COLLECTIVE NEUTRINO OSCILLATIONS ACCOUNTING FOR NEUTRINO QUANTUM DECOHERENCE

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QUANTUM DECOHERENCE IN THE NEUTRINO PHYSICS

Neutrino quantum decoherence is the effect engendered by the violation of the superposition of different neutrino states.

Experimental studies of the neutrino quantum decoherence

Reactor neutrinos

A.Capolupo,S.M.Giampaolo,G.Lambiase, Phys.Lett.B 792 (2019)298
J.A.B.Coelho, W.A.Mann, S.S.Bashar, *Phys.Rev.Lett.118* (2017)221801
Y.Farzan, T.Schwetz, A.Y.Smirnov, J. High Energy Phys. (2008) 067
G.Barenboim et al, *Nucl.Phys.B* 758 (2006) 90

Solar neutrinos

P.C. de Holanda, *JCAP 03* (2020) 012

Atmospheric neutrinos

E.Lisi, A.Marrone, D.Montanino, *Phys.Rev.Lett.85* (2000) 1166

Theoretical studies of the neutrino quantum decoherence

Matter fluctuations

C.P.Burgess, D.Michaud, *Ann. Phys.* (1997) 256
F. Benatti, R. Florianini, *Phys. Rev. D 71* (2005) 013003

Neutrino radiative decay

K. Stankevich, A. Studenikin, *Phys.Rev.D 101* (2020) 056004
K. Stankevich, A. Studenikin, *J.Phys.Conf.Ser.* 1468 (2020) 012148
K. Stankevich, A. Studenikin, *J.Phys.Conf.Ser.* 1342 (2020) 012131
K. Stankevich, A. Studenikin, *PoS ICHEP2018* (2019) 925
K. Stankevich, A. Studenikin, *PoS EPS-HEP2017* (2018) 645

Non-forward scattering

J.F.Nieves, S.Sahu, *Phys. Rev.D 100* (2019) 115049
J.F.Nieves, S.Sahu, *Phys.Rev.D 99* (2019) 095013

INFLUENCE OF THE NEUTRINO QUANTUM DECOHERENCE ON COLLECTIVE NEUTRINO OSCILLATIONS

Master equations for neutrino density matrix

$$i\frac{d\rho_f}{dt} = [H, \rho_f] + D[\rho_f]\,, \qquad i\frac{d\bar{\rho}_f}{dt} = [\bar{H}, \bar{\rho}_f] + D[\bar{\rho}_f]$$

Hamiltonian

$$H = H_{vac} + H_M + H_{\nu\nu}$$

Dissipative term (in the Lindblad form)

$$D\left[\rho_{\tilde{m}}(t)\right] = \frac{1}{2}\sum_{k=1}^{3}\left[V_k, \rho_{\tilde{m}} V_k^\dagger\right] + \left[V_k \rho_{\tilde{m}}, V_k^\dagger\right]$$

Linearized (in)stability analysis

D.Väänänen, G.McLaughlin, *Phys.Rev.D 93* (2016) 1050

Supernovae model

C.J.Stapleford et al, Phys. Rev. D 94 (2016) 093007

Stability equation

$$(\omega - i\Gamma_1)\begin{pmatrix}\rho'_{12}\\ \bar{\rho}'_{21}\end{pmatrix} = \begin{pmatrix}A_{12} & B_{12}\\ \bar{A}_{21} & \bar{B}_{21}\end{pmatrix}\begin{pmatrix}\rho'_{12}\\ \bar{\rho}'_{21}\end{pmatrix}$$

Conditions for collective neutrino oscillations (bipolar/nutations)

$$\begin{cases}(A_{12} - \bar{A}_{21})^2 + 4B_{12}\bar{B}_{21} < 0,\\ \mathcal{I}m\left((A_{12} - \bar{A}_{21})^2 + 4B_{12}\bar{B}_{21}\right) > \Gamma_1.\end{cases}$$

Elements of the stability matrix

$$A_{12} = (H^0_{11} - H^0_{22}) - \frac{\partial H_{12}}{\partial \rho_{12}}(\rho^0_{11} - \rho^0_{22}),$$
$$B_{12} = \frac{\partial H_{12}}{\partial \bar{\rho}^0_{21}}(\rho^0_{22} - \rho^0_{11}),$$
$$\bar{A}_{21} = (\bar{H}^0_{22} - \bar{H}^0_{11}) - \frac{\partial \bar{H}_{21}}{\partial \bar{\rho}_{21}}(\bar{\rho}^0_{22} - \bar{\rho}^0_{11}),$$
$$\bar{B}_{21} = \frac{\partial \bar{H}_{21}}{\partial \rho^0_{12}}(\bar{\rho}^0_{11} - \bar{\rho}^0_{22}).$$

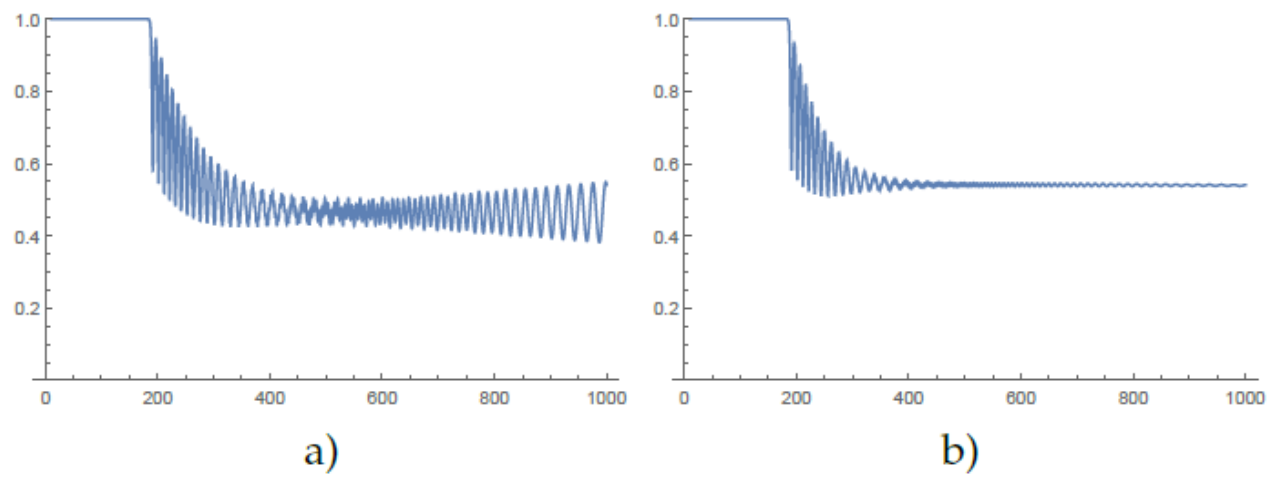

Figure 1: The survival probability of the electron neutrino in the absence of quantum decoherence (a) and for the case when the neutrino decoherence parameter is $\Gamma_1 = 10^{-21}$ GeV (b).

CONCLUSION

1) We considered for the first time the **interplay** of two effects: **neutrino quantum decoherence** and **collective neutrino oscillations**.

2) We derived **new conditions** of the existence of the **collective bipolar neutrino oscillations** that accounts the **neutrino quantum decoherence**.

3) The **importance** of the neutrino quantum decoherence studies are highlighted by new opportunities for a searching of **physics beyond the standard model** in astrophysical and terrestrial neutrino fluxes.

$0\nu\beta\beta$ in Left-right Theories with Higgs doublets and Gauge Coupling Unification

(Nucl. Phys. B951, 114875 (2020) [*arxiv* : 1809.10577])

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July 29, 2020

Motivation and Model Description

- Theoretical predictions of Standard Model match well with experimental findings so far. Though some discrepancies are there :
  - Explanation of small neutrino mass generation.
  - Parity violation in low-energy weak interactions.

  Left-Right Symmetric model (LRSM) has a unified answer for both.
- **Gauge Group** : $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$.
- **Particle Content** : $q_L \equiv (3, 2, 1, 1/3)$, $q_R \equiv (3, 1, 2, 1/3)$, $\ell_L \equiv (1, 2, 1, -1)$, $\ell_R \equiv (1, 1, 2, -1)$, $\Phi \equiv (1, 2, 2, 0)$, $H_L \equiv (1, 2, 1, 1)$, $H_R \equiv (1, 1, 2, 1)$, $\delta^+ \equiv (1, 1, 1, 2)$.

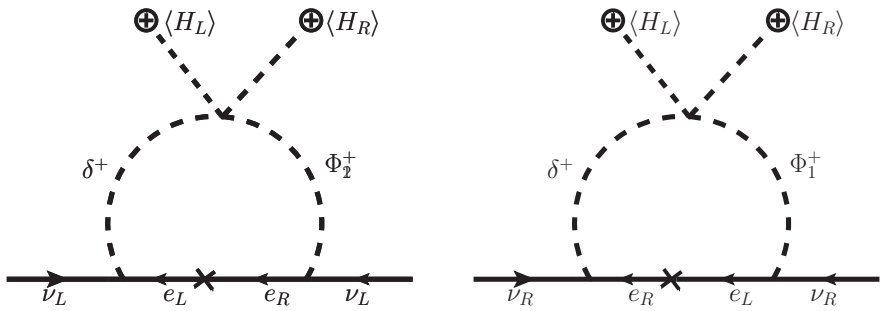
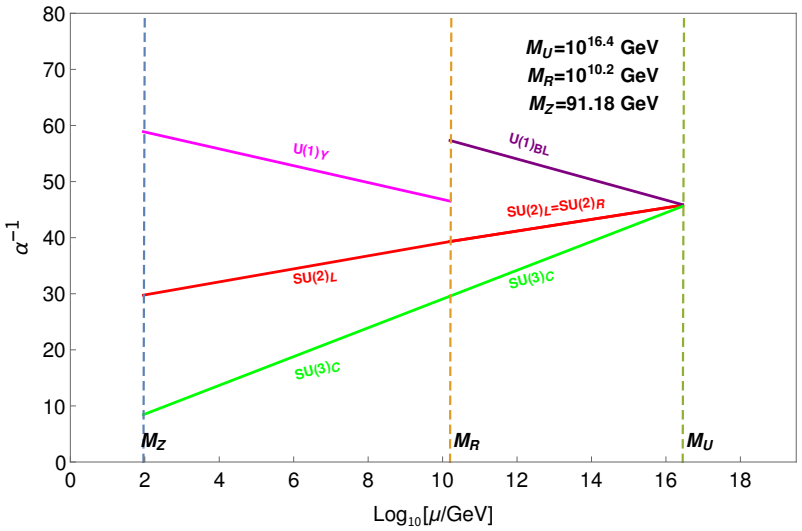


Figure: Radiative one-loop Majorana mass generation.

- $$M_{L,R}^{1-\text{loop}} \simeq \frac{\lambda' \langle H_L \rangle \langle H_R \rangle}{16\pi^2} \frac{\lambda^{L,R} M_\ell Y_\ell^T}{M^2} \mathcal{I}$$
- $$\mathcal{I} = \frac{\log\left[\frac{M_\ell^2}{M_{\delta^+}^2}\right] M_{\delta^+}^2}{M_{\delta^+}^2 - M_\ell^2} - \frac{\log\left[\frac{M_\ell^2}{M_\Phi^2}\right] M_\Phi^2}{M_\Phi^2 - M_\ell^2}$$

Gauge Coupling Unification

- We have achieved successful unification within this extended framework.



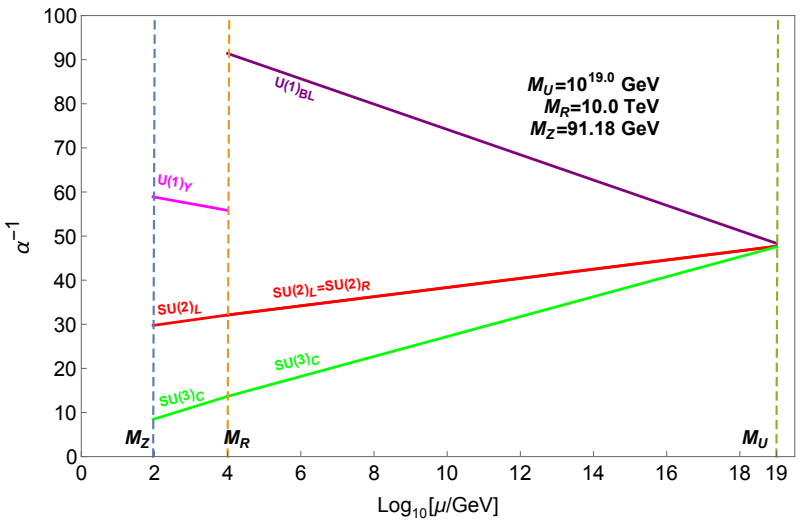


Figure: Left: Gauge Coupling unification with usual particle content of doublet LRSM described in Model Description section, LR breaking scale at about 10^{10} GeV (Out of collider reach). Right: Gauge coupling unification with extended scalar sector, now LR symmetry breaks at 10 TeV (can be easily probed in present-day collider searches).

$0\nu\beta\beta$ Signatures and Cosmological Connection

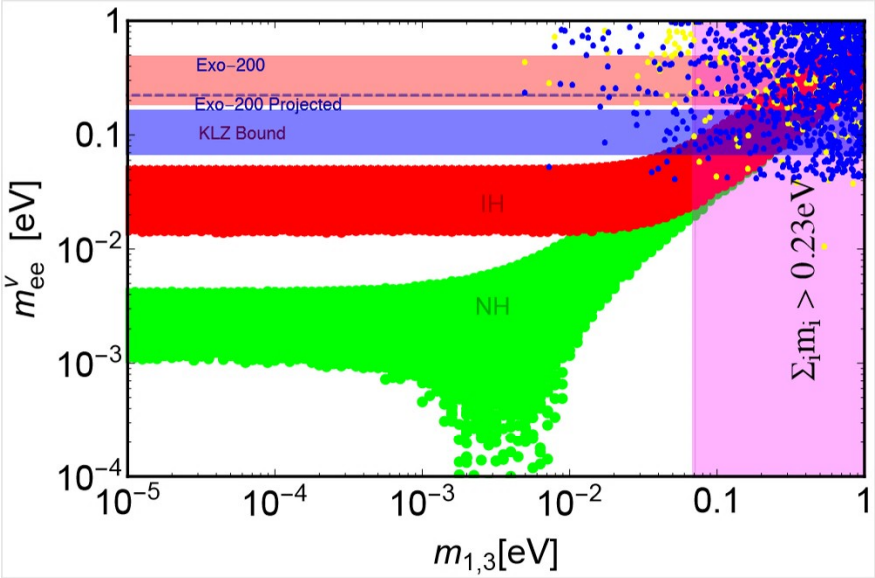


Figure: Plots for effective Majorana mass in context of $0\nu\beta\beta$ with various cosmological as well as collider constraints along this line.

- Yellow and Blue dots represent new physics contributions arising from λ and η diagrams can easily saturate current-day experimental bounds on $0\nu\beta\beta$.
- In this model we can have keV -MeV range massive right -handed neutrinos $\Rightarrow$ these can be visualised as warm DM candidate.

Thank You.

A Comparative Study of $0\nu\beta\beta$ in Symmetric and Asymmetric Left-right Model

(Nucl. Phys. B954, 115000 (2020) [*arxiv* : 2001.9488])

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Aim of the Work

- New physics contributions to neutrinoless double beta decay ($0\nu\beta\beta$) in a TeV scale LR model with spontaneous D-parity breaking.
- Comparative study for three different cases:
  - (i) for manifest symmetric left-right symmetric model ($g_L = g_R$),
  - (ii) for LR model with spontaneous D parity breaking ($g_L \neq g_R$),
  - (iii) for Pati-Salam symmetry with D parity breaking ($g_L \neq g_R$).

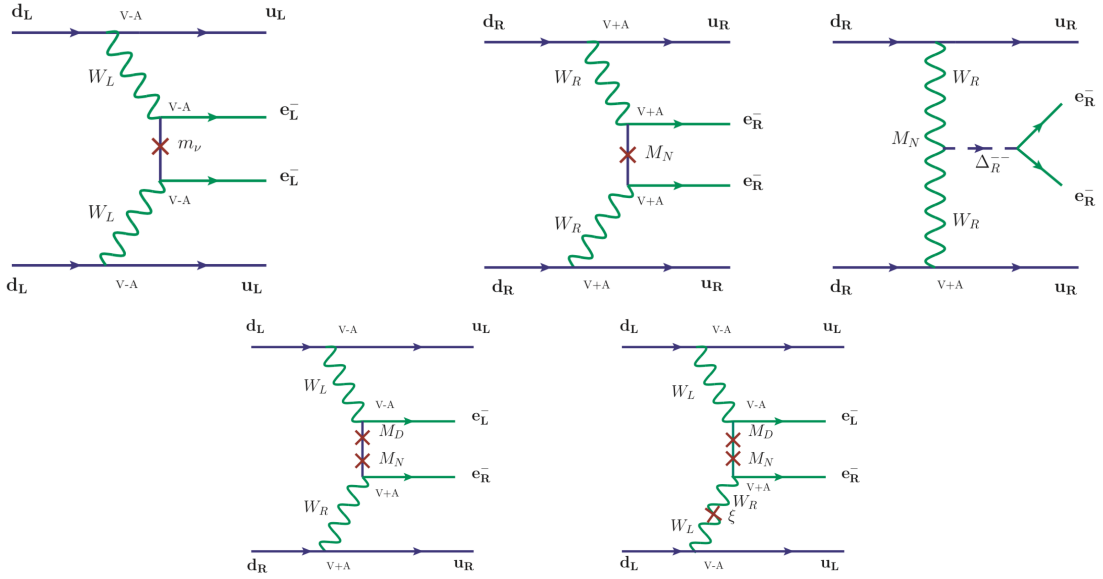

Figure: Relevant Feynman diagrams contributing to $0\nu\beta\beta$ process within the framework of left-right symmetric models.

Dependence of various parameters on $\delta \equiv \frac{g_R}{g_L}$

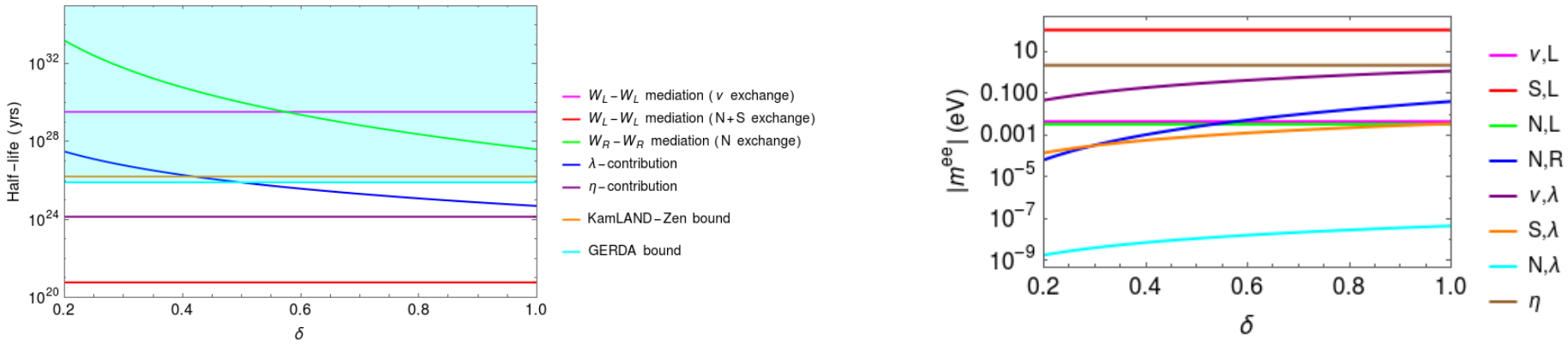

Figure: Left Panel : Dependence of half-life due to individual contribution on the ratio δ. Right Panel : Dependence of effective mass parameters arising due to individual contribution on δ.

- Cyan shaded region in left figure corresponds to allowed region for half-life permitted by GERDA experiment which is clearly saturating by various individual contributions within this framework.
- We have considered (from unification plots) $\delta = 1, 0.93, 0.62$ for symmetric LRSM, asymmetric LRSM without and with Pati-Salam symmetry respectively.

Dependence of various parameters on M_{W_R} (for different δ's)

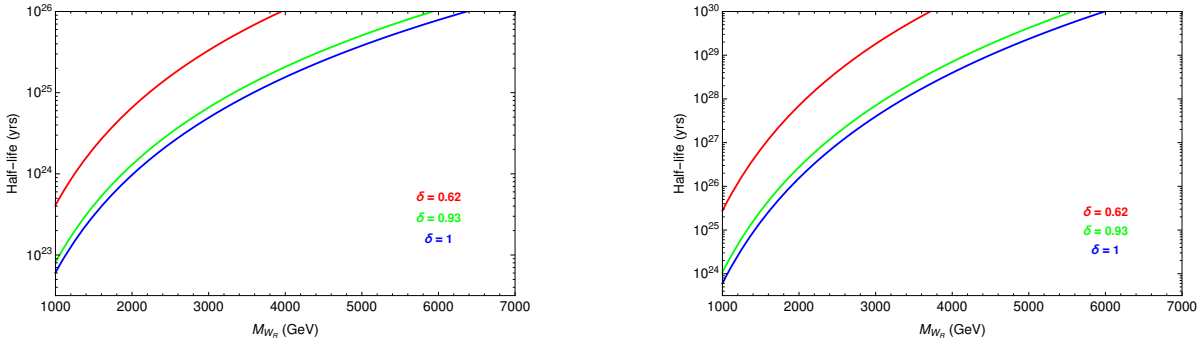

Figure: In the left panel the dependency of half-life due to λ-contribution and in the right panel the same due to RH neutrino exchange on M_{W_R} are shown.

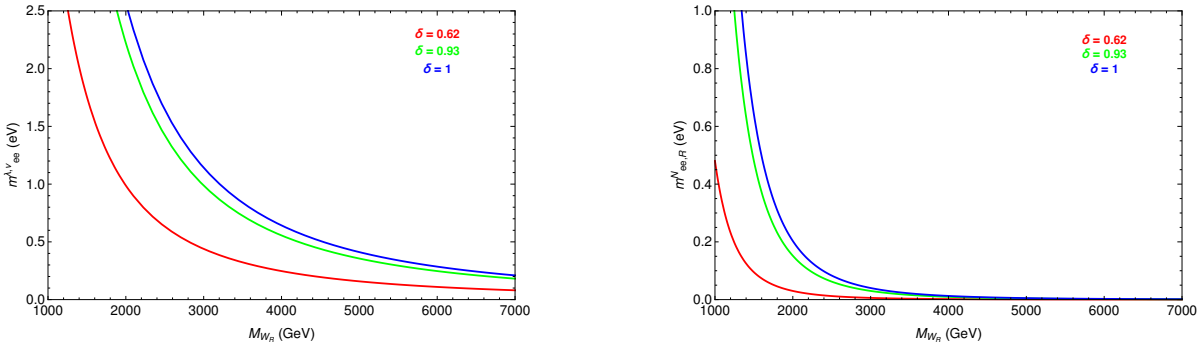

Figure: Left : Plots for effective mass parameter due to λ-diagram *vs* M_{W_R}. Right : Plots for effective mass parameter due to RH neutrino exchange *vs* M_{W_R}.

Thank You.

Electromagnetic neutrino interactions in elastic neutrino-proton scattering

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ICHEP2020
29/07/2020

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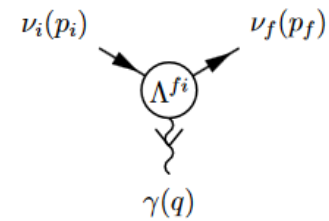
Search for neutrino electromagnetic properties

Electromagnetic properties of neutrinos are of fundamental interest

- Already in the Standard Model, neutrinos have ***charge radii*** of the order of
$$< r_\nu^2 > \sim 10^{-32}\mathrm{cm}^2$$
- The Minimally Extended Standard Model predicts a nonzero ***magnetic moment***
$$\mu_\nu = 3{,}2 \times 10^{-19} \left(\frac{m_\nu}{1\ \mathrm{eV}}\right) \mu_B$$
- Neutrinos can have other electromagnetic properties such as ***millicharge, electric and anapole moments***

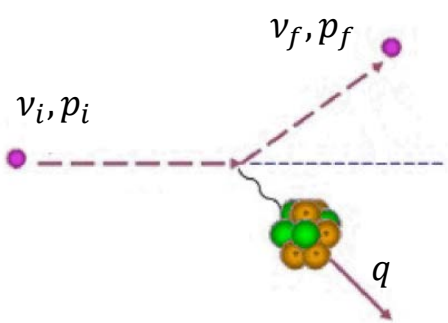


C. Giunti, A. Studenikin, Rev. Mod. Phys. **87**, 531 (2015)

$$(\Lambda_\mu(q))_{jk} = (\gamma_\mu - \frac{q_\mu \not{q}}{q^2})[(f_Q(q^2))_{jk} + \gamma_5 (f_A(q^2))_{jk} q^2] - i\sigma_{\mu\nu} q^\nu (f_M(q^2))_{jk} + \sigma_{\mu\nu} q^\nu \gamma_5 (f_E(q^2))_{jk}$$

$$f_Q^{jk}(0) = e_{jk}, \quad f_M^{jk}(0) = \mu_{jk}, \quad f_E^{jk}(0) = \epsilon_{jk}, \quad f_A^{jk}(0) = a_{jk}, \quad \langle r_\nu^2 \rangle = 6 \frac{df_Q(q^2)}{dq^2}\Big|_{q^2=0}$$

CEνNS



The neutrino electromagnetic properties can be probed with CEνNS

- In 2017 the COHERENT collaboration observed CEνNS for the first time
- The COHERENT data has already been used to obtain the bounds on neutrino millicharge, charge radii and magnetic moment
- In near future there will be a number of CEνNS experiments: CONUS, CONNIE, NU-CLEUS, MINER, CEVENS, Ricochet, TEXENO, vGEN,…
- For searching the neutrino electromagnetic properties in CEνNS experiments we need a theoretical apparatus that accounts for ALL the neutrino and nuclear form factors
- The proton is the simplest nuclear target and the elastic neutrino-proton scattering is a promising tool for detecting supernova neutrinos (JUNO yellow book arXiv:1507.05613)

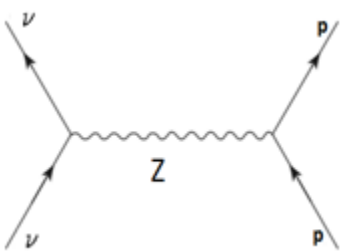
Neutrino-proton scattering

If the neutrino is born in the source in the flavor state $|\nu_\ell\rangle$, then its state in the detector is

$$|\nu_l(L)>=\sum_{k=1}^{3} U_{lk}^{*} e^{-i\frac{m_k^2}{2E}L}|\nu_k>$$

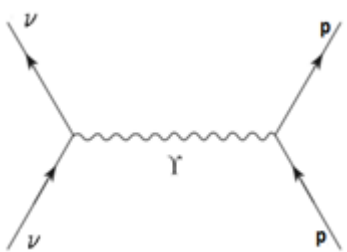
L is the source-detector distance

The amplitude of the process accounting for both the neutrino and the proton electromagnetic form factors:



$$=\frac{G_F}{\sqrt{2}}\bar{u}_{\vec{p}',s'}\left(g_V\gamma^\mu - g_A\gamma^\mu\gamma^5\right)u_{\vec{p},s}U_{lj}^{*}e^{i\frac{m_j^2}{2E}L}\bar{u}^{(j)}_{\vec{k}',\lambda'}\gamma^\mu\left(1-\gamma^5\right)u^{(j)}_{\vec{k},\lambda}$$

+



proton electromagnetic vertex

neutrino electromagnetic vertex

$$=-\frac{4\pi\alpha}{q^2}\sum_k \bar{u}_{\vec{p}',s'}\Gamma^\mu(-q)u_{\vec{p},s}U_{lk}^{*}e^{i\frac{m_k^2}{2E}L}\bar{u}^{(j)}_{\vec{k}',\lambda'}(\Lambda_\mu(q))_{jk}u^{(k)}_{\vec{k},\lambda}$$

The cross section

$$\frac{d\sigma}{dT}(\nu_L \to \nu_L) = \frac{G_F^2 m}{2\pi}\{[C_{q,Q} + 2ReC_{q,Q/A} + g_A^2] + [C_{q,Q} - 2ReC_{q,Q/A} + g_A^2](1 - \frac{T}{E})^2$$
$$+ [g_A^2 - C_{q,Q}]\frac{mT}{E^2} + \frac{T}{2m}[C_{q,M} - C_{q,E}] + \frac{T}{2m}[C_{q,M} - C_{q,E}\frac{mT}{E^2}]\}$$

These terms have not been discussed previously for CEvNS processes

$$\frac{d\sigma}{dT}(\nu_L \to \nu_R) = \frac{\pi\alpha^2}{m_e^2}|\mu_\nu^L(L,E)|^2\{(\frac{1}{T} - \frac{1}{E})|F_q|^2 - \frac{T}{2E^2}Re(F_q F_M^*) + \frac{(2 - \frac{T}{E})^2 - \frac{2mT}{E^2}}{8m}|F_M|^2 -$$
$$- \frac{(2 - \frac{T}{E})^2}{8m}|F_E|^2\}$$

This term has not been discussed previously for CEvNS processes.
It is also important in the case of neutrino-neutron scattering

$F_{Q,M,E}$ are the proton charge (Q), magnetic (M) and electric (E) form factors

The information about neutrino electromagnetic form factors is contained in the following coefficients:

$$C_{q,Q} = \sum_j |\sum_k U_{lk}^* e^{i\frac{m_k^2}{2E}L}(\delta_{jk} g_V - F_q \tilde{Q}_{jk})|^2 \qquad \tilde{Q}_{jk} = \frac{2\sqrt{2}\pi\alpha}{G_F q^2}(e_{jk} + \frac{q^2}{6}(r_L^2)_{jk}), (r_L^2)_{jk} = r_{jk}^2 - 6a_{jk}$$

$$C_{q,M} = \sum_j |\sum_k U_{lk}^* e^{i\frac{m_k^2}{2E}L}(-iF_M \tilde{Q}_{jk})|^2 \qquad C_{q,Q/A} = \sum_j \left(\sum_k U_{lk}^* e^{i\frac{m_k^2}{2E}L}(\delta_{jk} g_V - F_q \tilde{Q}_{jk})\right)\left(\sum_n U_{ln} e^{-i\frac{m_n^2}{2E}L}(-\delta_{jn} g_A)\right)$$

$$C_{q,E} = \sum_j |\sum_k U_{lk}^* e^{i\frac{m_k^2}{2E}L}(F_E \tilde{Q}_{jk})|^2 \qquad |\mu_L(L,E)|^2 = \sum_j |\sum_k U_{lk}^* e^{i\frac{m_k^2}{2E}L}(\mu_{jk} - i\epsilon_{jk})|^2$$

Interplay of neutrino flavor, spin and collective oscillations in supernovae

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and

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Poster at ICHEP-2020 (Prague)

Supported by the joint project of NSFC and RFBR

Neutrino evolution in astrophysical environment

- **Density matrix formalism for the neutrino evolution:**

$$i\frac{d\rho}{dt} = [H, \rho]$$ **with** $$H = H_{vac} + H_{mat} + H_v + H_B + H_{\nu\nu}$$

where the density matrix is for both left- and right- handed (Dirac or Majorana) neutrinos:

$$\rho = \begin{pmatrix} \rho_\nu & X \\ X^\dagger & \rho_{\bar{\nu}} \end{pmatrix}$$ **and** $$X = \begin{pmatrix} \rho_{\nu_e\bar{\nu}_e} & \rho_{\nu_e\bar{\nu}_x} \\ \rho_{\nu_x\bar{\nu}_e} & \rho_{\nu_x\bar{\nu}_x} \end{pmatrix}$$

- **The Hamiltonian H includes:**

a) vacuum oscillation term; b) isotropic matter potential

c) matter potential of moving matter; d) magnetic field term

e) neutrino self interaction potential

- **Supernova neutrino flavor conversion with a), b), e) has been intensively studied.** ***See reviews: 1001.2799, 1508.00785, etc.***

Connecting different spin components

- **Magnetic field:**

$$\gamma_\alpha^{-1} = \frac{m_\alpha}{E_\alpha}, \quad \gamma_{\alpha\beta}^{-1} = \frac{1}{2}\left(\gamma_\alpha^{-1} + \gamma_\beta^{-1}\right), \quad \tilde{\gamma}_{\alpha\beta}^{-1} = \frac{1}{2}\left(\gamma_\alpha^{-1} - \gamma_\beta^{-1}\right)$$

$$H_B^D = \begin{pmatrix} \left(\frac{\mu}{\gamma}\right)_{ee} B_{||} & \left(\frac{\mu}{\gamma}\right)_{ex} B_{||} & -\mu_{ee} B_\perp e^{i\phi} & -\mu_{ex} B_\perp e^{i\phi} \\ \left(\frac{\mu}{\gamma}\right)_{ex} B_{||} & \left(\frac{\mu}{\gamma}\right)_{xx} B_{||} & -\mu_{ex} B_\perp e^{i\phi} & -\mu_{xx} B_\perp e^{i\phi} \\ -\mu_{ee} B_\perp e^{-i\phi} & -\mu_{ex} B_\perp e^{-i\phi} & -\left(\frac{\mu}{\gamma}\right)_{ee} B_{||} & -\left(\frac{\mu}{\gamma}\right)_{ex} B_{||} \\ -\mu_{ex} B_\perp e^{-i\phi} & -\mu_{xx} B_\perp e^{-i\phi} & -\left(\frac{\mu}{\gamma}\right)_{ex} B_{||} & -\left(\frac{\mu}{\gamma}\right)_{xx} B_{||} \end{pmatrix},$$

- **Transversal matter current:**

$$\left(\frac{\eta}{\gamma}\right)_{ee} = \frac{\cos^2\theta}{\gamma_{11}} + \frac{\sin^2\theta}{\gamma_{22}}, \quad \left(\frac{\eta}{\gamma}\right)_{xx} = \frac{\sin^2\theta}{\gamma_{11}} + \frac{\cos^2\theta}{\gamma_{22}}, \quad \left(\frac{\eta}{\gamma}\right)_{ex} = \frac{\sin 2\theta}{\tilde{\gamma}_{21}}.$$

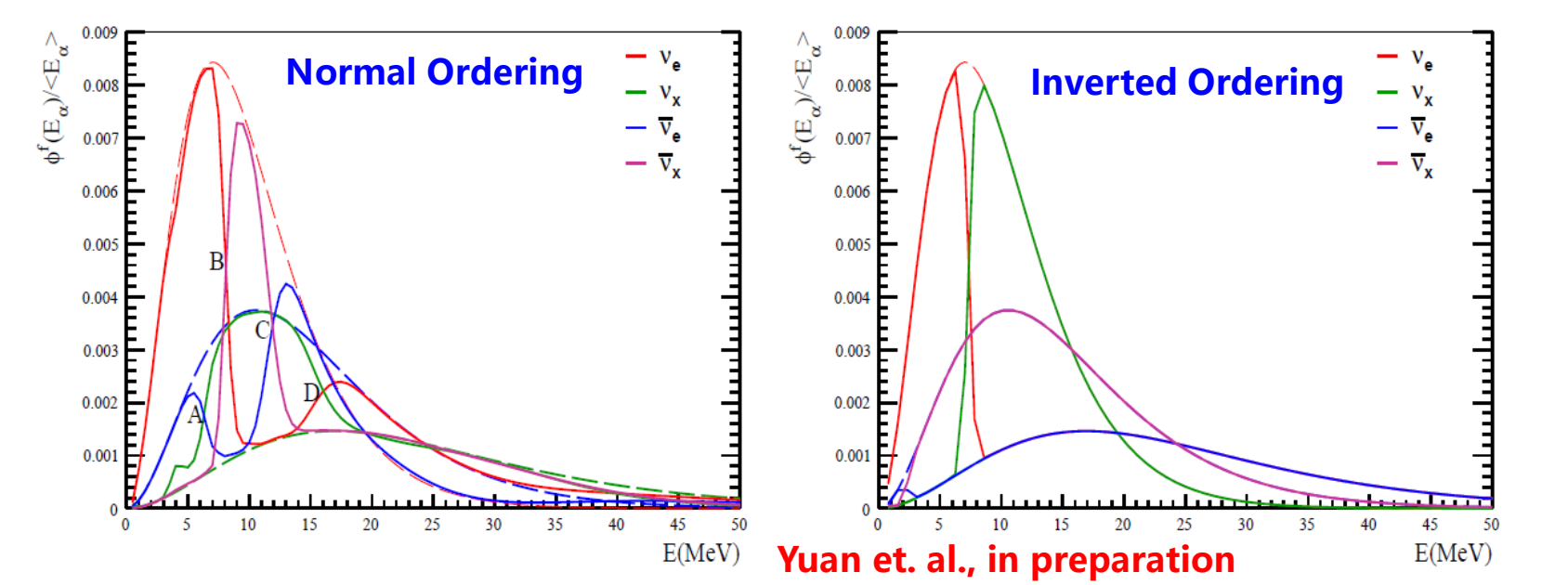
$$H_{mat}^D = \frac{G_F}{2\sqrt{2}} \begin{pmatrix} 2(2n_e - n_n)\left(1 - v_{||}\right) & 0 & (2n_e - n_n) v_\perp \left(\frac{\eta}{\gamma}\right)_{ee} & (2n_e - n_n) v_\perp \left(\frac{\eta}{\gamma}\right)_{ex} \\ 0 & -2n_n\left(1 - v_{||}\right) & -n_n v_\perp \left(\frac{\eta}{\gamma}\right)_{ex} & -n_n v_\perp \left(\frac{\eta}{\gamma}\right)_{xx} \\ (2n_e - n_n) v_\perp \left(\frac{\eta}{\gamma}\right)_{ee} & -n_n v_\perp \left(\frac{\eta}{\gamma}\right)_{ex} & 0 & 0 \\ (2n_e - n_n) v_\perp \left(\frac{\eta}{\gamma}\right)_{ex} & -n_n v_\perp \left(\frac{\eta}{\gamma}\right)_{xx} & 0 & 0 \end{pmatrix}$$

- **For the case of Majorana neutrinos, see our poster, and more discussions in** ***Phys. Atom. Nucl. 67 (2004) 993, Phys. Rev. D 98 (2018) 113009.***

Spectral splits of spin-flavor components

- **Using the neutrino bulb model and single angle approximation, the model of transversal matter current (v_T=0.067c) is from**

  Phys. Rev. D 98 (2018) 113009



Yuan et. al., in preparation

- **Magnetic field and neutrino magnetic moment can also have similar effects, see JCAP 10 (2012) 027, JCAP 04 (2013) 018**

- **Please join our Poster for more information and discussion!**

Neutrino oscillations in a magnetic field: the three-flavor case

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ICHEP 2020, PRAGUE
28 JULY - 6 AUGUST 2020

A.Popov, A. Studenikin, Eur. Phys. J. C (2019) 79:144

Supported by the Russian Foundation for Basic Research under grants No. 20-52-53022-GFEN-a

Main idea

Using equation:

Dirac equation:

$$(\gamma_\mu p^\mu - m_i - \mu_i \boldsymbol{\Sigma B})\nu_i^s(p) = 0$$

transform it:

$$\hat{H}_i \nu_i^s = E\nu_i^s$$

Where "Hamiltonian" is:

$$\hat{H}_i = \gamma_0 \boldsymbol{\gamma p} + \mu_i \gamma_0 \boldsymbol{\Sigma B} + m_i \gamma_0$$

Also we use this spin operator:

$$\hat{S}_i = \frac{m_i}{\sqrt{m_i^2 \boldsymbol{B}^2 + \boldsymbol{p}^2 B_\perp^2}} \cdot \left[\boldsymbol{\Sigma B} - \frac{i}{m_i} \gamma_0 \gamma_5 [\boldsymbol{\Sigma} \times \boldsymbol{p}] \boldsymbol{B} \right]$$

The resulting energy spectrum:

$$E_i^s = \sqrt{m_i^2 + p^2 + \mu_i{}^2 \mathbf{B}^2 + 2\mu_i s \sqrt{m_i^2 \mathbf{B}^2 + p^2 B_\perp^2}}$$

Stationary state

Spin operator commutes with hamiltonian:

$$\hat{S}_i \left|\nu_i^s\right\rangle = s \left|\nu_i^s\right\rangle, s = \pm 1, \left\langle \nu_i^s \middle| \nu_k^{s'} \right\rangle = \delta_{ik}\delta_{ss'}$$

Thus, we can build projective operator:

$$\hat{P}_i^\pm = \frac{1 \pm \hat{S}_i}{2}$$

$$\nu_i^L(t) = c_i^+ \nu_i^+(t) + c_i^- \nu_i^-(t)$$
$$\nu_i^R(t) = d_i^+ \nu_i^+(t) + d_i^- \nu_i^-(t)$$

$$|c_i^\pm|^2 = \langle \nu_i^L | \hat{P}_i^\pm | \nu_i^L \rangle$$
$$|d_i^\pm|^2 = \langle \nu_i^R | \hat{P}_i^\pm | \nu_i^R \rangle$$
$$(d_i^\pm)^* c_i^\pm = \langle \nu_i^R | P_i^\pm | \nu_i^L \rangle$$

General formulae for neutrino flavor and spin-flavor oscillations

$$P_{\nu_e^L \to \nu_i^L} = \left|\langle \nu_i^L | \nu_e^L \rangle\right|^2 = \left|\sum_{j=1}^{3} \left(|c_j^+|^2 e^{-iE_j^+ t} + |c_j^-|^2 e^{-iE_j^- t}\right) U_{1j} U_{ij}^*\right|^2$$

$$P_{\nu_e^L \to \nu_i^R} = \left|\langle \nu_i^R | \nu_e^L \rangle\right|^2 = \left|\sum_{j=1}^{3} \left(|d_j^+|^2 e^{-iE_j^+ t} + |d_j^-|^2 e^{-iE_j^- t}\right) U_{1j} U_{ij}^*\right|^2$$

Case 2-flavor example:

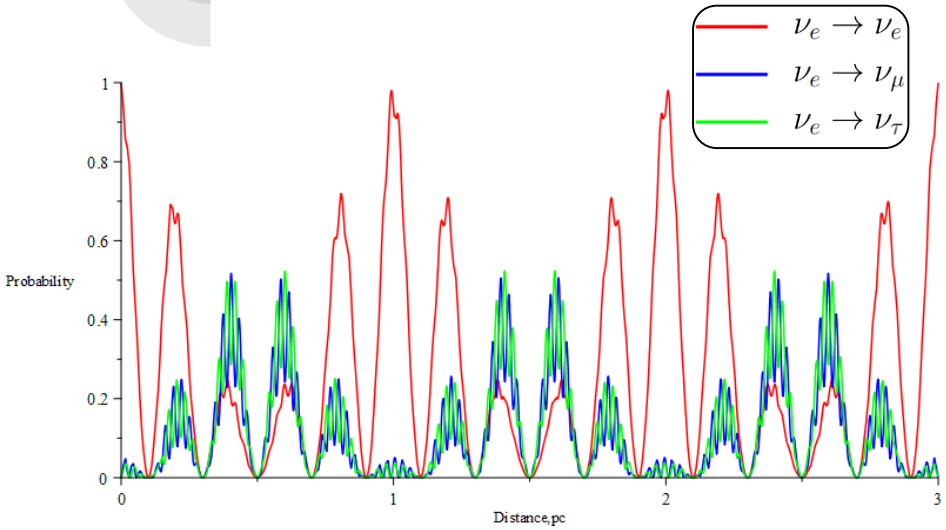
$$P_{\nu_e^L \to \nu_\mu^R} = \sin^2(\mu B_\perp t) \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4p} t$$

A.Popov, A. Studenikin, Eur. Phys. J. C (2019) 79:144

Weak field approximation:

$$E_i^s \approx p + \frac{m_i^2}{2p} + \frac{\mu_i^2 B^2}{2p} + \mu_i s B_\perp$$

Cosmic neutrino flavor oscillations



B = 2.9 μG, μ1=μ2=μ3=μ=10^(-20)μB, normal mass ordering, zero CP-phase, p=10^19 eV

Conclusions: We have confirmed that in the three-flavor neutrino case there is an inherent interplay between neutrino flavor oscillations on corresponding frequencies and neutrino spin (or spin-flavor) oscillations in the presence of a magnetic field. These phenomena should be accounted when neutrino oscillations are considered in magnetized astrophysical environments.

Astrophysical neutrino oscillations accounting for neutrino charge radii

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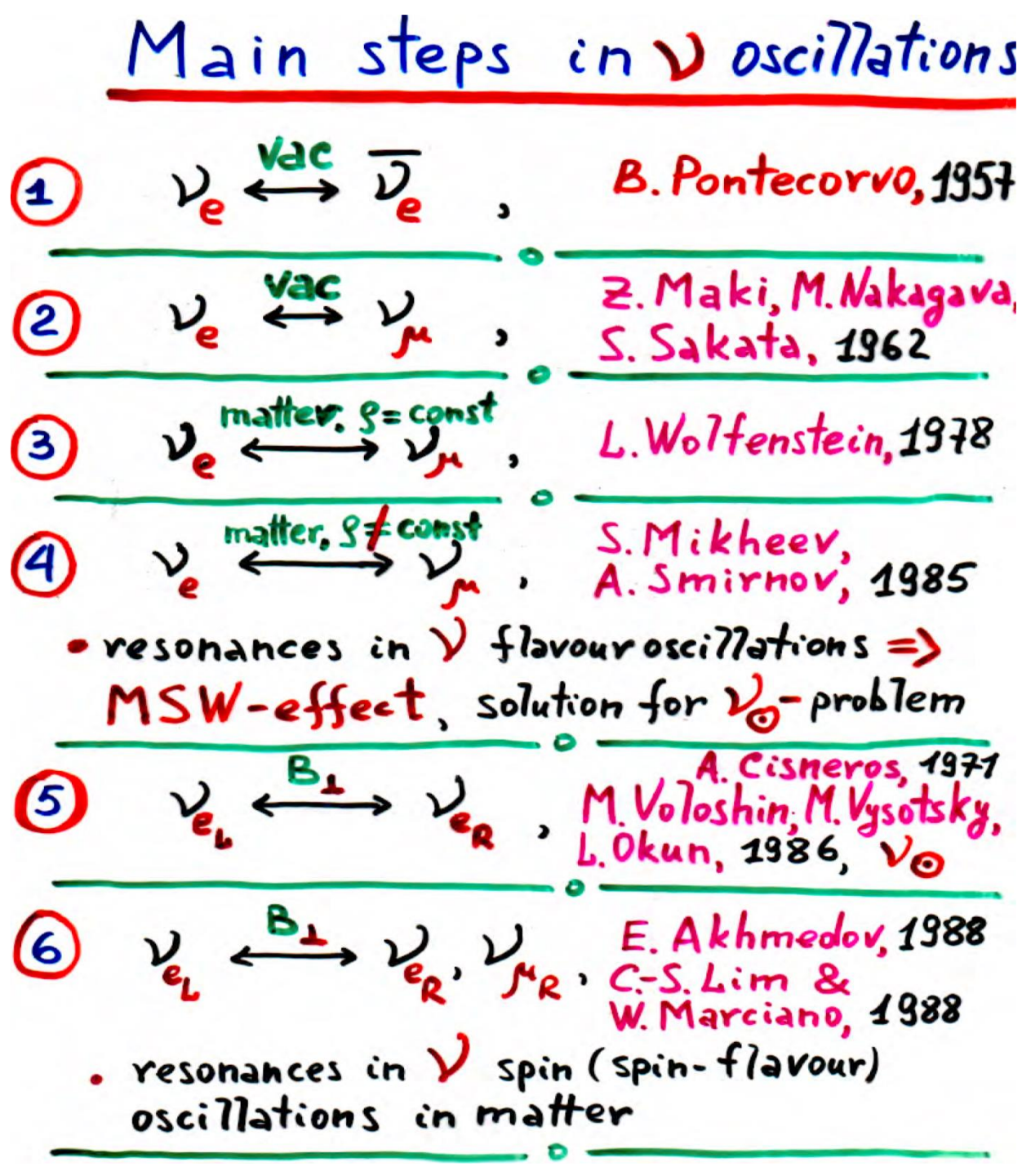

Neutrino oscillations in transversally moving matter

[1] *A.Studenikin*, Phys.Atom.Nucl. 67 (2004) 993

[2] *P.Pustoshny, A.Studenikin,* Phys.Rev. D98 (2018) 113009

It was shown that the nonzero transverse current component or matter polarization leads to neutrino spin and spin flavour oscillations:

- $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_e^R$
- $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_e^R$
- $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_\mu^R$
- $\nu_e^L \Leftarrow (j_\perp^{NSI}) \Rightarrow \nu_\mu^R$

We present the new possibility of the flavour, spin and spin-flavour oscillations engendered by the interaction of the neutrino charge radii and anapole moment with an external magnetic field

The electromagnetic interactions of a massive neutrino field ν(x) is described by the effective interaction Hamiltonian

C.Giunti, A.Studenikin, "*Neutrino electromagnetic interactions: a window to new physics*", Rev.Mod.Phys. 87 (2015) 531

$$H_{int}(x) = \sum_{k,j} \bar{\nu}_k(x) \Lambda_\mu^{kj} \nu_j(x) A^\mu(x) \qquad \Lambda_\mu^{fi}(q) = (q^2\gamma_\mu - q_\mu \gamma_\nu q^\nu)\left[\frac{\langle r^2\rangle^{fi}}{6} + f_A^{fi}\gamma_5\right]$$

$$H_{\alpha\alpha'}^{ss'} = u_{s\alpha}^\dagger \left\{ [\mathrm{rot}\boldsymbol{B}]_z \left(\frac{\langle r^2\rangle^{\alpha\alpha'}}{6} + f_A^{\alpha\alpha'}\sigma_3 \right) + [\mathrm{rot}\boldsymbol{B}]_\perp \left(\gamma_{\alpha\alpha'}^{-1} f_A^{\alpha\alpha'}\sigma_1 - i\tilde{\gamma}_{\alpha\alpha'}^{-1} \frac{\langle r^2\rangle^{\alpha\alpha'}}{6}\sigma_2 \right) \right\} u_{s'\alpha'}$$

$$\gamma_{\alpha\beta}^{-1} = \frac{1}{2}\left(\gamma_\alpha^{-1} + \gamma_\beta^{-1}\right) \qquad \gamma_\alpha^{-1} = \frac{m_\alpha}{E_\alpha} \qquad \tilde{\gamma}_{\alpha\beta}^{-1} = \frac{1}{2}\left(\gamma_\alpha^{-1} - \gamma_\beta^{-1}\right)$$

$$P_{\nu_e^L \to \nu_x^L} = \frac{E_{eff}^2}{E_{eff}^2 + \Delta_{eff}^2} \sin^2\left(\frac{\pi x}{L_{eff}}\right)$$

$$E_{eff} = \frac{\Delta m^2 \sin 2\theta}{4E_\nu} + [\mathrm{rot}\mathbf{B}]_z \left[\frac{1}{2}\left(\frac{\langle r^2\rangle^{22} - \langle r^2\rangle^{11}}{6} + f_A^{11} - f_A^{22}\right)\sin 2\theta + \left(\frac{\langle r^2\rangle^{12}}{6} - f_A^{12}\right)\cos 2\theta\right]$$

$$\Delta_{eff} = -\frac{\Delta m^2 \cos 2\theta}{4E_\nu} + [\mathrm{rot}\mathbf{B}]_z \left[\frac{1}{2}\left(\frac{\langle r^2\rangle^{11} - \langle r^2\rangle^{22}}{6} + f_A^{22} - f_A^{11}\right)\cos 2\theta + \left(\frac{\langle r^2\rangle^{12}}{6} - f_A^{12}\right)\sin 2\theta\right]$$

$$L_{eff} = \frac{\pi}{\sqrt{E_{eff}^2 + \Delta_{eff}^2}}$$

$$\langle r_{\nu_e}^2\rangle_{\mathrm{SM}} = -0.83 \times 10^{-32}\,\mathrm{cm}^2$$

$$\mu_\nu \lesssim 10^{-19}\mu_{\mathrm{B}}$$

$$[\mathrm{rot}\mathbf{B}]_z \frac{\langle r^2\rangle^{eff}}{6} \approx 10^{-11}\mathrm{eV}$$

$$\mu B \approx 10^{-15}\mathrm{eV}$$

Y. Suwa, T. Takiwaki, K. Kotake and K. Sato, Publ. Astron. Soc. Jap. 59 (2007), 771-785

Conclusions

- New type of neutrino oscillations (flavour and spin-flavour) engendered by neutrino charge radii and anapole moment interactions with an external magnetic field are proposed and investigated

- In a supernova environment the potential of neutrino interaction with magnetic field through the charge radii and anapole moment could be considerably higher than through the magnetic moment

- New type of oscillations might have important consequences in extreme astrophysical environments such as supernovae, jets and neutron stars