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Neutrinos as Tracers of Dark Matter?

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July 18, 2019
DSU 15$^{\text{th}}$ International Conference, Buenos Aires, Argentina

Content

Introduction

- Extragalactic neutrinos, produced in sources like GRBs, AGNs, SN explosions, etc, may experience flavor-oscillations and decoherence as they travel towards the Earth. Consequently, they may arrive in a pointer state completely different from the one at the moment of their creation at the source[1,2].

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- The oscillation pattern and the pointer state reached due to decoherence depend on the characteristics of the Dark Matter (DM) that is situated between the source and the Earth, and with the kind of interaction that takes place with the incoming neutrinos.

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- The oscillation pattern and the pointer state reached due to decoherence depend on the characteristics of the Dark Matter (DM) that is situated between the source and the Earth, and with the kind of interaction that takes place with the incoming neutrinos.
- From his perspective, neutrinos may be regarded as ‘DM tracers’.

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Procedure:

- Construction of the flavor states from the neutrino-mixing matrix in vacuum, starting from the eigenstates of the mass Hamiltonian H_m

[3] Smirnov, A. Y. 2005, Physica Scripta Volume T, 121, 57

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Procedure:

- Construction of the flavor states from the neutrino-mixing matrix in vacuum, starting from the eigenstates of the mass Hamiltonian H_m
- Inclusion of local interactions with DM and subsequent analysis of the resulting oscillations (MSW effect)[3,4]
- Follow-up of the time-evolution of the neutrino flavor-states and identification of the pointer states.

[3] Smirnov, A. Y. 2005, Physica Scripta Volume T, 121, 57
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Neutrinos come in three flavors: ν_e, ν_μ and ν_τ. Each flavor is a linear combination of the three mass eigenstates $|m_i\rangle$, $i = 1, 2, 3$.

$$|\nu_\alpha\rangle = \sum_i U_{\alpha\, i} \, |m_i\rangle \,, \tag{1}$$

where U is the mixing matrix[5]

$$U = \begin{bmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13}\, e^{-i\delta} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13}\, e^{i\delta} & c_{12} c_{23} - s_{12} s_{23} s_{13}\, e^{i\delta} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13}\, e^{i\delta} & -c_{12} s_{23} - s_{12} c_{23} s_{13}\, e^{i\delta} & c_{23} c_{13} \end{bmatrix}$$

[5] Bilenky, S. M. 2000, ArXiv High Energy Physics - Phenomenology e-prints

The Hamiltonian in the mass eigenbasis is

$$H_m = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix} \qquad (2)$$

and it has a diagonal form. To transform to the flavor basis (non-diagonal) we use

$$H_f = U\, H_m\, U^\dagger . \qquad (3)$$

Neutrino oscillations

Interaction potential of neutrinos with DM

$$V = \lambda \, G_F \, \frac{\rho(r)}{m_{DM}} \, \Lambda \tag{4}$$

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Neutrino oscillations
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- m_{DM}: DM mass (in units of energy)

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- $\rho(r)$: DM density distribution
- m_{DM}: DM mass (in units of energy)
- Λ: 3×3 matrix.

Isotropic

$$\rho_{\rm iso}(r) = \rho_\oplus \left(\frac{1 + (r_\oplus/r_s)^2}{1 + (r/r_s)^2} \right), \quad r_s = 5\,\mathrm{kpc} \tag{5}$$

Navarro-Frenk-White (NFW)[a]

[a] Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493

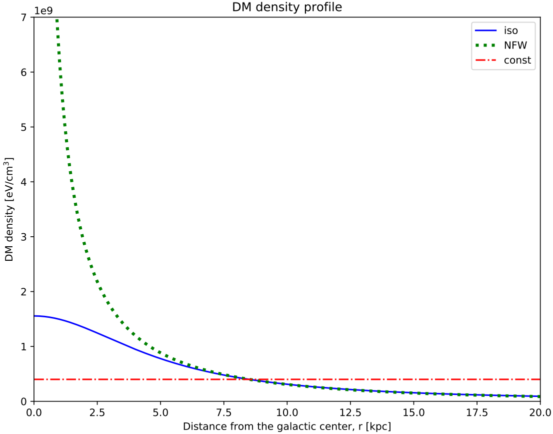
$$\rho_{\rm NFW}(r) = \rho_\oplus \left(\frac{r_\oplus}{r} \right) \left(\frac{1 + (r_\oplus/r_s)}{1 + (r/r_s)} \right)^2, \quad r_s = 20\,\mathrm{kpc} \tag{6}$$

Constant

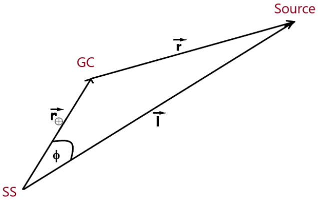
$$\rho_{\rm Const}(r) = \rho_\oplus \tag{7}$$

- $\rho_\oplus = 0.4$ GeV cm^{-3}, $r_\oplus = 8.5$ kpc

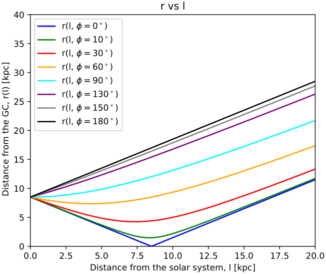
Neutrino oscillations
DM density distribution



- $\overrightarrow{r_\oplus}$ = distance from the Solar System (SS) to the Galactic Center (GC)



$$|r| = \sqrt{r_\oplus^2 + l^2 - 2\, l\, r_\oplus \cos\phi}$$



If the source is located at a distance $L_{\max}$ from the solar system, then $l = L_{\max} - ct$.

- $\overrightarrow{r_\oplus}$ = distance from the Solar System (SS) to the Galactic Center (GC)
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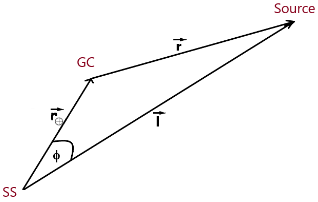

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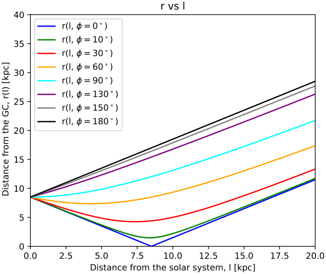

- $\overrightarrow{r_\oplus}$ = distance from the Solar System (SS) to the Galactic Center (GC)
- $\overrightarrow{l}$ = distance from the SS to the Source
- $\overrightarrow{r}$ = distance from the GC to the Source

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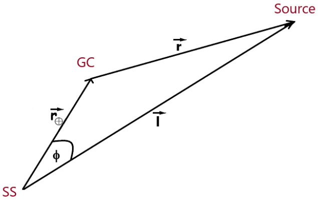
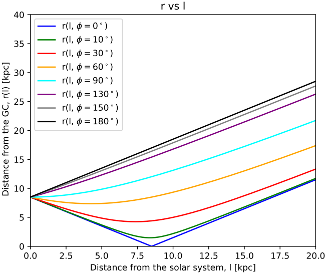


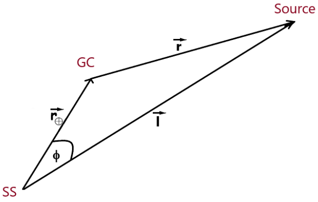


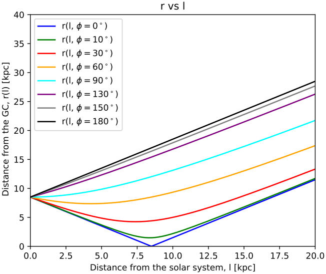
Neutrino oscillations
Distances

- $\overrightarrow{r_\oplus}$ = distance from the Solar System (SS) to the Galactic Center (GC)
- $\overrightarrow{l}$ = distance from the SS to the Source
- $\overrightarrow{r}$ = distance from the GC to the Source
- ϕ = angle between $\overrightarrow{r_\oplus}$ and $\overrightarrow{l}$

$$|r| = \sqrt{r_\oplus^2 + l^2 - 2\, l\, r_\oplus \cos\phi}$$

If the source is located at a distance $L_{\max}$ from the solar system, then $l = L_{\max} - ct$.





Neutrino oscillations in vacuum

Neutrino flavor-states (eigenstates of H_f) evolve with time according to

$$|\nu_\alpha(t)\rangle = \sum_k U_{\alpha k}(t) e^{-iE_i t/\hbar} |m_k\rangle \,, \tag{8}$$

where $E_i = \sqrt{p^2c^2 + m_i^2c^4} = pc\left(1 + \frac{m_i^2c^4}{p^2c^2}\right)^{1/2} \approx pc + \frac{m_i^2c^4}{2E}$ is the channel energy and E is the energy of the flavor state. If $\delta_k^2(t) \equiv \frac{m_k^2c^4t}{2E\hbar}$, we have

$$|\nu_\alpha(t)\rangle = e^{-ipct/\hbar} e^{-i\delta_1^2(t)} \sum_k U_{\alpha k} e^{-i(\delta_k^2(t) - \delta_1^2(t))} |m_k\rangle \,. \tag{9}$$

Transition from flavor α at $t = 0$ to flavor β at time t (α, $\beta =$e$, \mu, \tau$)

Transition ($\alpha \neq \beta$)/ survival ($\alpha = \beta$) amplitudes

$$A_{\alpha\beta}(t) = \langle \nu_\beta(t) | \nu_\alpha(0) \rangle = e^{i\delta_1^2(t)} \sum_k U_{\alpha k} U^*_{\beta k} e^{i(\delta_k^2(t) - \delta_1^2(t))}. \qquad (10)$$

Transition ($\alpha \neq \beta$)/ survival ($\alpha = \beta$) probabilities

$$\begin{aligned} P_{\alpha\beta}(t) &= |A_{\alpha\beta}(t)|^2 = (\mathrm{Re}\,\mathrm{A}_{\alpha\beta}(\mathrm{t}))^2 + (\mathrm{Im}\,\mathrm{A}_{\alpha\beta}(\mathrm{t}))^2 \\ &= \sum_{kk'} U_{\alpha k} U^*_{\beta k} U^*_{\alpha k'} U_{\beta k'} \cos(\delta^2_{\mathrm{k}}(\mathrm{t}) - \delta^2_{\mathrm{k}'}(\mathrm{t})), \end{aligned} \qquad (11)$$

Neutrino oscillations in a DM environment

We obtain the flavor-transition probabilities by diagonalizing the new Hamiltonian[6]

$$H = H_f + V(l, \phi). \tag{12}$$

For $E >> m_i c^2$ we write the mass Hamiltonian in the form

$$H_m = \frac{1}{2E_\nu} \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{12}^2 & 0 \\ 0 & 0 & \Delta m_{13}^2 \end{bmatrix}, \tag{13}$$

where $\Delta m_{1j}^2 = (m_j^2 - m_1^2)c^4$ are squared mass differences and E_ν is the neutrino energy.

[6] de Salas, P. F., Lineros, R. A., & Tórtola, M. 2016, Phys. Rev. D, 94, 123001

- A neutrino is created at the source in the electron flavor, ν_e.
  $H(t_0) = H_f + V(L_{max}, \phi)$

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- Diagonalize and transform back to the mass basis:
  $H'_m = WH(t_0)W^{-1} \neq H_m$

Neutrino oscillations in a DM environment

Iterative procedure

- A neutrino is created at the source in the electron flavor, ν_e.
  $H(t_0) = H_f + V(L_{max}, \phi)$
- Diagonalize and transform back to the mass basis:
  $H'_m = WH(t_0)W^{-1} \neq H_m$
- At time $\Delta t = \Delta l/c$, the new Hamiltonian becomes
  $H(t_0 + \Delta t) = H(t_0) + V(L_{max} - \Delta l, \phi)$.

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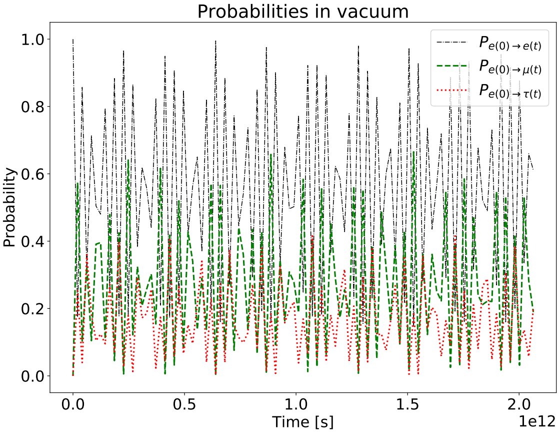
- By applying this procedure recursively we will obtain a Hamiltonian at Earth that will keep memory of the distribution of DM along the neutrino path, and an oscillation pattern that is entirely dependent on the value of the effective potential at each point along the trajectory.

Results

We calculated the survival ($\nu_e \to \nu_e$) and disappearance ($\nu_e \to \nu_{\mu(\tau)}$) probabilities under the following assumptions:

- $L_{\mathrm{max}} = 20$ kpc
- Distance between the Earth and the Sun ($\approx 4.86 \times 10^{-9}$ kpc) negligible as compared with $r_{\oplus}$
- Emission of $E_\nu = 1$ TeV electron-neutrinos from the source at $t = 0$
- $\phi = 0$
- Normal-Hierarchy (NH) for the initial mass-eigenstates

Results
Oscillations in vacuum



Unknown parameters:

- mass of the DM particles, m_{DM}
- DM density profile $\rho(r)$
- Texture of the matrix Λ
- Value of the dimensionless parameter λ which renormalises the Fermi constant.

Cases a), b), c): $m_{DM} = 1$ eV, $\lambda = 10^{15}$, $\rho(r) = \rho_{\oplus}$,

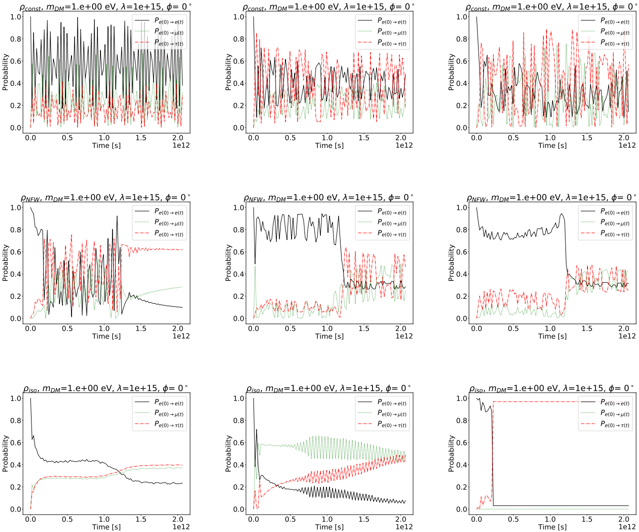
$$\Lambda_{(a,b,c)} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}, \text{and } \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

Cases d), e), f): $m_{DM} = 1$ eV, $\lambda = 10^{15}$, $\rho_{\mathrm{NFW}}(r)$,

$$\Lambda_{(d,e,f)} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix}, \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix}, \text{and } \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

Cases g), h), i): $m_{DM} = 1$ eV, $\lambda = 10^{15}$, $\rho_{\mathrm{iso}}(r)$,

$$\Lambda_{(g,h,i)} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & -1 & 0 \end{bmatrix}, \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}, \text{and } \begin{bmatrix} -1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix}.$$



ρ_{const}, m_{DM}=1.e+00 eV, λ=1e+15, ϕ= 0°
ρ_{NFW}, m_{DM}=1.e+00 eV, λ=1e+15, ϕ= 0°
ρ_{iso}, m_{DM}=1.e+00 eV, λ=1e+15, ϕ= 0°
$P_{e(0)\to e(t)}$
$P_{e(0)\to \mu(t)}$
$P_{e(0)\to \tau(t)}$
Probability
Time [s]
1e12

a), b), c)

d), e), f)

g), h), i)

Discussion

- $\Lambda_{(a)}$ introduces a dependence of the mass eigenstates upon the DM properties, opening the possibility for a MSW effect.
- $\Lambda_{(b)}$ may partially suppress components of the neutrino density matrix of a given flavor
- $\Lambda_{(c)}$ activates all channels of the interaction.

For $\Lambda_{(a)}$ there are no noticeable effects on the oscillation pattern with respect to the case in vacuum. Instead, we notice a difference in the oscillation pattern in the cases of $\Lambda_{(b)}$ and $\Lambda_{(c)}$.

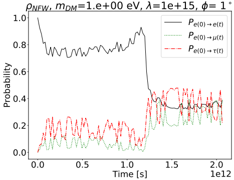
Discussion

- For the NFW DM distribution the effect of the interaction is negligible at the source but it gains importance as the neutrino travels to the detector. the local dependence of ρ_{NFW} induces huge effects when the neutrinos cross the GC at $r = 0$ around the time $t \sim 1.18 \times 10^{12}$ s.
- The non-diagonal structure of the matrix Λ for cases (d) and (f) produces a noticeable effect transforming the density matrix of the electron-neutrino from pure to mixed, thus resulting in decoherence.
- $\Lambda_{(e)}$ consists of diagonal elements, so the oscillation pattern is dominated by the MSW effect.

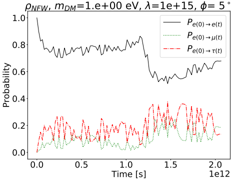
Discussion

- $\Lambda_{(g)}$ has only non-diagonal terms, so decoherence dominates over oscillations.
- $\Lambda_{(h)}$ mixed elements. This leads to a combined effect: oscillations are present with a very high frequency, but globally the three states tend to a pointer state.
- In case (i) the interaction is repulsive, leading to the suppression of the oscillations and the appearance of marked pointer states.

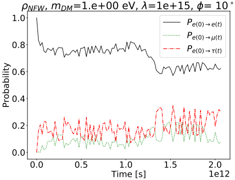
For $\phi >$ a few cents of a degree, the neutrino path does not cross the GC, which is the zone where $\rho(r)$ reaches its maximum value[7].



$\phi = 1°$



$\phi = 5°$

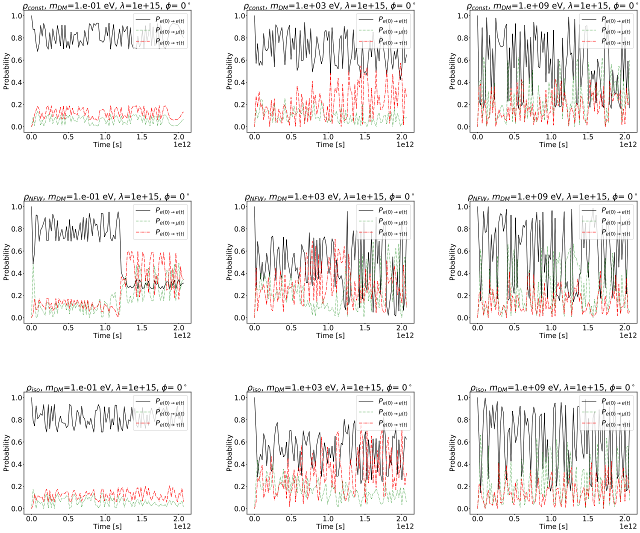


$\phi = 10°$

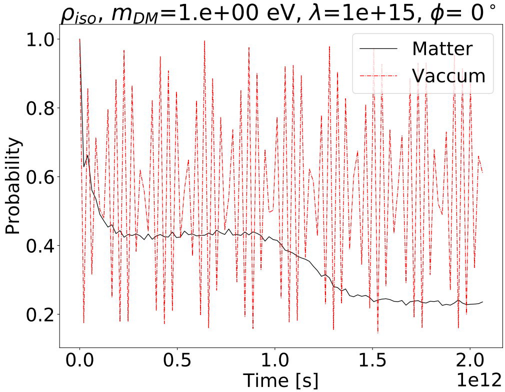
[7] The other parameters are the same as in Figure (e).

Discussion

Dependence on m_{DM} and $\rho(r)$,



Comparison between vacuum and matter



A few words about right-handed neutrinos

- Since light neutrinos have a mass, then right-handed neutrinos should be present in the electroweak Lagrangian, at the same level of the left-handed neutrinos.
- From the point of view of the SM Lagrangian to the mass term one should add left-right and right-right interactions mediated by heavier (right-handed) massive bosons.
- The masses of the right-handed bosons, as well as that of the right-handed neutrinos, could be determined either by direct measurements (LHC), or indirect ones (neutrinoless double beta decay).

The propagator

$$h_K(r_{mn}, E_k) = \frac{2}{\pi} R_{\mathrm{A}} \int dq \frac{q h_K(q^2)}{q + E_k - (E_{\mathrm{i}} + E_{\mathrm{f}})/2} j_0(q r_{mn})$$

$$M_K^{(0\nu)} = \sum_{J^\pi, k_1, k_2, J'} \sum_{pp' nn'} (-1)^{j_n + j_{p'} + J + J'} \sqrt{2J' + 1} \times \left\{ \begin{array}{ccc} j_p & j_n & J \\ j_{n'} & j_{p'} & J' \end{array} \right\}$$
$$(pp' : J' || \mathcal{O}_K || nn' : J') \times (0_f^+ || \left[c_{p'}^\dagger \tilde{c}_{n'} \right]_J || J_{k_1}^\pi) \langle J_{k_1}^\pi | J_{k_2}^\pi \rangle (J_{k_2}^\pi || \left[c_p^\dagger \tilde{c}_n \right]_J || 0_i^+)$$

$$\mathcal{O}_{\mathrm{F}} = h_{\mathrm{F}}(r, E_k) , \quad \mathcal{O}_{\mathrm{GT}} = h_{\mathrm{GT}}(r, E_k) \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 , \quad r = |\mathbf{r}_1 - \mathbf{r}_2| ,$$

Comments: transitions between structureless nucleons, momentum cut-off dependent, renormalization effects upon g_A

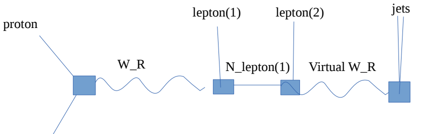
RL currents from LHC

$$h_{\mathrm{W}} = \frac{G}{\sqrt{2}} \cos\theta_{\mathrm{CKM}} \left(j_{\mathrm{L}} J_{\mathrm{L}}^{\dagger} + \eta j_{\mathrm{R}} J_{\mathrm{L}}^{\dagger} + \lambda j_{\mathrm{R}} J_{\mathrm{R}}^{\dagger} \right) + \mathrm{h.c.}\ ,$$

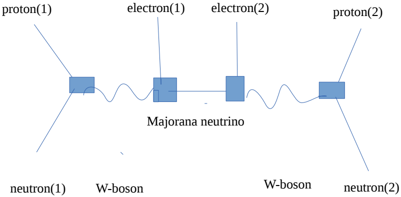
$$\begin{aligned} \mathrm{W_L} &= \mathrm{W_1} \cos\zeta - \mathrm{W_2} \sin\zeta \\ \mathrm{W_R} &= \mathrm{W_1} \sin\zeta + \mathrm{W_2} \cos\zeta \end{aligned}$$

$$\begin{aligned} \left[T_{1/2}^{(0\nu)} \right]^{-1} &= C_{mm}^{(0\nu)} \left(\frac{\langle m_\nu \rangle}{m_{\mathrm{e}}} \right)^2 + C_{m\lambda}^{(0\nu)} \langle \lambda \rangle \left(\frac{\langle m_\nu \rangle}{m_{\mathrm{e}}} \right) \\ &+ C_{m\eta}^{(0\nu)} \langle \eta \rangle \left(\frac{\langle m_\nu \rangle}{m_{\mathrm{e}}} \right) + C_{\lambda\lambda}^{(0\nu)} \langle \lambda \rangle^2 \\ &+ C_{\eta\eta}^{(0\nu)} \langle \eta \rangle^2 + C_{\lambda\eta}^{(0\nu)} \langle \eta \rangle \langle \lambda \rangle \end{aligned}$$

Diagrams

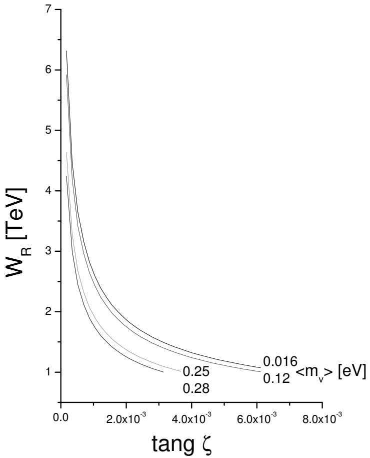


proton-proton to W_R to lepton+neutrino to two leptons+virtual W_R to two-leptons and quark-antiquark pairs.

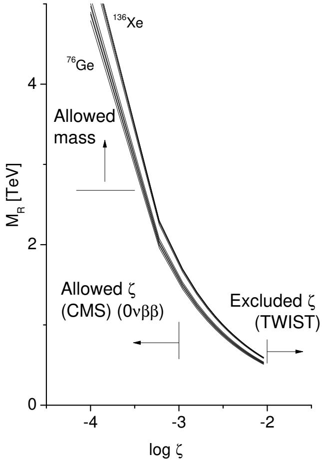


Neutrinoless double beta decay with LL , LR and RR interactions

Dependence on the neutrino mass



Mass of the right-handed boson



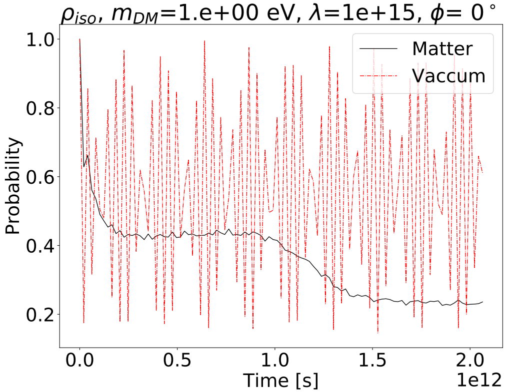
Some remarks

- Our results show that a mass $\mathrm{M_R}$ of the order of 3 TeV, for the right handed boson, and a mixing angle ζ of the order of 10^{-3}, are compatible with the measured $0\nu\beta\beta$ half-life limits and with the extracted upper limit of the average neutrino mass. These values may be ultimately explored at large by the three $0\nu\beta\beta$ experiments, in conjunction with the ATLAS and CMS measurements.

Conclusions

- In this work we have explored the effects of the interactions of neutrinos emitted from a distant source with a background of DM.
- ν-flavor survival (disappearance) probabilities are sensitive to the parameters associated with the ν-DM interactions, either showing signals of the occurrence of the MSW effect or letting the ν-flavor states evolve to pointer states due to the onset of decoherence.
- We conclude that changes in the flavor composition of neutrinos emitted in distant sources can be attributed to the presence of DM, once the emission mechanism is fixed.

Conclusions



Thank you for your attention!