Neutrino oscillations unlocked

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NOW 2022, Ostuni
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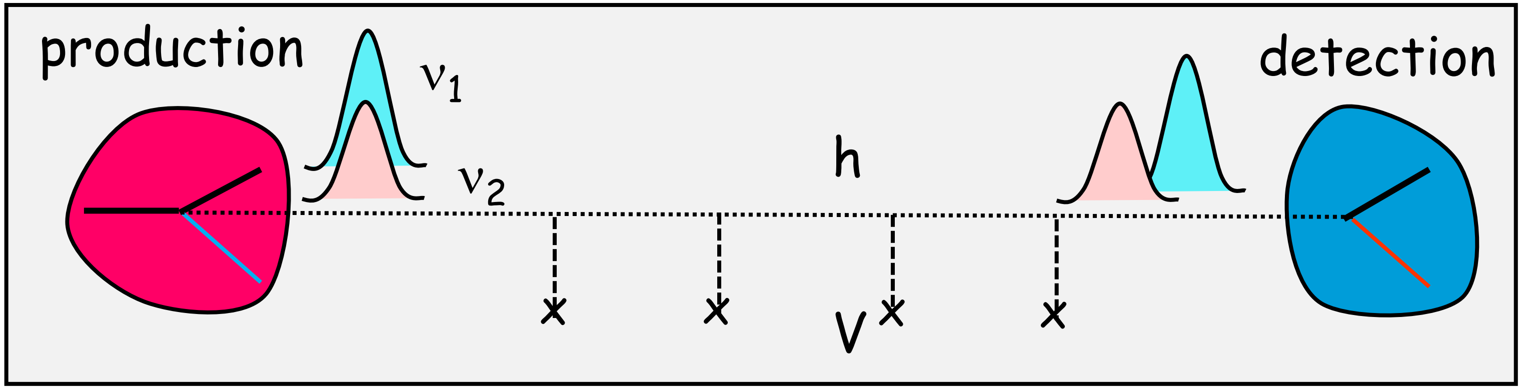
105 papers with neutrino oscillation in titles since September 2021

Oscillations in vacuum

Wave packets of the eigenstates of propagation ν_i



Entanglement with accompanying particles

Vacuum : VEV V(x,t), interactions of ν with VEV
h V → m, θ, h = h(< τ >)

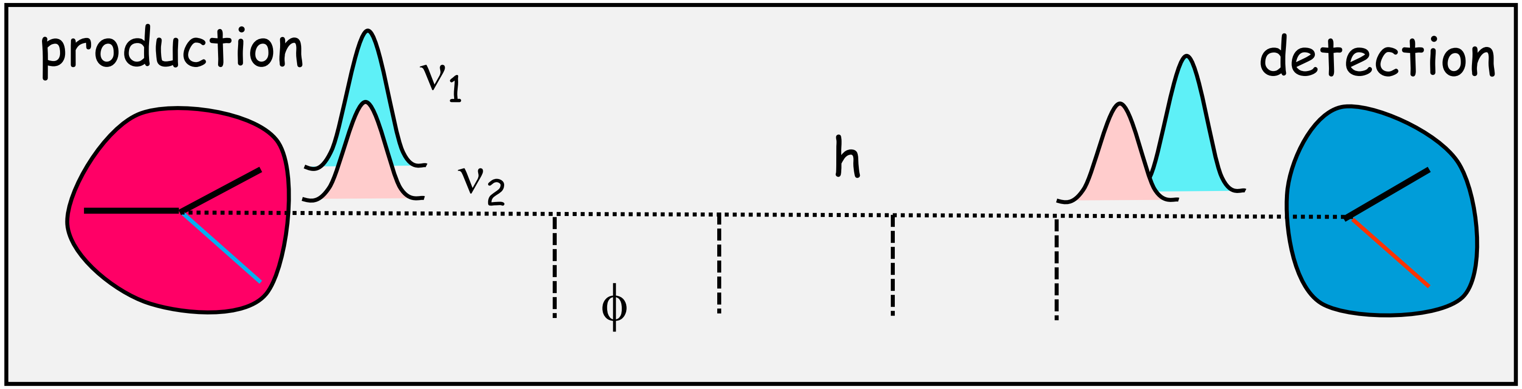
Interference: coherence at production propagation, detection

NO:

effect of propagation in space - time → Modification of geometry of x-t, metrics, GR, NO in the GW background

Quantum mechanical effect (superposition, interference) → Tests of QM, modification of QM, evolution equation..

Oscillations in media



Classical fields (e.g. magnetic fields)

Matter Particle densities

From microscopic picture: scattering on individual electrons, to macroscopic one in terms of effective potentials.

Interactions with scalar bosons (DM) $< \phi > \rightarrow \phi$

Effective mass squared $m^2 \sim n_\phi \sim z^3$ increases with decrease of t_U

Oscillating neutrino medium - treatment as open system

Content

Space-time localization diagrams

Coherence, entanglement and wave packets

Matter , vacuum and propagation

Talks on other aspects
of oscillations

B. Dasgupta,
L. Johns
M. Blasone

Space-time

Localization diagrams

Space-time localization diagram

E.Kh. Akhmedov, D. Hernandez, A.Y.S. 1201.4128 [hep-ph]

Reflects computations of oscillation amplitude in QFT, visualizes various subtle issues

Produced and propagated neutrino state

$$|\nu^P\rangle = \psi_1^P|\nu_1\rangle + \psi_2^P|\nu_2\rangle$$

where the wave packets

$\psi_i^P = \psi_i^P(x - v_i t)$ v_i - group velocities

Detected state

$$|\nu^D\rangle = \psi_1^D|\nu_1\rangle + \psi_2^D|\nu_2\rangle$$

$\psi_i^D = \psi_i^D(x - x_D, t - t_D)$ - the detection WP

Amplitude: projection of propagated state onto detection state:

For simplicity $\psi_i^D(x - x_D, t - t_D) = \delta(x - L)\, \psi_i^D(t - t_D)$ L- baseline

$$A(L, t_D) = \langle\nu^D|\nu^P\rangle = \Sigma_i \int dt\, \psi_i^{D*}(t - t_D)\, \psi_i^P(L - v_i t)$$

Space-time localization diagram

Oscillation probability

$$P(L) = \int dt_D |A(L, t_D)|^2 =$$

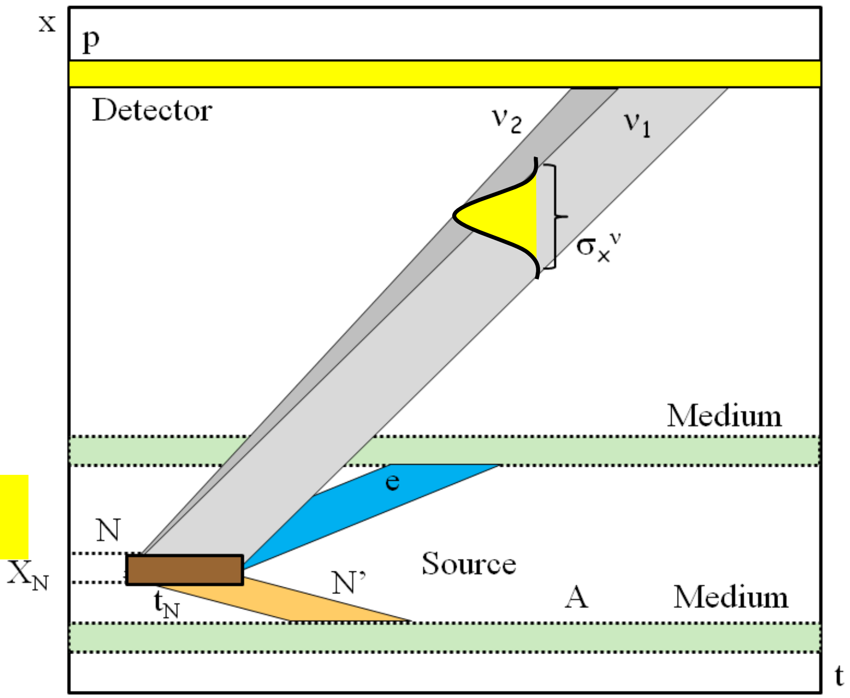
$$\int dt_D \, [|A_1(L, t_D)|^2 + |A_2(L, t_D)|^2]$$

$$+ \, 2\mathrm{Re} \int dt_D \, A_1(L, t_D)^* A_2(L, t_D)$$

interference

$$A_i(L, t_D) = \int dt \; \psi_i^{D*}(t - t_D) \; \psi_i^{P}(L - v_i t)$$

- generalized WP



Further integration over interval of baseline L due to finite sizes of the source and detector

The slopes of bands are determined by group velocities

Detection

two extreme cases

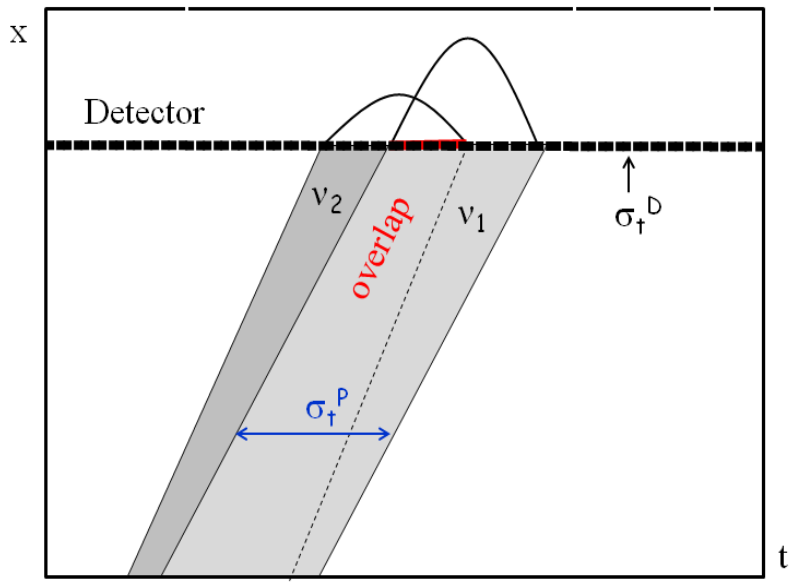
$\sigma_t^D \ll \sigma_t^P$

short detection coherence time

$\psi_i^D(t - t_D) \sim \delta(t - t_D)$

$A_i(L, t_D) \sim \psi_i^P(L - v_i t_D)$

Interference is determined by overlap of produced WP



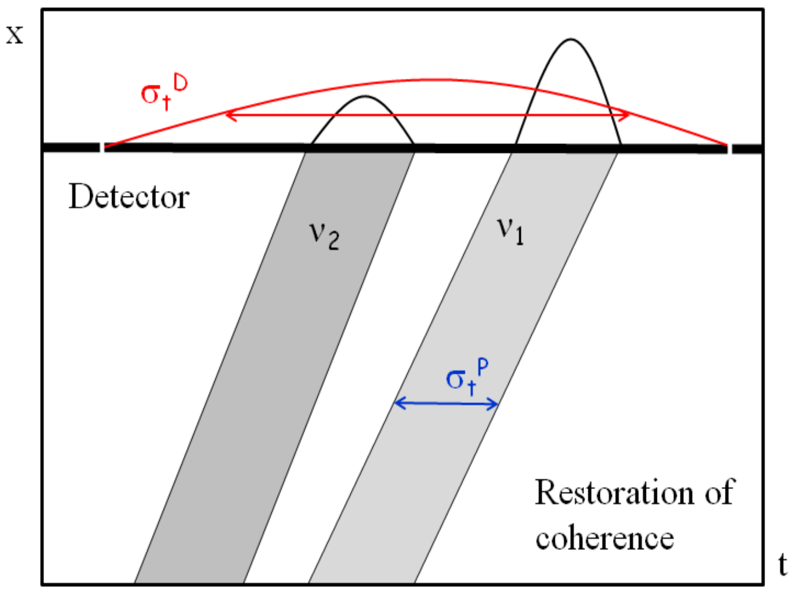
$\sigma_t^D \gg \sigma_t^P$

long detection coherence time

$A_i(L, t_D) \sim \psi_i^D(L/v - t_D)$

restoration of coherence if

$\sigma_t^D \gg t_{sep}$



Production

E.Kh. Akhmedov and A.Y.S. [hep-ph]

WP's are determined by localization region of the production process: overlap of localization regions of all particles involved but neutrinos.

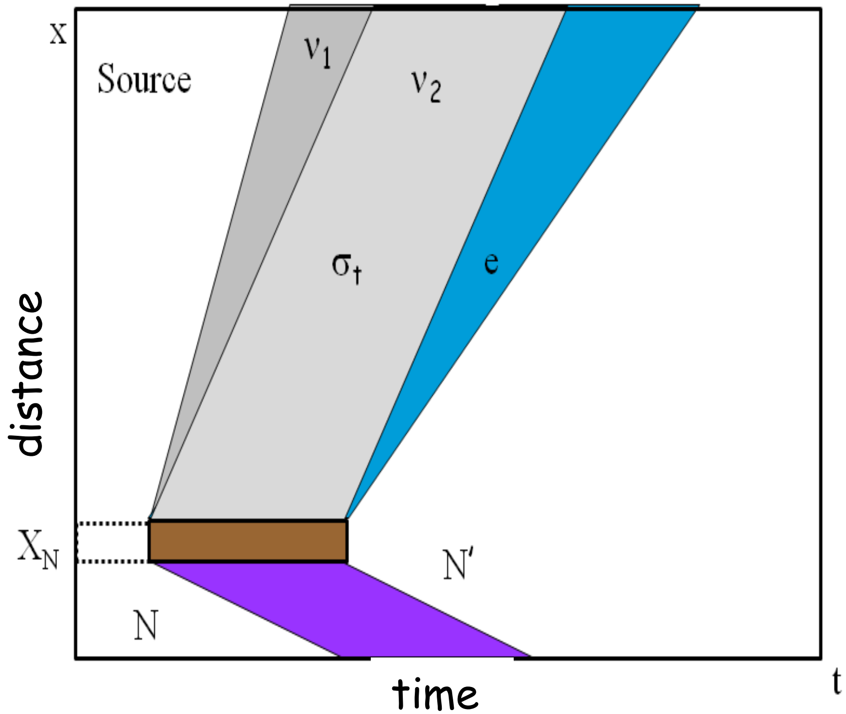
E.g. in the β decay, $N \rightarrow N' + e^- + \bar{\nu}$

If N' and e^- are not detected or their interactions can be neglected localization of process is given by localization of atom N

The latter is determined by time between two collisions of N, t_N

$\sigma_x \sim v_\nu t_N \sim X_N \, c/v_N$

enhancement factor



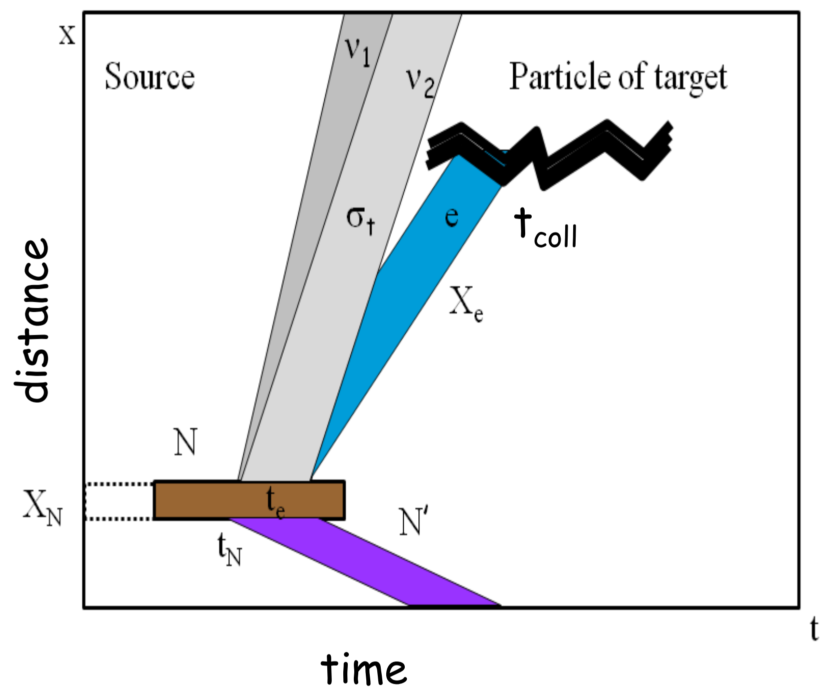
Entanglement and correlations

If N′ or/and e^- are detected or interact, this may narrow their WP's and therefore the neutrino WP.

If e^- is detected during time interval $t_e < t_N$, the size of ν WP will be determined by t_e

If e^- interacts with particles of medium which have very short time between collisions t_{coll}, then $\sigma_x \sim c t_{coll}$

Similar to the EPR paradox



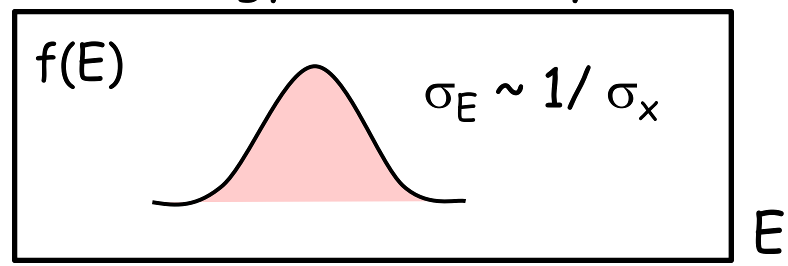
consider ν emission and interactions of e^- as unique process; contributions to its amplitude from different interactions regions appear with random phases ξ_k - incoherent $A_{tot} = A_k e^{i\xi_k}$

Propagation coherence

Observing propagation decoherence

x –t space: separation of wave packets of mass states due to difference of group velocities

equivalent to integration over the energy uncertainty



Suppression of interference → damping of oscillations

Survival probability :

$$P_{ee} = \overline{P}_{ee} + \tfrac{1}{2} D(E, L) \sin^2 2\theta \cos \phi$$

Damping factor for Gaussian WP

$$D(E, L) = \exp [- \tfrac{1}{2}(L/L_{coh})^2]$$

Coherence length

$$L_{coh} = \sigma_x \frac{E^2}{\Delta m^2}$$

Information is not lost and can be restored at detection

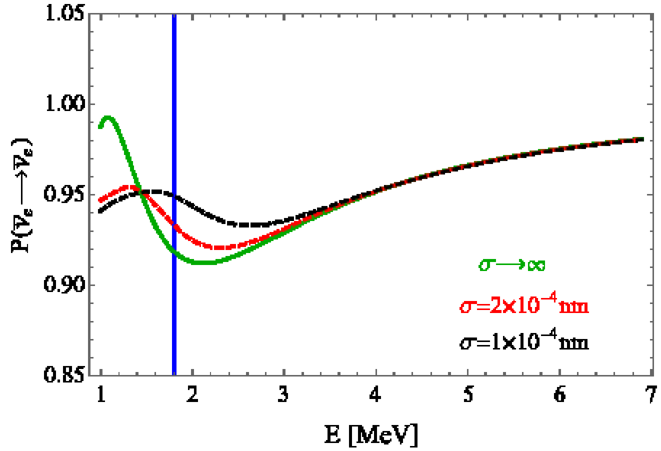
Decoherence of reactor neutrinos

A de Gouvea, V De Romeri, C.A. Termes, 2104.05806 [hep-ph]

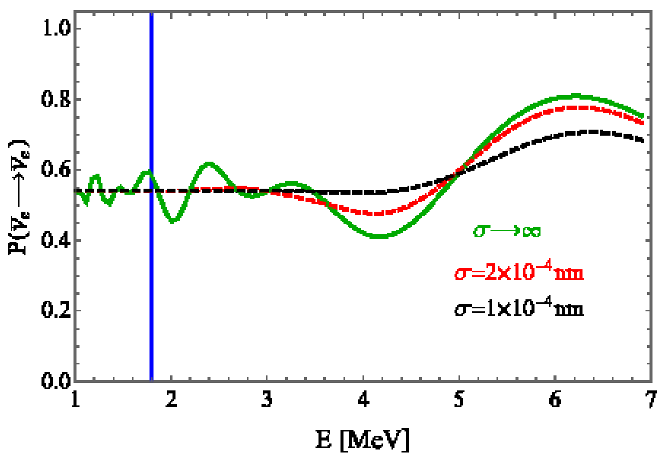
Bound on size of the WP

Expected damping effect

Daya Bay, RENO



KamLAND



Absence of decoherence (damping) effect means

$$L \ll L_{coh} \Rightarrow \sigma_x > L \frac{\Delta m^2}{2E^2}$$

Analysis of data: $\sigma_x > 2.1 \times 10^{-11}$ cm (90% C.L.)

The bound corresponds to the energy resolution of detectors δ_E

$$\sigma_x \sim 1/\delta_E$$

Other studies

Daya Bay: decoherence due to finite momentum spread σ_p

$\sigma_p / p < 0.23$ (95% C.L.)

for p = 3 MeV: $\sigma_x \sim 1/\sigma_E = 2.8 \times 10^{-11}$ cm

F.P. An, et al, 1608.01661 [hep-ex]

JUNO in future may set the limit

$\sigma_p / p < 10^{-2}$ (95% C.L.) $\rightarrow \sigma_x > 2.3 \times 10^{-10}$ cm

J. Wang et al. 2112.14450 [hep-ex]

Decoherence in oscillations active – eV scale sterile

Damping effects in various experiments computed for $\sigma_x = 2.1 \times 10^{-11}$ cm (as found in A de Gouvea et al).

C.A.Arguelles et al, 2201.05108 [hep-ph]

Claims:

- decoherence allows to reconcile BEST result with reactor bounds;
- results of analysis should be presented in two forms: with and without decoherence

Propagation decoherence and energy resolution

integration over the energy resolution of setup
– another sources of damping

E.Kh. Akhmedov and A.Y.S.
2208.03736[hep-ph]

$R(E_r, E)$ energy resolution in experimental set-up (width δ_E):
- spectrum of produced neutrinos (line), or
- energy resolution of a detector

$f(E, \bar{E})$ – WP of produced neutrino in energy representation
acts on oscillations, as R does, and can be attached to $R(E_r, E)$

Effective resolution function

$$R_{eff}(E_r, E) = \int d\bar{E}\, R(E_r, \bar{E})\, |f(E, \bar{E})|^2$$

For Gaussian f and R, R_{eff} is also Gaussian with width

$$\delta_E^2 + \sigma_E^2$$

The problem: to disentangle the two contributions

WP's of reactor neutrinos

Source: β-decays of fragments N of nuclear fission

$$N \rightarrow N' + e^- + \bar{\nu}$$

N quickly thermalise → in equilibrium with medium in the moment of decay → the average velocity:

$$v_N \sim [3T/ m_N]^{-1/2}$$

If N' and e^- are not detected or their interactions can be neglected, localization of ν production process is given by localization of N.

$$\sigma_x \sim v_\nu t_N \sim X_N\, c/v_N$$

t_N - time between two collisions of N with other atoms

$$t_N \sim [\sigma_{AA}\, n_U\, v_N]^{-1}$$

σ_{AA} geometric cross-section $\sigma_{AA} \sim \pi(2r_{vdW})^2$ Van der Waals radius

n_U - number density of Uranium

$$\sigma_x = 2.8 \times 10^{-3} \text{ cm}$$

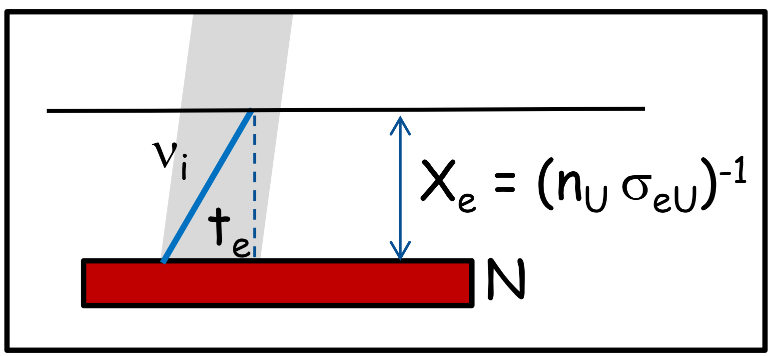
Effect of accompanying particles

Duration of ν production process is given by the shortest mean free time among particles involved

Electrons have the shortest

$\sigma_t = t_e = X_e/v_e$

X_e is determined by ionization of uranium, σ_{eU}

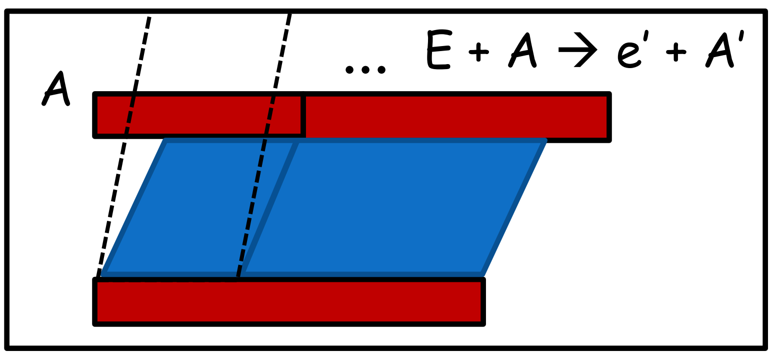


$\sigma_x = 2 \times 10^{-5}$ cm

"short cut" estimation: can be considered as the upper bound

Consideration of x-t localization of interactions of accompanying particles.

Chain of k processes of secondary interactions till equilibration (thermalization)



$\sigma_t \sim t_N / 2^k$

$\sigma_x = (5 - 10) \times 10^{-5}$ cm

Implications

1. $\sigma_x / \sigma_x^{exp} = 10^5 - 10^6$ $\sigma_x \gg \sigma_x^{exp}$

2. Corresponding energy uncertainty $\sigma_E \sim 1$ eV
   while energy resolution $\delta_E \sim 10^5$ eV

   To be sensitive to WP separation energy resolution function should be known with better that 10^{-5} accuracy

3. For Cr source: $\sigma_x = 1.4 \times 10^{-4}$ cm

4. Large Δm^2 does not help since oscillatory pattern shows up at $L \sim l_\nu$

   but $L_{coh} \sim l_\nu \sim 1/\Delta m^2$ $\rightarrow$ Δm^2 cancels in damping factor

5. If some additional damping is found, it is due to some new physics and not due to WP separation

6. Experiments with $L \sim L_{coh}$? Lower energies? Widening lines?

Comments and replies

B.J.P. Jones, 2209.00561 [hep-ph]

Three points appear to undermine that WP separation is unobservable:

Causality violation

The statement is based on figures which do not correspond to our computations

Integration in non-orthogonal basis of entangled recoil

We are not making integration over characteristics of recoil

Nuclear interactions inside nucleus measure position of initial particle (nucleon)

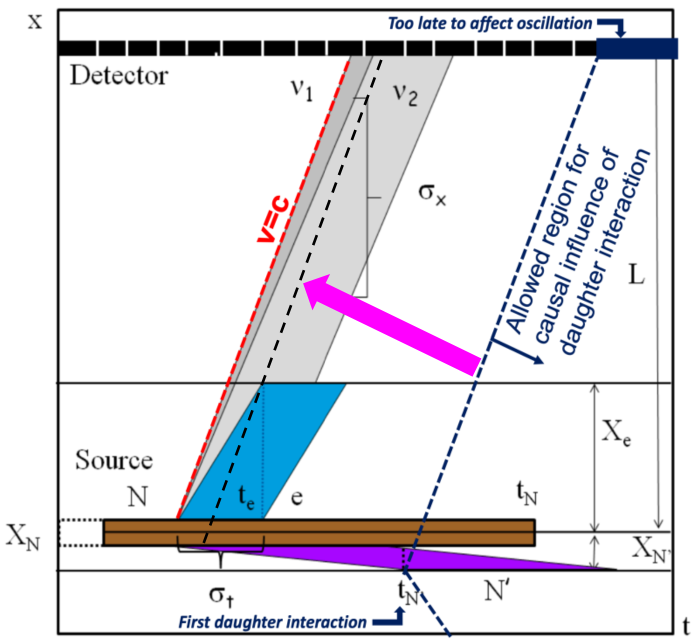
WP are determined by absolute localization of parent particle in the source i.e. wrt other atoms

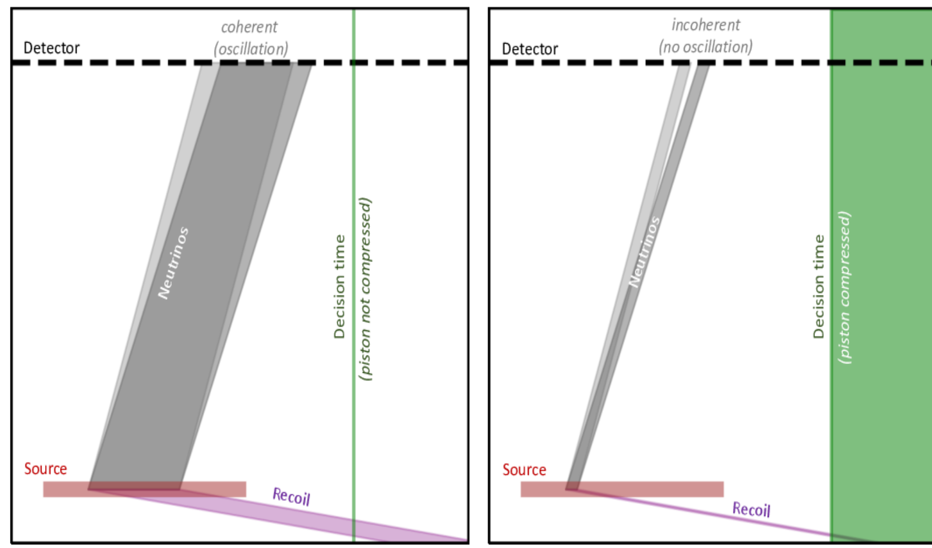
Comments

B.J.P. Jones, 2209.00561 [hep-ph]

No problem with casuality

Figs do not correspond to our estimations





Electron interaction decides
→ light cone should be constructed differently

In this setup $t_{N'} \gg t_N$ recoil does not affect WP of neutrinos which is determined by t_N

–

Matter vacuum and propagation

From micro to macro picture

From interactions with individual scatteres to effective potential (mean field approximation)

E.Kh. Akhmedov 2010.07847 [hep-ph]

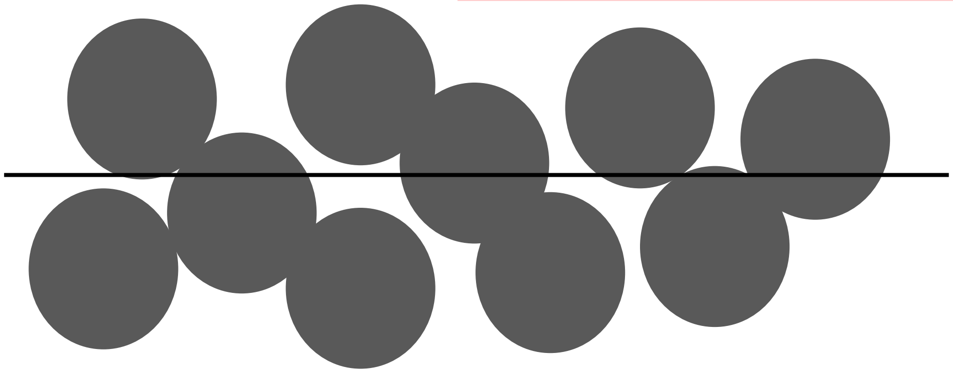
Point-like scatterers, a coarse graining – coordinate space averaging over macroscopic volumes with large number of particles

A. Y.S. , Xun-jie Xu

Summation of potentials produced by individual scatteres.

e.g., G Fantini, A.G. Rosso, F. Vissani 1802.05781

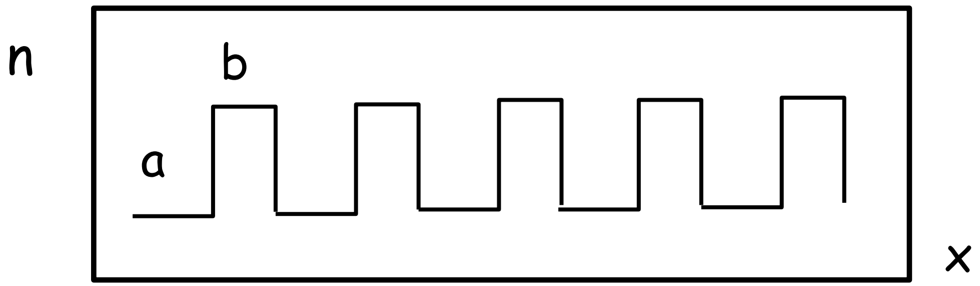
For short range interactions r_{WI}, localization of scatterers should be taken into account $X_e \gg r_{WI}$, e.g. localization of e in atom



since $\lambda_\nu \sim 1/p_\nu \ll X_e$

→ make sense to consider propagation of neutrino inside atom

Modeling with castle wall profile



$V_a \quad V_b$ Half – phases: $\phi_a \quad \phi_b$

$L_a \quad L_b$ Mixing angles: $\theta_a \quad \theta_b$

Oscillation probability

E. Kh. Akhmedov

$$P = [1 - I^2/(1 - R^2)] \sin^2 (n\,\zeta)$$

ζ = arcos R   n – number of periods

$$I = I(\phi_a, \phi_b, \theta_a, \theta_b), \quad R = R(\phi_a, \phi_b, \theta_a, \theta_b)$$

For $\phi_a \ \phi_b \ll 1$ the probability can be reduced to

$$P = \sin^2 2\theta_m(\bar{V}) \ \sin^2 \tfrac{1}{2}\phi(\bar{V})$$

$$\bar{V} = \frac{V_a L_a + V_b L_b}{L_a + L_b}$$ - averaged potential

WP's and non-adiabatic evolution

Partially ionized atoms as the electron density perturbations

Number density profile of electrons in atom (O, C, He) is non adiabatic

M. Kusakabe
2109.11942 [hep- ph]

Interplay of non-adiabatic evolution and separation (relative shift) of the WP's leads to new effects: additional averaging of oscillations

Applications to Supernova neutrinos

No new effects without WP separation and adiabatic evolution

No new effects for very sharp (step-like) density profile

Evolution of WP's

WP's are formed at the production (at boundaries)

$$\psi(t\ x) = \int dp\ f(p)\ \phi_p(t\ x)$$

$\phi_p(t\ x)$ - plane waves

If there is no absorption or p-dependent interactions, f(p) does not change in the process of evolution

Evolution equation $\quad i d\psi/dt - H\,\psi = 0$, $\quad$ insert $\psi(t\ x)$:

$$\int dp\ f(p)\ [i d\phi_p/dt - H\phi_p\ ] = 0$$

Superposition principle and linearity of evolution equation → solve eq for ϕ_p, then integrate over p (which takes care about WP nature)
No effects predicted in *2109.11942 [hep- ph]*

In t-x space WP can change form in the course of evolution, but integrated over time result coincides with result in E-p rep.

Y. P. Porto-Silva , A Y S
2103.10149 [hep-ph]

$\nu\nu$ - scattering → $H = H(\phi_p)$ – non-linear equation ?

Non-linear generalization of QM

T. Gherghetta A. Sherin 2208.10567 [hep-ph]

Evolution matrix

$$U(t, t_p, \nu^{(p)}(t)) = U_0(t, t_p) + \varepsilon U_1(t, t_p, \nu^{(p)}(t))$$

Standard linear evolution matrix — expansion parameter — non-linear correction

Produced state $\nu^{(p)}(t) = U(t, t_p, \nu^{(p)}) \nu^{(p)}(t_p)$

$$\nu^{(p)}(t) = \nu^{(p,0)}(t) + \varepsilon \nu^{(p,1)}(t)$$

Equation for correction $\nu^{(p,1)}(t)$ in coordinate representation:

$$i d\nu^{(1)}(t) / dt = H_0 \nu^{(1)}(t) + G(t, x, \nu^{(0)})$$ inhomogeneous term

Weinberg 5D operator → interaction with scalar → state dependent term → G

$$P = \sin^2 2\theta \left[\sin^2 \tfrac{1}{2}\phi - \frac{\varepsilon'}{4} \frac{m_1 - m_2}{m_1 + m_2} \sin\phi\right]$$

$\varepsilon' = A \varepsilon (m_1 + m_2)^2/v^2$ $\quad A = 81.5$

Correction is very small

Casual framework for non-linear QM

D E Kaplan S Rajendran
2106.10576 [hep-th]

Schrodinger equation for single particle

$$i d\nu(t, x)/dt = \left[H_0 + \varepsilon \frac{q^2}{4\pi} \int d^4x_1 \, |\nu(t_1, x_1)|^2 \, G_r(t\, x, t_1\, x_1) \right] \nu(t, x)$$

G_r - retarded Green function for scalar ϕ

q – charge, Yukawa coupling constant of ν and ϕ

$q = m_\nu / v$

Vacuum and properties of oscillations

G.Dvali , L Funcke, 1602.03191 [hep-ph]

Neutrino vacuum condensate due to gravity. Order parameter

$$\langle \Phi_{\alpha\beta} \rangle = \langle \nu_\alpha^T C \nu_\beta \rangle \sim \Lambda_G = \text{meV - 0.1 eV}$$

Cosmological phase transition at $T \sim \Lambda_G$

Neutrinos get masses $m_{\alpha\beta} \sim \langle \Phi_{\alpha\beta} \rangle$

Flavor is fixed by weak (CC) interactions and charged leptons with definite mass generated by usual Higgs field

$$m \sim U(\theta)^T \langle \Phi \rangle U(\theta)$$

$\langle \Phi \rangle = \text{diag}(\Phi_{11}, \Phi_{22}, \Phi_{33})$, mixing matrix

$T < \Lambda_G$ Relic neutrinos form bound states $\phi = (\nu_\alpha^T \nu_\beta)$ decay and annihilate into ϕ (neutrinoless Universe)

Symmetry of system SU(3)xU(1) spontaneously broken by neutrino condensate - ϕ are goldstone bosons

ϕ get small masses due explicit symmetry breaking by WI via loops

Mixing and topological defects

G.Dvali , L Funcke,
T Vachaspati
2112.02107 [hep-ph]

Symmetry breaking: $SU(3) \rightarrow Z_2 \times Z_2 \rightarrow I$ ⇒ string-wall network

global strings   domain walls

Length scale of strings ~ inter-string separation

$$\xi = 10^{14}\ \mathrm{m}\ (\lambda/a_G) \left(\frac{\Lambda_G}{1\ \mathrm{meV}}\right)^{7/2}$$

(self-coupling of string field Φ/scale factor of phase transition)

Travelling around string winds VEV $\langle\Phi\rangle$ by the SU(3) transformation:

$$\langle \Phi (\theta_S) \rangle = \omega(\theta_W)^T \langle\Phi\rangle\, \omega(\theta_W)$$

$\omega(\theta_W)$ path - O(3) transformation with angles $\theta_W = (\theta_W^{12}, \theta_W^{13}, \theta_W^{23})$.

After the path ω lepton mixing changes as $U = U(\theta)\, \omega(\theta_W)$

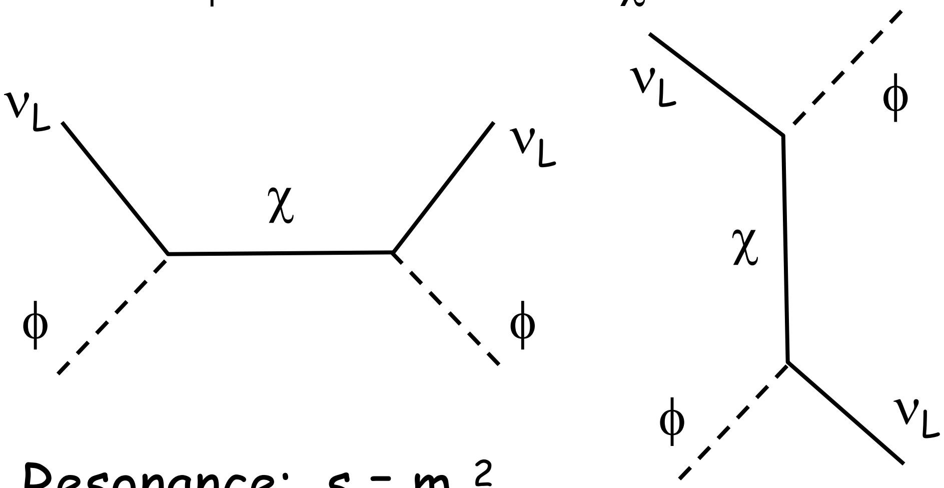
over length ξ, $\theta_W = O(1)$

Solar system moves through the frozen string-DW background with v = 230 km/sec. For 6 years (operation of Daya Bay) $d = vt = 4 \times 10^{13}$ m - comparable with expected ξ

VEV or refraction on scalar DM?

S. F Ge and H Murayama, 1904.02518 [hep-ph]
Ki-Yong Choi, Eung Jin Chun, Jongkuk Kim, 1909.10478 [hep-ph]
2012.09474 [hep-ph]

Elastic forward scattering of ν on background scalars ϕ with fermionic χ mediator



Resonance: $s = m_\chi^2$

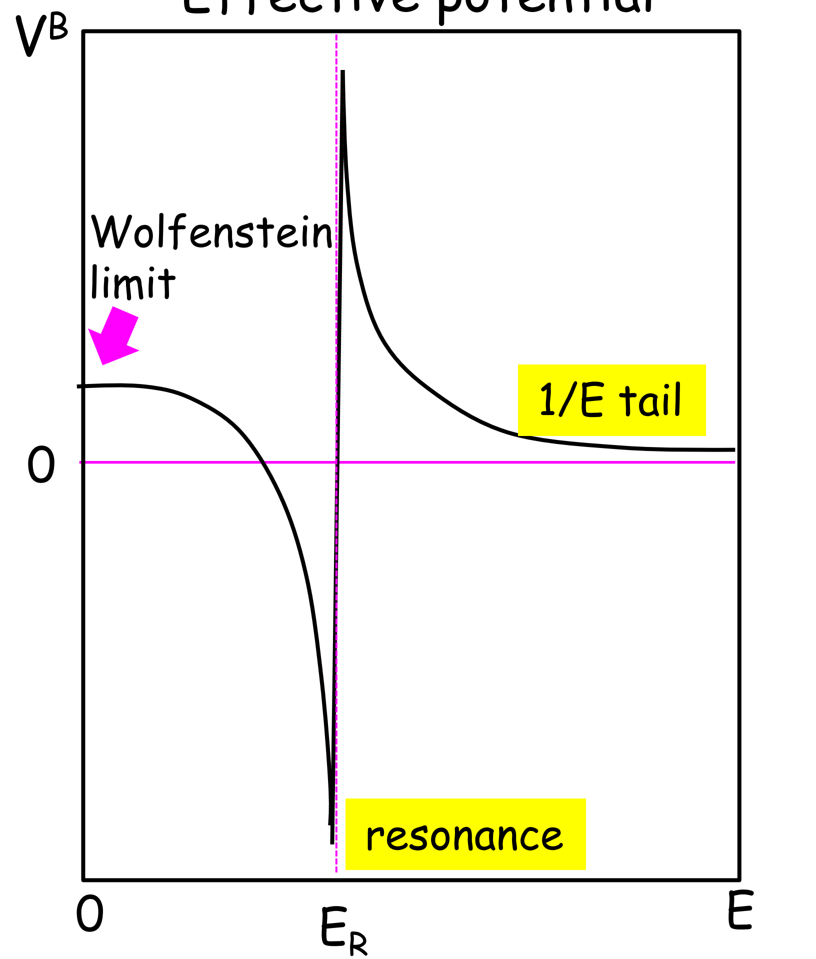
for ϕ at rest the resonance ν energy:

$$E_R = \frac{m_\chi^2}{2m_\phi}$$

For small m_ϕ resonance at low, observable energies

A.Y.S. , V. Valera, 2106.13829 [hep-ph]

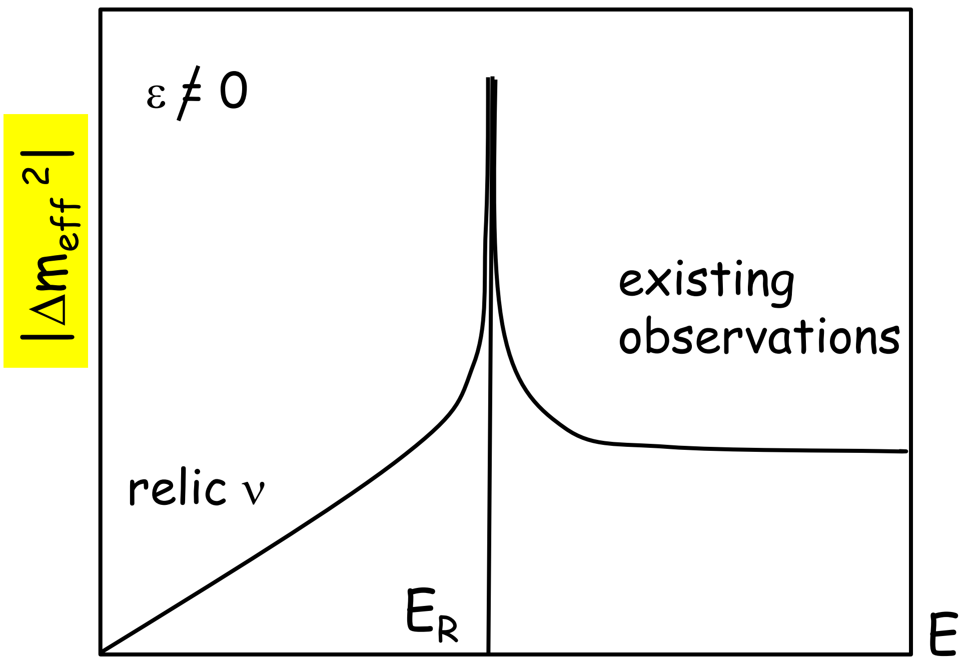
Effective potential



Effective Δm^2

$\Delta m_{eff}^2 \sim 2EV^B$

$$\Delta m_{eff}^2 \sim \frac{y^2 n_\phi}{4\, m_\chi} \begin{cases} 1, & E \gg E_R \\ \varepsilon \dfrac{E}{E_R}, & E \ll E_R \end{cases}$$



Δm_{eff}^2 = constant - checked down to 0.1 MeV

→ take $E_R \ll 0.1$ MeV

For $E_R = 0.01$ MeV:

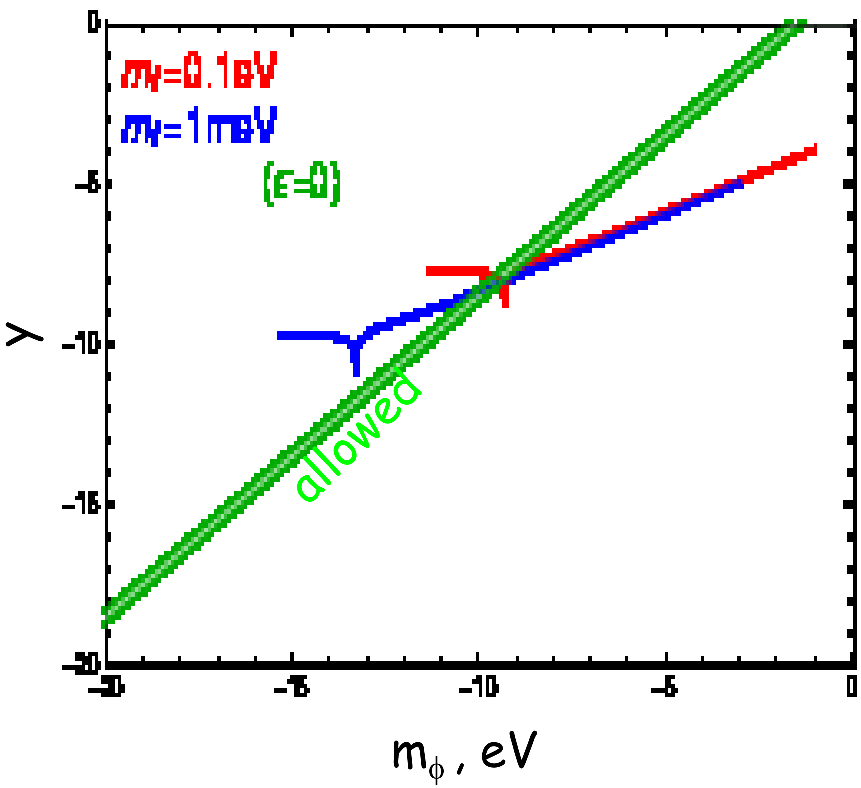
KATRIN, E ~ 1 eV: $m_{eff} < 2\ 10^{-4}$ eV - undetectable

COSMOLOGY $m_{eff}^2 \sim n_\phi \sim (1 + z)^3$ → increased in the past while VEV = const

Relic ν, $E = 10^{-4}$ eV: $m_{eff}(0) < 5\ 10^{-6}$ eV: $m_{eff}(z = 1000) \sim 0.15$ eV, no problem

Bounds on parameters

Ki-Young Choi, Eung Jin Chun, Jongkuk Kim, 2012.09474 [hep-ph]



Green band: $\Delta m_{eff}^2 = \Delta m_{atm}^2$

Upper bounds on y from scattering of neutrinos from SN1987A on DM ϕ with zero C- asymmetry and two different masses of mediator f

Similar bound from Lyα (relic neutrinos) .

Allowed values:

$m_f < 10^{-3}$ eV
$m_\phi < 10^{-10}$ eV
$y < 10^{-9}$

the corresponding resonance energy E_R = 0.01 MeV

Cosmological bound is satisfied

Summary

Space-time localization diagrams visualize (uncover) the key aspects of neutrino oscillations

Neutrino oscillations – the tool for explorations of properties of space and time, subtle aspects of QM fundamental symmetries (beyond measurements of neutrino parameters)

Effect of propagation decoherence (damping) is unobservable in the present reactor and source experiments. If some additional damping is found → due to new physics

Evolution of ν state and construction of WP in the momentum space commute → propagation decoherence is boundary (for linear case) phenomenon (as well as production and detection decoherence)

Effects of complex structure of vacuum, neutrino condensates, Non-linear generalization of QM can affect NO

Important study: search for time, space and energy Dependences of oscillation parameters.

Landscape of studies 2021- 2022

About 100 papers with “Neutrino oscillations “ in titles

Topics:

Coherence,
Entanglement in neutrino oscillations
Collective neutrino oscillations
Micro vs. macro description
Quantumness, Tests of quantum mechanics
Oscillations in modified metric, gravity
Oscillations in gravitational waves background
Mater, medium effects in presence of new interactions (long range forces, DM),
Modification of QM, evolution equation
Effects of Lorentz invariance violation,
Equivalence principle violation
Parameter symmetries

All aspects, components, characteristics of oscillations are under investigation. They can be classified as…