Impact of Beyond the Standard Model physics in the detection of the Cosmic Neutrino Background

Martín Arteaga[1], Enrico Bertuzzo[1], Yuber F. Perez-Gonzalez[1,2] and R. Zukanovich Funchal[1].

[1]Departamento de Física Matemática, Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
[2]ICTP South American Institute for Fundamental Research & Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil.

Abstract

We discuss the effect of Beyond the Standard Model charged current interactions on the detection of the Cosmic Neutrino Background by neutrino capture on tritium in a PTOLEMY-like detector. We show that the total capture rate can be substantially modified for Dirac neutrinos if scalar or tensor right-chiral currents, with strength consistent with current experimental bounds, are at play.

Cosmic Neutrino Background (CνB)

Neutrinos were maintained in equilibrium due to

$$\nu e \longleftrightarrow \nu e \text{ and } \nu\bar{\nu} \longleftrightarrow e^+e^-.$$

When do they decouple?

$$\frac{\Gamma_W}{H} \approx \frac{G_F^2 T_\nu^5}{T_\nu^2/M_{Pl}} = \left(\frac{T_\nu}{1\ \text{MeV}}\right)^3$$

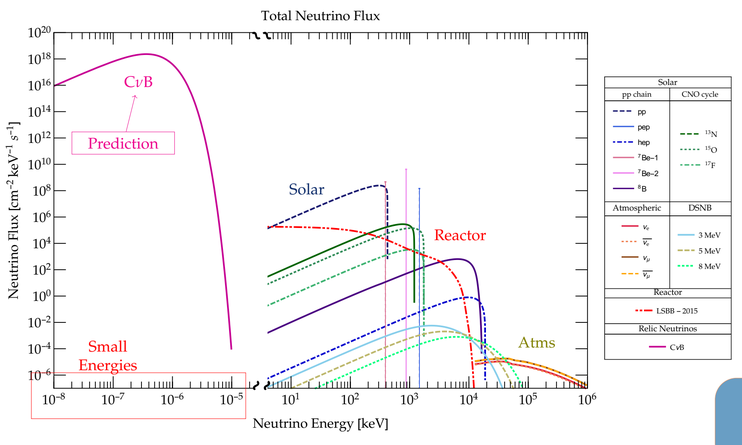
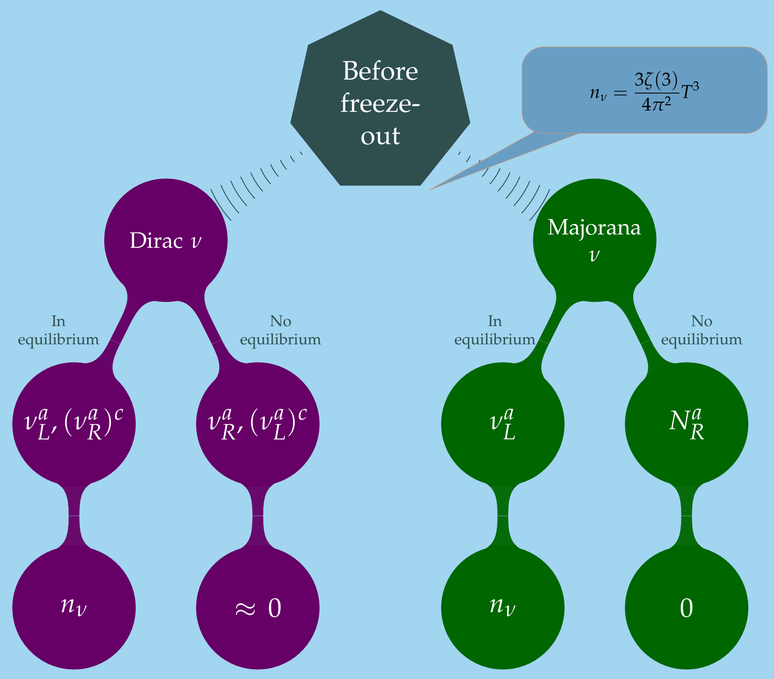


Fig. 1: Neutrino Fluxes from some sources

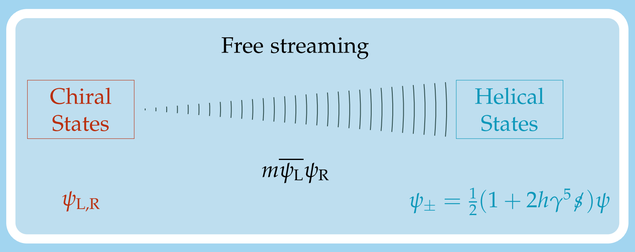
Temperature and root-mean-square momentum per neutrino species at the present time

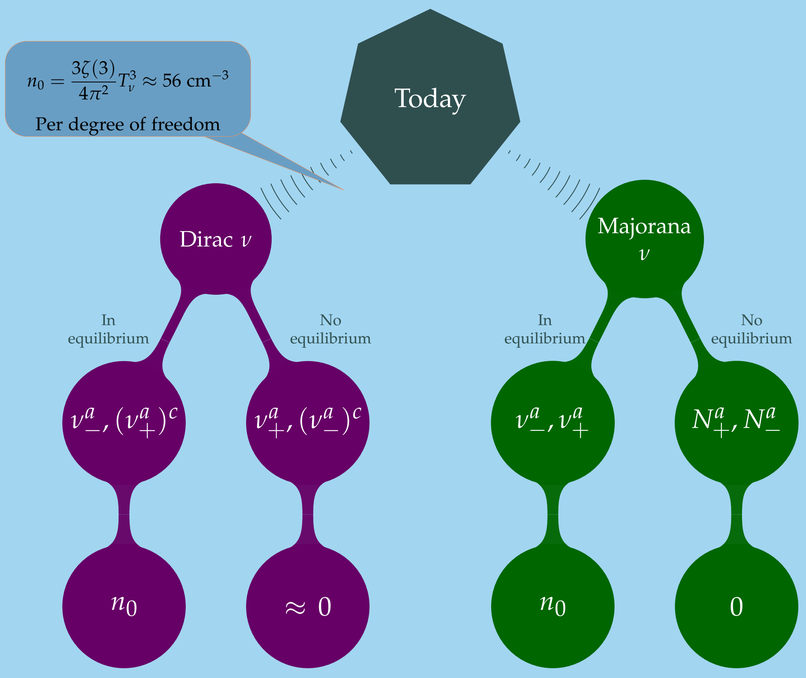
$$T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma \approx 0.168\ \text{meV}, \quad \bar{p}_a = \sqrt{\frac{p_{\nu_a}^2}{n_{\nu_a}^0}} \approx 0.604\ \text{meV}$$

Relic neutrinos are non-relativistic today[1]



After freeze-out?





CνB Capture Rate

PTOLEMY intends to detect the CνB through the *thresholdless* process

$$\nu_a + {}^3\text{H} \longrightarrow {}^3\text{He} + e^-$$

Capture rate:

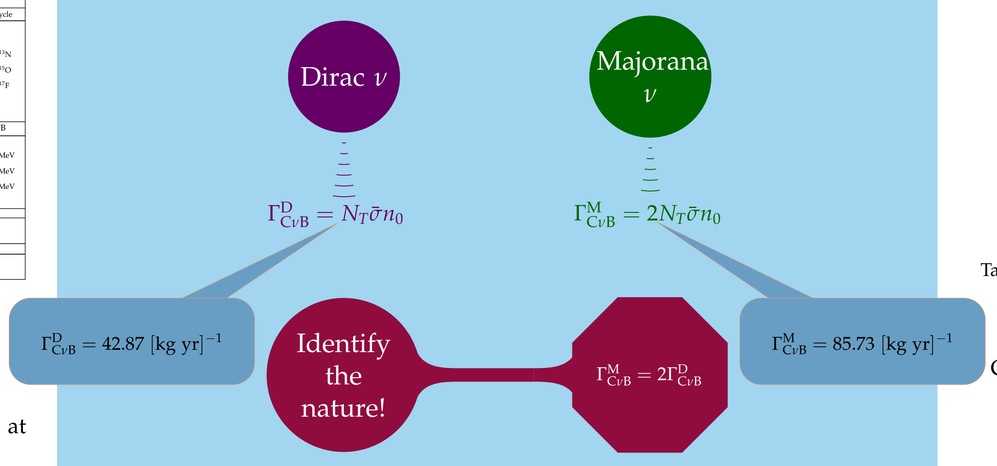
$$\Gamma^a_{C\nu B} = \underbrace{N_T}_{\text{Number of Targets}} \left[\underbrace{\sigma_a(+1/2)v_a}_{\text{Capture cross section times velocity}} n_{\nu^a_+} + \sigma_a(-1/2)v_a \underbrace{n_{\nu^a}}_{\text{Number Density}}\right]$$

Capture cross section times velocity

$$\sigma_a(h_\nu)v_a = \frac{G_F^2}{2\pi}\underbrace{|V_{ud}|^2|U_{ea}|^2}_{\text{PMNS}} F_Z(E_e)\frac{m_{^3\text{He}}}{m_{^3\text{H}}}E_e\, p_e\, \underbrace{\mathcal{A}(h_\nu)}_{1-2h_\nu v_a}\underbrace{(g_A^2 + 3g_V^2)}_{\text{Nuclear Form Factors}}$$

CKM

Non-relativistic CνB $\longrightarrow \mathcal{A}(h_\nu) \approx 1$



How would be the detection?

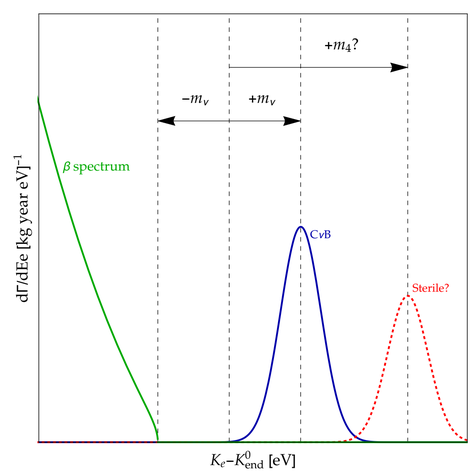


Fig. 2: Cartoon of the possible relic neutrino capture

Neutrino mass ordering?

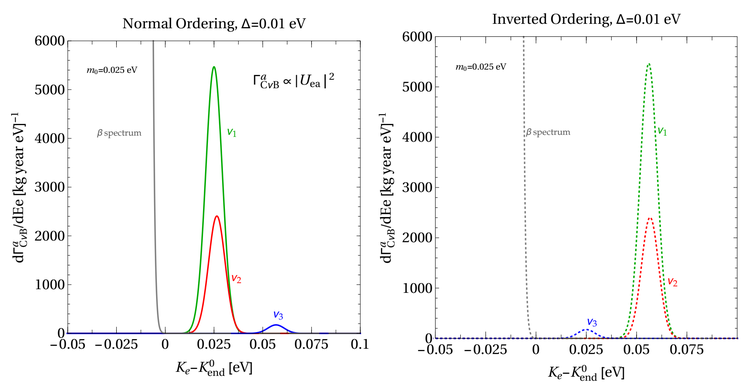


Fig. 3: Simulated spectra of the electrons created by the relic neutrino capture for $\Delta = 0.01$ eV for each mass eigenstate contribution: ν_1 (green), ν_2 (red), ν_3 (blue).

Criteria to distinguish neutrino peaks

$$\Xi^a_{C\nu B} = \sum_{b=1}^{3}\left\{1 - \Theta\left(D_B\left(\frac{d\Gamma^b_{C\nu B}}{dE_e}, \frac{d\Gamma^a_{C\nu B}}{dE_e}\right) - 4.5\right)\right\}\Gamma^b_{C\nu B}$$

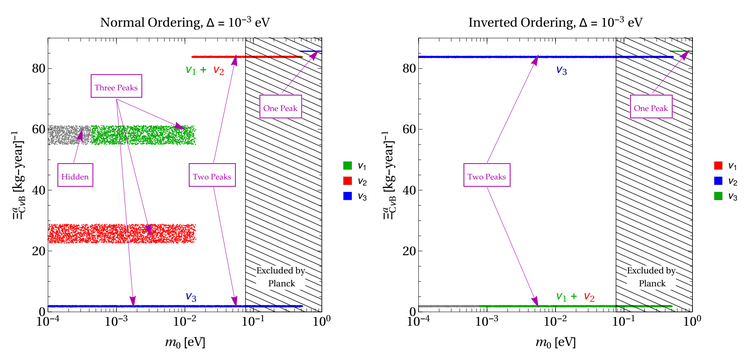


Fig. 4: Dependence of the $\Xi^a_{C\nu B}$ function on the value of the lightest neutrino mass m_0. The experimental resolution is chosen to be $\Delta = 10^{-3}$ eV.

Introducing physics BSM

$$\mathscr{L}_{\text{BSM}} = \mathscr{L}^{(4)}_{\text{SM}} + \mathscr{L}_{m_\nu} + \boxed{\frac{1}{\Lambda^2}\sum_{k=1}^{12} c_k^{(6)} Q_k^{(6)}} \longrightarrow \text{6-dimensional operators}$$

Four-fermion Operators		Vertex Corrections
$Q^{(6)}_{\nu_L}$	$Q^{(6)}_{\nu_R}$	$Q^{(6)}_{\Phi}$
$(\overline{l_L}e_R)(\overline{d_R}q_L)$	$(\overline{l_L}\nu_R)\varepsilon(\overline{q_L}d_R)$	$i(\Phi^T\varepsilon D_\mu\Phi)(\overline{u_R}\gamma_\mu d_R)$
$(\overline{l_L}e_R)\varepsilon(\overline{q_L}u_R)$	$(\overline{\nu_R}l_L)(\overline{q_L}u_R)$	$i(\Phi^T\varepsilon D_\mu\Phi)(\overline{\nu_R}\gamma^\mu e_R)$
$(\overline{l_L}\gamma^\mu\tau^A l_L)(\overline{q_L}\gamma_\mu\tau^A q_L)$	$(\overline{e_R}\gamma^\mu\nu_R)(\overline{u_R}\gamma_\mu d_R)$	$(\Phi^\dagger i\overleftrightarrow{D}^a_\mu\Phi)(\overline{q_L}\gamma_\mu\tau^A q_L)$
$(\overline{l_L}\sigma^{\mu\rho}e_R)\varepsilon(\overline{q_L}\sigma_{\mu\rho}u_R)$	$(\overline{l_L}\sigma^{\mu\rho}\nu_R)\varepsilon(\overline{q_L}\sigma_{\mu\rho}d_R)$	$\Phi^\dagger i\overleftrightarrow{D}^a_\mu\Phi)(\overline{l_L}\gamma^\mu\tau^A l_L)$

Table 1. Dimension-six operators relevant for neutrino capture.

Relevant lagrangian:

$$\mathscr{L}^{C\nu B}_{\text{eff}} = -\frac{G_F}{\sqrt{2}}V_{ud}U_{ea}\left\{\underbrace{[\bar{e}\gamma^\mu(1-\gamma^5)\nu_a][\bar{u}\gamma_\mu(1-\gamma^5)d]}_{\text{SM}} + \underbrace{\sum_{Lq}\epsilon_{lq}[\bar{e}\mathscr{O}_l\nu][\bar{u}\mathscr{O}_q d]}_{\text{BSM}}\right\}$$

ϵ_{lq}	$\mathscr{O}_l$	$\mathscr{O}_q$
ϵ_{LL}	$\gamma^\mu(1-\gamma^5)$	$\gamma_\mu(1-\gamma^5)$
ϵ_{LR}	$\gamma^\mu(1-\gamma^5)$	$\gamma_\mu(1+\gamma^5)$
ϵ_{RL}	$\gamma^\mu(1+\gamma^5)$	$\gamma_\mu(1-\gamma^5)$
ϵ_{RR}	$\gamma^\mu(1+\gamma^5)$	$\gamma_\mu(1+\gamma^5)$
ϵ_{LS}	$1-\gamma^5$	1
ϵ_{RS}	$1+\gamma^5$	1
ϵ_{LP}	$1-\gamma^5$	$-\gamma^5$
ϵ_{RP}	$1+\gamma^5$	$-\gamma^5$
ϵ_{LT}	$\sigma^{\mu\nu}(1-\gamma^5)$	$\sigma_{\mu\nu}(1-\gamma^5)$
ϵ_{RT}	$\sigma^{\mu\nu}(1+\gamma^5)$	$\sigma_{\mu\nu}(1+\gamma^5)$

Table 2. Parameters and their corresponding Lorentz structures for the BSM currents considered in this work.

Compatible at 3σ C.L:

$$-10^{-3} \le \epsilon_{LL} \le 10^{-3}, \qquad -10^{-3} \le \epsilon_{LR} \le 10^{-3},$$
$$-2.8\times10^{-3} \le \epsilon_{LS} \le 5\times10^{-3}, \quad -2\times10^{-3} \le \epsilon_{LT} \le 2.1\times10^{-3},$$

and

$$|\epsilon_{Rq}| \le 10^{-1}.$$

BSM Capture Rate

$$\sigma^{\text{BSM}}_a(h_a)v_a = \frac{G_F^2}{2\pi}|V_{ud}|^2|U_{ea}|^2 F_Z(E_e)\frac{m_{^3\text{He}}}{m_{^3\text{H}}}E_e\, p_e\, \boxed{T_a(h_a, \epsilon_{lq})} \longrightarrow \text{Dependence on epsilon par.}$$

Right-handed couplings are relevant.

$$T_a(h_a, \epsilon_{lq}) \supset 2\underbrace{\frac{m_a}{E_a}}_{\text{Large!}}\{g_S\, g_V\, \epsilon_{RS}\,(\epsilon_{LL} + \epsilon_{LR} + 1) + \epsilon_{LS}\,(\epsilon_{RR} + \epsilon_{RL})) - 12\, g_A\, g_T(\epsilon_{RT}\,(\epsilon_{LL} - \epsilon_{LR} + 1) + \epsilon_{LT}\,(\epsilon_{RR} - \epsilon_{RL}))\}$$

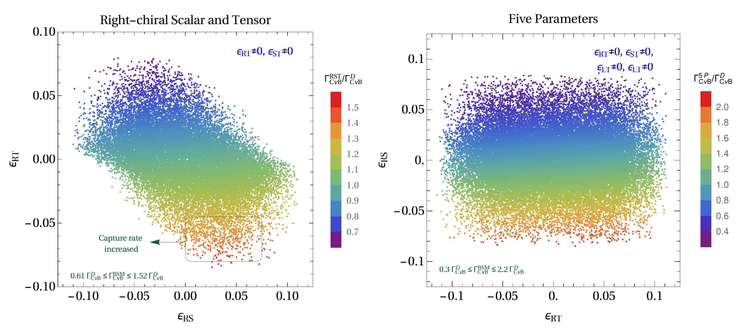


Fig. 5: Ratio between the BSM capture rate for two scenarios with respect to the SM Dirac case in the plane (ϵ_{RS} versus ϵ_{RT}). We use a color code to indicate the range of values of the ratio.

Conclusions

- The detection of the cosmic neutrino background could shed some light on the neutrino fermionic nature and the absolute values of the masses
- We found that BSM physics can hinder the discovery of the neutrino nature, as it can modify the capture rate in a PTOLEMY-like detector

Acknowledgments

This work was supported by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Conselho Nacional de Ciência e Tecnologia (CNPq).

References

[1] A. J. Long, C. Lunardini and E. Sabancilar, JCAP **1408**, 038 (2014).

[2] S. Betts *et al.*, "PTOLEMY Collaboration", arXiv:1307.4738 [astro-ph.IM].

[3] N. Severijns, M. Beck and O. Naviliat-Cuncic, Rev. Mod. Phys. **78**, 991 (2006).

[4] M. Arteaga, E. Bertuzzo, Y. F. Perez-Gonzalez and R. Zukanovich Funchal, JHEP **1709**, 124 (2017).