Impact of Beyond the Standard Model Physics in the Detection of the Cosmic Neutrino Background

UNIVERSIDADE DE SÃO PAULO

Martín Arteaga Tupia*†, Enrico Bertuzzo*,
Yuber F. Perez-Gonzalez*, Renata Zukanovich Funchal*

*Departamento de Física Matemática. Instituto de Física. Universidade de São Paulo

†martin77@if.usp.br

INSTITUTO DE FÍSICA

Introduction and motivation

The Cosmic Microwave Background (CMB) predicts the existence of a Cosmic Neutrino Background (CνB) radiation, which is a relic radiation that appeared when neutrinos decoupled from matter when the Universe was merely a second old. This radiation is present in the form of anisotropies in the CMB and it is expected to have played a crucial role in primordial nucleosynthesis and in large scale structures formation.
For a long time direct detection was believed to be an impossible task because the so called relic neutrinos, with a mass $m_\nu \approx 0.1\, eV$ and an average momentum today $\overline{p}_0 \approx 10^{-4}\, eV$, have a non-relativistic behavior. However, recent developments have allowed to revive the old suggestion (by Weinberg) of capturing them on β-decaying nuclei, a process with no energy threshold.
In the present research we try to answer the following question: *if neutrinos have new Beyond the Standard Model (BSM) interactions, how would this affect the relic neutrino detection rate in PTOLEMY-like detectors?* We implement these possible deviations using an effective lagrangian approach.

CMB and CνB

The discovery of the Cosmic Microwave Background radiation, CMB, represents a cornerstone in Cosmology. The CMB anisotropies are an indirect imprint of the CνB.

Definitions

- CMB: Radiation from the epoch of recombination, photons started to travel freely.
- CνB: Radiation from neutrinos after they decoupled from matter

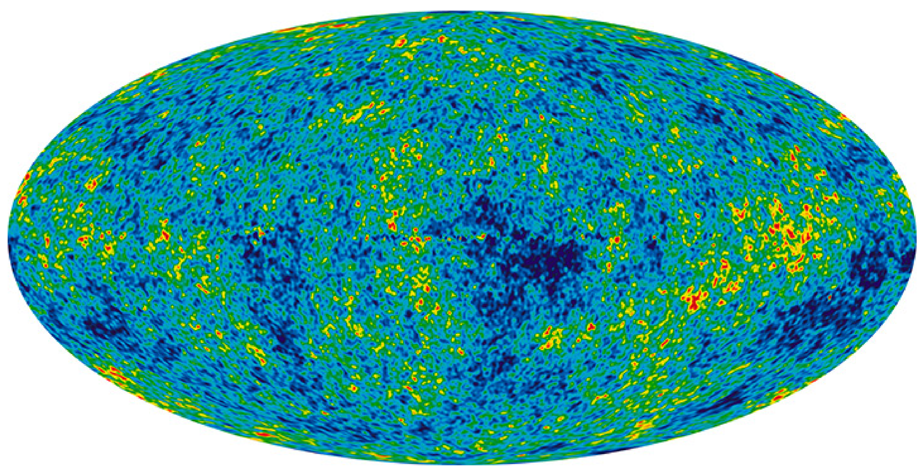

Fig.1 CMB, 13.77 billion year old temperature fluctuations (color differences)[Credit: NASA / WMAP Science Team]

Helicity composition of the CνB

In order to understand why the classification based on helicity and not in chirality is more appropriate for relic neutrinos, we star by comparing the range of values of the neutrino masses and the average momentum. The root mean square momentum of relic neutrinos is

$$\overline{p}_0 \approx 0.6\,\text{meV}$$

and because

$$m_\nu \approx \mathcal{O}(0.1\, eV)$$

$\Rightarrow$ Relic neutrinos are non-relativistic.
Therefore, while in the relativistic regimen there is no distinction between chirality and helicity, in the non-relativistic regimen chirality is not conserved, the Helicity operator, $\widehat{h}$, commutes with the free Hamiltonian

$$\left[\widehat{H}_{\text{free}}, \widehat{h}\right] = 0,$$

so, the helicity is conserved.
The today abundances of Relic neutrinos for the Dirac and Majorana cases are respectively:

- Dirac neutrinos:

$$\begin{aligned} n(\nu_-^j) = n(\overline{\nu}_+^j) &= n_0 \approx 56\, cm^{-3} \\ n(\nu_+^j) \approx \quad 0 \quad &\approx n(\overline{\nu}_-^j) \end{aligned}$$

- Majorana neutrinos:

$$\begin{aligned} n(\nu_+^j) = n(\nu_-^j) &= n_0 \\ n(N_-) = n(N_+) &= 0 \end{aligned}$$

We focus in the capture of these relic neutrinos, through

$$\Gamma_{C\nu B} = \sum_{j=1}^{3} \Gamma_{C\nu B}(j) = N_T \sum_{j=1}^{3} \left[\sigma_j(+1) v_j n_{\nu_+^j} + \sigma_j(-1) v_j n_{\nu_-^j}\right]$$

- Capture rate for Majorana Fermions is twice the Dirac ones, considering only SM.

$$\Gamma^M_{C\nu B} = 2\,\Gamma^D_{C\nu B}.$$

PTOLEMY

The Princeton Tritium Observatory for Light Early Universe, Massive Neutrinos Yield (PTOLEMY) focus on the captured of relic neutrinos by Tritium. The background in this experiment is the β-decay, because this process has no threshold. Considering $m_{^3H} \approx m_{^3He} \gg m_e \gg m_\nu$, we have

$$K_e^{C\nu B} \approx K_{end} + 2m_\nu$$

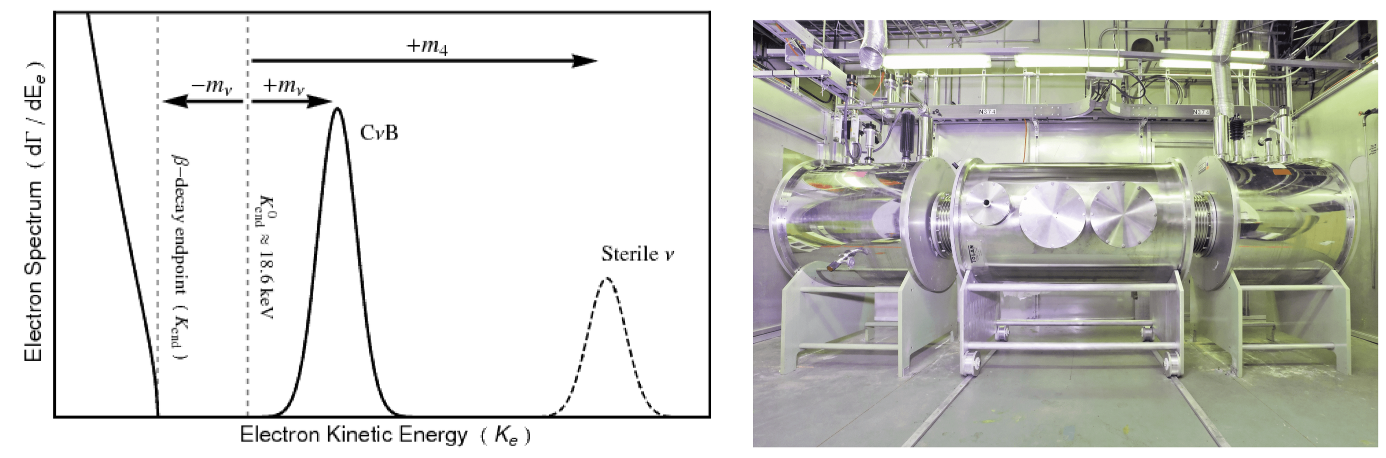

Fig.2 (*Left*) Signal of non-relativistic relic neutrinos captured by Tritium in the background of the β-decay at PTOLEMY.[1]. (*Right*) A prototype of PTOLEMY detector at the Princeton Plasma Physics Laboratory (February 2013). [2]

What is the effect of turning on BSM interactions?

Using the Effective field theory approach the physics is described by the following lagrangian

$$\mathcal{L}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{ud} U_{ej} \left\{ [\overline{e}\gamma^\mu \mathbb{P}_L \nu_j][\overline{u}\gamma^\mu \mathbb{P}_L d] + \sum_{l,q} \epsilon_{lq} [\overline{e}\gamma^\mu \mathcal{O}_l \nu_j][\overline{u}\gamma^\mu \mathcal{O}_q d] \right\}$$

where we turn-on additional six-dimensional operators. They are summarized in the next table:

ϵ_{lq}	$\mathcal{O}_l$	$\mathcal{O}_q$
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}	$\sigma^{\mu\nu}(1+\gamma^5)$	$\sigma_{\mu\nu}(1+\gamma^5)$

Results and Conclusions

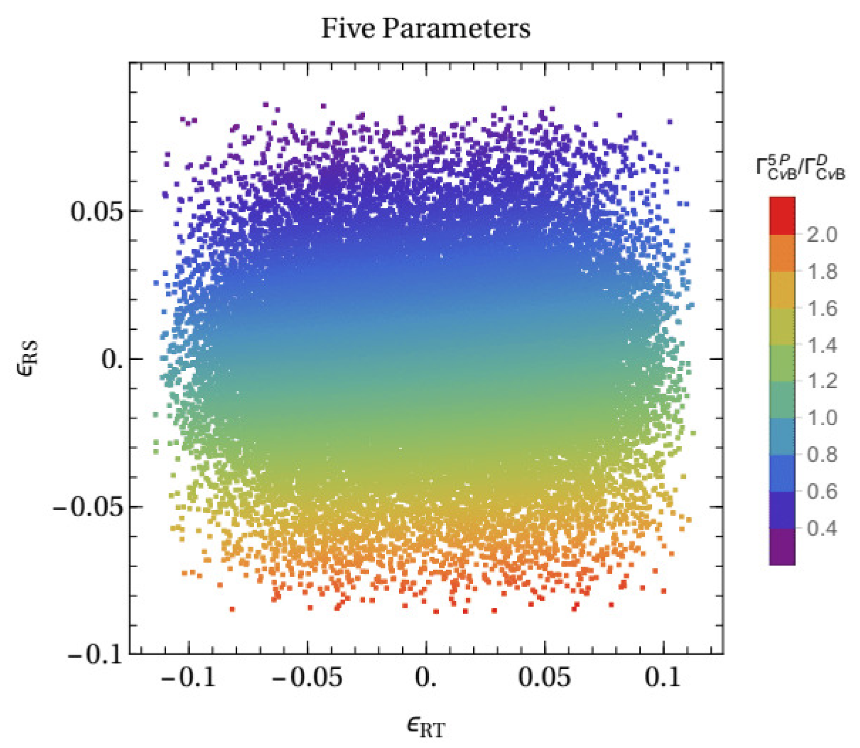

Fig.4 Ratio between the capture rate turning-on BSM interactions $\Gamma^{BSM}_{C\nu B}$ and considering only SM interactions $\Gamma^D_{C\nu B}$.

BSM interactions can mimic SM Majorana neutrinos!

$$\Rightarrow \Gamma^{BSM}_{C\nu B} \approx 2\,\Gamma^D_{C\nu B} = \Gamma^M_{C\nu B}$$

Conclusions

- These predictions would be a new test for the Standard Model of Cosmology,
- They also give light for understanding the nature of neutrinos,
- If we consider effective operators of dimension 6, the capture rate $\Gamma^{BSM}_{C\nu B}$ can mimic the capture rate of Majorana neutrinos with only SM operators.

Acknowledgments

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References

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

[2] S. Betts et al., Development of a Relic Neutrino Detection Experiment at PTOLEMY: Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield, in *Proceedings, 2013 Community Summer Study on the Future of U.S. Particle Physics: Snowmass on the Mississippi (CSS2013): Minneapolis, MN, USA, July 29-August 6, 2013*, 2013.