mu\nu}(k') E_{\nu,-+}$$

$$- \delta^{(4)}(k+p+p'-k') N_{\mu\nu}(p,-p') M^{\mu\nu}(k') E_{\nu,+-}$$

$$+ \delta^{(4)}(k+p'-k'-p) N_{\mu\nu}(-p,-p') M^{\mu\nu}(k') E_{\nu,--}$$

$$- \delta^{(4)}(k+p+k'-p') N_{\mu\nu}(p,p') M^{\mu\nu}(-k') E_{\bar{\nu},++}$$

$$+ \delta^{(4)}(k+k'-p'-p) N_{\mu\nu}(-p,p') M^{\mu\nu}(-k') E_{\bar{\nu},-+}$$

$$+ \delta^{(4)}(k+p+p'+k') N_{\mu\nu}(p,-p') M^{\mu\nu}(-k') E_{\bar{\nu},+-}$$

$$\left. - \delta^{(4)}(k+p'+k'-p) N_{\mu\nu}(-p,-p') M^{\mu\nu}(-k') E_{\bar{\nu},--} \right\} ,$$

8 nonforward scattering Processes

1	$E_{\nu,++} = f(1-f') - f'_\nu(f-f')$	$\nu_a(k) + f(p) \leftrightarrow \nu_a(k') + f(p')$
	$E_{\nu,-+} = (1-\bar{f})(1-f') - f'_\nu(1-\bar{f}-f')$	$\nu_a(k) \leftrightarrow \nu_a(k') + \bar{f}(p) + f(p')$
	$E_{\nu,+-} = f\bar{f}' - f'_\nu(f+\bar{f}'-1)$	$\nu_a(k) + f(p) + \bar{f}(p') \leftrightarrow \nu_a(k')$
4	$E_{\nu,--} = (1-\bar{f})\bar{f}' - f'_\nu(\bar{f}'-\bar{f})$	$\nu_a(k) + \bar{f}(p') \leftrightarrow \nu_a(k') + \bar{f}(p)$
	$E_{\bar{\nu},++} = (1-f)f' + \bar{f}'_\nu(f-f')$	$\nu_a(k) + \bar{\nu}_a(\bar{k}') + f(p) \leftrightarrow f(p')$
	$E_{\bar{\nu},-+} = \bar{f}f' + \bar{f}'_\nu(1-\bar{f}-f')$	$\nu_a(k) + \bar{\nu}_a(\bar{k}') \leftrightarrow \bar{f}(p) + f(p')$
	$E_{\bar{\nu},+-} = (1-f)(1-\bar{f}') + \bar{f}'_\nu(f+\bar{f}'-1)$	$\nu_a(k) + \bar{\nu}_a(\bar{k}') + f(p) + \bar{f}(p') \leftrightarrow 0$
	$E_{\bar{\nu},--} = \bar{f}(1-\bar{f}') + \bar{f}'_\nu(\bar{f}'-\bar{f})$	$\nu_a(k) + \bar{\nu}_a(\bar{k}') + \bar{f}(p') \leftrightarrow \bar{f}(p)$

The quantities that enter in the formula for Γ are then,

I_i → Momentum and distribution function dependent integrals, evaluated under different background conditions: R, NR, ND, D etc.

$$n \cdot \left(V_i^{(Z,f)}(\kappa, \vec{\kappa})\right)_{ba} = -4K_{ba}^{(Z)} \Big\{ -m_f^2(a_f^2 - b_f^2)(I_0^{(f)} + I_0^{(\bar{f})}) + (a_f + b_f)^2 (I_1^{(f)} + I_2^{(\bar{f})}) + (a_f - b_f)^2 (I_2^{(f)} + I_1^{(\bar{f})}) \Big\} ,$$

$$-\frac{1}{2}\Gamma^{(\nu)} = n \cdot V_i^{(W)}(\kappa, \vec{\kappa}) + \sum_{f=e,n,p} n \cdot V_i^{(Z,f)}(\kappa, \vec{\kappa}) ,$$

$$\Gamma_{ba}^{(\nu)} = \left(\frac{g^2}{2m_W^2}\right)^2 \left[\gamma_e^{(W)} \delta_{be}\delta_{ae} + \left(\sum_f \gamma_f^{(Z)}\right) \delta_{ba}\right]$$

$$\gamma_f^{(Z)} = -m_f^2(a_f^2 - b_f^2)(I_0^{(f)} + I_0^{(\bar{f})}) + (a_f + b_f)^2(I_1^{(f)} + I_2^{(\bar{f})}) + (a_f - b_f)^2(I_2^{(f)} + I_1^{(\bar{f})})$$

$$\gamma_e^{(W)} = (I_2^{(e)} + I_1^{(\bar{e})}) .$$

How (nonforward scattering, $\Gamma^{(2)}$) is related to the decoherence effect ?

$\Gamma^{(2)}$ ⟶ Coming from the 2-loop neutrino Self-energy

- Damping matrix arises from nonforward scattering processes, not from the decay process. The Initial neutrino state is depleted but does not disappear and we argue that the damping matrix should be associated with the decoherence effects in terms of the Linblad Equation (Master Equation).

$$i\partial_t\rho = -i[H_r, \rho] + \sum_n\{L_n\rho L_n^\dagger - \frac{1}{2}L_n^\dagger L_n\rho - \frac{1}{2}\rho L_n^\dagger L_n\}$$

L_n → **Jump Operator**

Comparison with other representations

$$\frac{d\rho}{dt} = -i[H,\rho] - \mathcal{D}[\rho] \qquad \mathcal{D}[\rho] = \sum_m \left[\{\rho, D_m D_m^\dagger\} - 2D_m\rho D_m^\dagger\right]$$

- We assume that the evolution due to the damping effects expressed by $\boldsymbol{\Gamma}^{(2)}$ accompanied by a stochastic evolution that cannot be described by the coherent evolution of the state vector.
- So, $\boldsymbol{\Gamma}^{(2)}$ must be expressed in terms of the Jump operator L_n.

Consider the evoluation of a state vector (wave function)

$$i\,\partial_t\phi(t) = H\phi(t)$$

$$i\frac{d\phi(t)}{dt} = \left(H_r - \frac{i\Gamma}{2}\right)\phi(t)$$

In an Interval dt, the state vector would have evolved coherently to

$$\phi_1(t+dt) \equiv (1 - iHdt)\phi$$

Norm of the vector is

$$\phi_1^\dagger\,(t+dt)\,\phi_1\,(t+dt) = 1\text{-p},$$

where **p** $\equiv \phi^\dagger\,\Gamma\phi dt$ **is the probability p that the systen has decayed (1-p survival probability) due to the coherent but non-Hermitian evolution.**

We asume: the coherent evolution is accompanied by stocastic processes that caused the system to Jump from the initial state to a set of posible states, thus causing the damping.

To define the construction, suppose $\boldsymbol{\Gamma}$ has the form

$$\boldsymbol{\Gamma = \Sigma_i L_i^\dagger L_i}$$

Then

$$\boldsymbol{p_i \equiv \phi^\dagger L_i^\dagger L_i \phi \quad ; p = dt \Sigma_i p_i}$$

Now we want to tell that the stocastic processes cause the state vector to jump to any of the normalized state vectors given by

$$\boldsymbol{\phi^{(i)} \equiv \frac{L_i \phi}{\sqrt{(\phi^\dagger L_i^\dagger L_i \phi)}} = \frac{L_i \phi}{\sqrt{p_i}}}$$

With a probability π_i *and*

$$\boldsymbol{\Sigma_i \pi_i = p}$$

Which we satisfy by assuming that

$$\boldsymbol{\pi_i = p_i dt}$$

The main assumption is that the evolution of the system, taking into account both the coherent and stocastic evolution, is described by the density matrix (in the sense that we can use it to calculate average of the quantum expection values)

$$\rho(t+dt) = \phi_1 \phi_1^\dagger + \Sigma_i \pi_i \phi^{(i)} {\phi^{(i)}}^\dagger$$
$$= (1 - iHdt)\rho\left(1 - iH^\dagger dt\right) + \Sigma_i L_i \rho L_i^\dagger$$
$$= \rho(t) - i\left[H\rho - \rho H^\dagger\right]dt + dt\Sigma_i L_i \rho L_i^\dagger$$
$$= \rho(t) - i[H_r, \rho]dt - \frac{1}{2}\{\Gamma, \rho\}dt + dt\Sigma_i L_i \rho L_i^\dagger$$

$$\boldsymbol{i\partial_t \rho = -i[H_r, \rho] + \sum_i \{L_i \rho L_i^\dagger - \frac{1}{2} L_i^\dagger L_i \rho - \frac{1}{2} \rho L_i^\dagger L_i\}}$$

Linblad Equation

$$\Gamma = L_e^{(W)\dagger} L_e^{(W)} + \sum_{f=e,n,p} L_f^{(Z)\dagger} L_f^{(Z)},$$

$$\Gamma_{ba}^{(\nu)} = \left(\frac{g^2}{2m_W^2}\right)^2 \left[\gamma_e^{(W)} \delta_{be}\delta_{ae} + \left(\sum_f \gamma_f^{(Z)}\right)\delta_{ba}\right],$$

$$L_f^{(Z)} = \left(\frac{g^2}{2m_W^2}\right)\sqrt{\gamma_f^{(Z)}}\, I,$$

$$L_e^{(W)} = \left(\frac{g^2}{2m_W^2}\right)\sqrt{\gamma_e^{(W)}}\, I_e,$$

Identity matrix

$$I_e = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

The Lindblad equation in the flavor density matrix

$$\partial_t \rho = -i[H_r, \rho] + \sum_{\substack{X=Z,W \\ f=e,n,p}} \left\{ L_f^{(X)} \rho L_f^{(X)\dagger} - \frac{1}{2} L_f^{(X)\dagger} L_f^{(X)} \rho - \frac{1}{2} \rho L_f^{(X)\dagger} L_f^{(X)} \right\} ,$$

Since $L^{(Z)}_f$ matrices are proportional to identity matrix, they drop out from the Lindblad Equstion giving

$$\partial_t \rho = -i[H_r, \rho] + D \, ,$$

$$D = 2\gamma \left\{ I_e \rho I_e - \frac{1}{2} I_e \rho - \frac{1}{2} \rho I_e \right\} ,$$

$$\gamma = \frac{1}{2} \left(\frac{g^2}{2m_W^2} \right)^2 \gamma_e^{(W)} .$$

→ **Decoherence is driven by CC interaction**

Solution of the Lindblad Equation for two generations

$$\partial_t \rho = -i[H_r, \rho] + D \,, \qquad D = 2\gamma \left\{ I_e \rho I_e - \frac{1}{2} I_e \rho - \frac{1}{2} \rho I_e \right\} \,,$$

Normalization condition $\quad \mathrm{Tr}\, \rho(0) = 1 \,.$

$$\rho(0) = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} = \frac{1}{2} (1 + \vec{\sigma} \cdot \vec{e}_3) \,,$$

$$H_r = \frac{1}{2} \vec{\sigma} \cdot \vec{h} \,, \qquad \vec{h} = \left(\frac{\Delta m_{21}^2}{2\kappa} \sin 2\theta, \; 0, \; -\frac{\Delta m_{21}^2}{2\kappa} \cos 2\theta + V_e \right) \,.$$

Parametrization of the density matrix

$$\rho = \frac{1}{2} \left(\sigma_0 \rho_0 + \vec{\sigma} \cdot \vec{\rho} \right) \,,$$

$$\gamma_\ell = n_1^2 \gamma = \gamma \sin^2 2\theta_m \,,$$

$$\gamma_t = \frac{1}{2} (1 + n_3^2) \gamma = \frac{\gamma}{2} (1 + \cos^2 2\theta_m) \,.$$

$$\left. \begin{matrix} P_{ee} \\ P_{e\mu} \end{matrix} \right\} = \frac{1}{2} \pm \frac{1}{2} e^{-\gamma_\ell t} \pm \frac{1}{2} \left[e^{-\gamma_t t} \cos(ht) - e^{-\gamma_\ell t} \right] \sin^2 2\theta_m \,.$$

For $\gamma_{\ell,t} = 0$ they reduce to the standard decoherence-free solutions

$$h = \frac{\Delta_m^2}{2\kappa} ,$$

$$P_{ee} = 1 - \sin^2 2\theta_m \sin^2(ht/2) ,$$

$$P_{e\mu} = \sin^2 2\theta_m \sin^2(ht/2) ,$$

$$\cos 2\theta_m = -\vec{e}_3 \cdot \vec{n} = \frac{1}{\Delta_m^2} \left(\Delta m_{21}^2 \cos 2\theta - 2\kappa V_e\right) ,$$

$$\sin^2 2\theta_m = 1 - (\vec{e}_3 \cdot \vec{n})^2 = \left(\frac{\Delta m_{21}^2 \sin 2\theta}{\Delta_m^2}\right)^2 .$$

Comments:

- **This form of the equation has been used by others consider the decoherence effects, in which $\boldsymbol{D}$ is unknown and treated at a phenomenological level.**
- **In those contexts the assumption is that the decoherence terms are diagonal in the basis of the effective mass eigenstates.**
- **In our notation this translates to the statement that the $\boldsymbol{D}$ term does not mix the parallel and perpendicular components of the ρ.**
- **The decoherence term that we have calculated is diagonal in flavor space.**
- We make a correspondence with those phenomenological treatments, through γ_ℓ and γ_t .

Type of matter background and neutrino energy:

Neutrinos Energy κ

Consider **μ** -- **τ** Neutrino Oscillation parameters

$$n_e = 10^{24} n_0 \text{ cm}^{-3}.$$

Electron number density in the Earth

Intermediate $m_N > \kappa > m_e$

$\boldsymbol{\kappa}$ **=100** $\boldsymbol{\kappa_0}$ **MeV**

In this case

$$\sin 2\theta_m \simeq 1$$

$$\gamma_e^{(W)} = 7.8 \times 10^{-24} \kappa_0 n_0 \,\text{GeV}^5 \,,$$

$$\gamma_t \simeq \frac{\gamma_\ell}{2} \simeq 2.1 \times 10^{-33} \kappa_0 n_0 \,\text{GeV} \,.$$

High $\kappa > m_e, m_N$ $\boldsymbol{\kappa}$ **=100** $\boldsymbol{\kappa_0}$ **GeV**

$$\sin^2 2\theta_m \simeq 1.5 \times 10^{-3},$$

$$\gamma_e^{(W)} = 7.8 \times 10^{-21} \kappa_0 n_0 \,\text{GeV}^5 \,.$$

$$\gamma_l \simeq 6.6 \times 10^{-33} \, \kappa_0 n_0 \,\text{GeV},$$

$$\gamma_t \simeq 4.3 \times 10^{-30} \, \kappa_0 n_0 \,\text{GeV} \,.$$

From pure phenomenological fit to the DUNE gives $\gamma_\ell \sim$ 10^{-23} GeV and γ_t ~ 10^{-24} GeV

Summary:

- In this work we have considered the effects of the non-forward neutrino scattering processes on the propagation of neutrinos in a normal matter background.
- We calculated the contribution to the imaginary part of the neutrino thermal self-energy (2-loops) from the non-forward neutrino scattering processes.
- The initial neutrino state is depleted but does not actually disappear, we have argued that such processes should be associated with decoherence effects.
- More precisely, the non-forward scattering processes produce a stochastic contribution to the evolution of the system that cannot be described in terms of the coherent evolution of the state vector.

- **A precise prescription is given to determine the jump operators, as used in the context of the master or Lindblad equation (non-forward neutrino scattering contribution to the imaginary part of the neutrino self-energy).**
- **As an example, we gave explicit formulae for the decoherence terms for different background conditions.**
- **Our results indicate that the effects of the decoherence terms are not appreciable in the context of long baseline experiments.**
- **If significant decoherence effects were to be found, they would be due to non-standard contributions to the decoherence terms.**

Thank You