PROCEEDINGS OF SCIENCE

Constraining the Gauged $U(1)_{L_\mu - L_\tau}$ Model by Supernova Neutrino Observation

Kwang-Chang Lai,[b] Chun Sing Jason Leung,[a,*] Guey-Lin Lin[a] and Thi Dieu Hien Van[a]

[a] *Institute of Physics, National Yang Ming Chiao Tung University, No. 1001, Daxue Rd, East District, Hsinchu City, 30010, Taiwan*

[b] *Chang Gung University, No. 259, Wenhua 1st Rd, Guishan District, Taoyuan City, 33302, Taiwan*

E-mail: jasonleung.py04g@g2.nctu.edu.tw

The $U(1)_{L_\mu - L_\tau}$ model is one of the simplest anomaly free models to feature a new gauge boson Z' by extending the Standard Model (SM) group $G_{\rm SM} \equiv SU(3)_{\rm QCD} \otimes SU(2)_{\rm Weak} \otimes U(1)_Y \to G_{\rm SM} \otimes U(1)_{L_\mu - L_\tau}$. This hypothetical new gauge boson Z' could affect the cooling mechanism of core-collapse supernovae (CCSNe). The production of Z' might over contribute to the energy loss of a CCSN depending on the magnitude of the coupling between Z' and μ, τ leptons. Consequently, the production of SN neutrino might be affected and contradict the recent SN neutrino observation, SN 1987A. We calculate the Z' production and absorption/decay rates through pair-coalescence, semi-Compton, loop-Bremsstrahlung from proton-neutron scattering, and their inverse processes in a benchmark SN simulation SFHo18.8 (Thomas Janka *et al.*, Phys. Rev. Lett. 125, 051104 (2020)) and put constraints on the parameter space $(m_{Z'}, g_{Z'})$ in this new gauged $U(1)_{L_\mu - L_\tau}$ model. Although such constraints have been studied in previous literature, our study gives more stringent constraints on the model by carefully considering the competition between Z' production and absorption/decay effects to Z' luminosity at the very outermost shell of the neutrino sphere. We point out that Z' luminosity will tend to a constant plateau value depending on $m_{Z'}$ instead of monotonically decreasing down to zero as the coupling constant increases. This plateau phenomenon can be understood by physical arguments and justified by numerical calculations. We found that the plateau value of Z' luminosity will become greater than Raffelt's criterion when $m_{Z'}$ is lower than a specific value ~ 2 eV. For $m_{Z'} < 2$ eV, the so-called trapping limit shall disappear completely. We stress that the plateau behavior of Z' luminosity in the large coupling limit should also occur for other BSM models that introduce new light bosons. Hence our work has extended applications.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

*Speaker

PoS(ICHEP2022)1121

1. Introduction

The $U(1)_{L_\mu - L_\tau}$ model is one of the most simplest anomaly free leptophilic models that features a new massive gauge boson Z' [2]. Unlike other leptophilic models, the Z' in $U(1)_{L_\mu - L_\tau}$ symmetry is only allowed to interact with the standard model unstable heavy leptons μ, τ, as well as their corresponding neutrinos according to the Lagrangian [5]

$$\begin{aligned}\mathcal{L}_{Z'} = &-\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_{Z'}^2 Z'_\mu Z'^\mu \\ &+ g_{Z'}Z'_\mu\left(\bar{l}_1\gamma^\mu l_1 - \bar{l}_2\gamma^\mu l_2 + \bar{\mu}_R\gamma^\mu\mu_R - \bar{\tau}_R\gamma^\mu\tau_R\right)\end{aligned} \tag{1}$$

In which, the kinetic mixing parameter ϵ arises due to an irreducible μ and τ loop contribution as indicated in figure 1. Integrating out the μ and τ loop results in

$$\epsilon(g_{Z'}) \approx -\frac{e g_{Z'}}{2\pi^2}\int_0^1 x(1-x)\ln\left[\frac{m_\tau^2 - x(1-x)k^2}{m_\mu^2 - x(1-x)k^2}\right] \tag{2}$$

in which $k = (\omega, \vec{k})$ is the 4-momentum of the final state new gauge boson Z', i.e., $k^2 = m_{Z'}^2$. Therefore, the model has only two parameters $(m_{Z'}, g_{Z'})$.

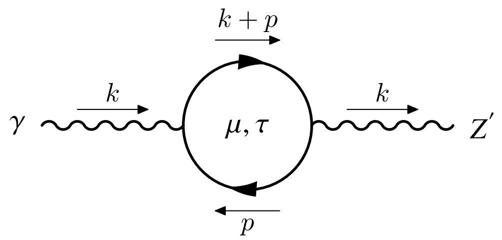

Figure 1: Feynman diagram that leads to the kinetic mixing between the new gauge boson Z' and the standard model photon γ.

Supernova neutrino luminosity had an experimental value given by the previous observation on SN1987A. Its value at a characteristic post-bounce time $t_{\text{pb}} = 1$ s in all flavours is found to be $\sim 3 \times 10^{52}$ [erg/s]. Therefore, the luminosity of any new particles that potentially can carry energy out of the supernova must not exceed this limit at $t_{\text{pb}} = 1$ s, otherwise, it might over contribute to the energy loss of the supernova and affect the neutrino luminosity, consequently, contradicting the experimental observation on SN1987A. This requirement is known as the *Raffelt criterion* [1].

$$\text{Raffelt criterion}: L_{\text{new particles}} < L_{\text{Raffelt}} = 3 \times 10^{52}\ \text{[erg/s] at } t_{\text{pb}} = 1\ \text{s}$$

This criterion put an upper bound constraint on the luminosity of the new gauge boson $L_{Z'}(m_{Z'}, g_{Z'})$. In other words, any parameter space $(m_{Z'}, g_{Z'})$ that corresponds to a Z' luminosity $L_{Z'} > L_{\text{Raffelt}}$ has to be excluded according to the Raffelt criterion.

Although McDermott *et al.* [4][5] have done similar work with a supernova simulation SFHo18.8 [3], the regions of production and absorption/decay processes of Z' were not on an equal footing. The radius of the spherical volume corresponds to the absorption region of the new gauge boson Z' was taken as an arbitrary value that was greater than the one for production region, i.e., $R_{\text{far}} > R_\nu$. Hence, the production rate of the new gauge boson Z' was undoubtedly underestimated. To point out this, we also adopted the supernova simulation SFHo18.8 [3] in this work as a comparison. In addition, we treated the Z' production and absorption/decay on an equal footing, i.e., $R_{\text{far}} = R_\nu$, and let the numerical integration to handle the competition between them.

2. Constraining the $U(1)_{L_\mu - L_\tau}$ model

The new gauge boson Z' associated with the $U(1)_{L_\mu - L_\tau}$ model [2] can be produced by interactions between ordinary standard model particles and unstable heavy leptons, muons as well as taus, according to the aforementioned Lagrangian. On the other hand, the simulation data of supernova neutrino with muons have been provided recently [3]. By considering the production rates, as well as the absorption/decay rates of muonic interactions within a particular supernova simulation, the luminosity of the new gauge boson Z', can be calculated precisely within a parameter space $(m_{Z'}, g_{Z'})$.

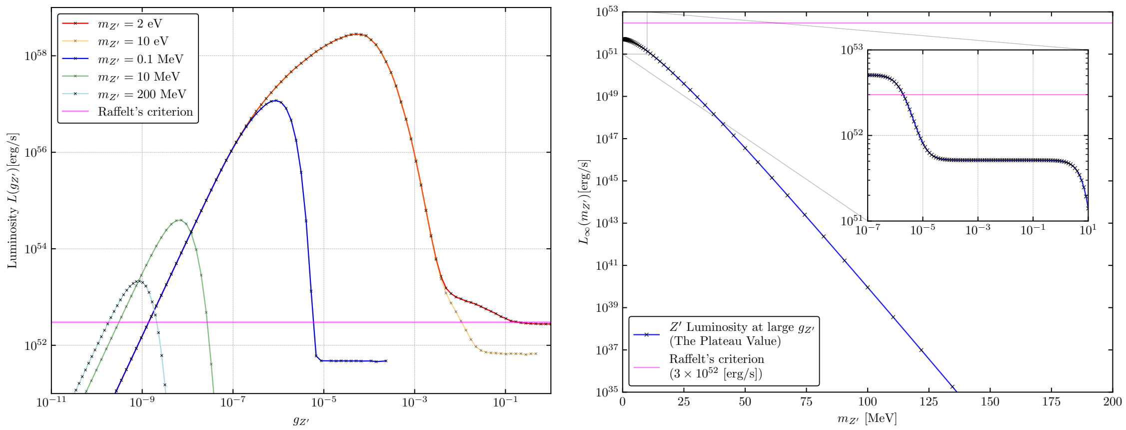

Figure 2: (Left) Luminosity of the new gauge boson Z' in various mass m'_Z.
(Right) The plateau value in function of the mass of the new gauge boson mass $m_{Z'}$.

The luminosity of the new gauge boson $L_{Z'}$ of some particular Z' masses was computed according to the aforementioned luminosity formula

$$L_{Z'}(m_{Z'}, g_{Z'}, R_\nu) = 4\pi \int_0^{R_\nu} \int_{m_{Z'}}^{\infty} r^2 \bar{\mathcal{A}}(\lambda_{\text{att}}(\omega, T), R_\nu) \sum_i \frac{d\dot{\epsilon}_i}{d\omega} d\omega dr \tag{3}$$

with $i \in$ {pair coalescence, semi Compton, loop Bremsstrahlung}, and is shown on the left panel of figure 2. It can be seen that when $g_{Z'}$ is greater than a certain value, each of the luminosity curves reaches a constant plateau value instead of monotonically decreasing down to zero. This interesting plateau phenomenon is a manifestation of the competition between Z' production and absorption/decay, its magnitude depends on the mass of the new gauge boson Z' as shown on the right panel of figure 2.

It can be seen that the plateau value increases as $m_{Z'}$ decreases on the right panel of figure 2. Moreover, it gets greater than the bound put by the Raffelt criterion when $m_{Z'}$ below around 2 eV. In other words, when $m_{Z'} < 2$ eV the excluded parameter region will not bound from above (the

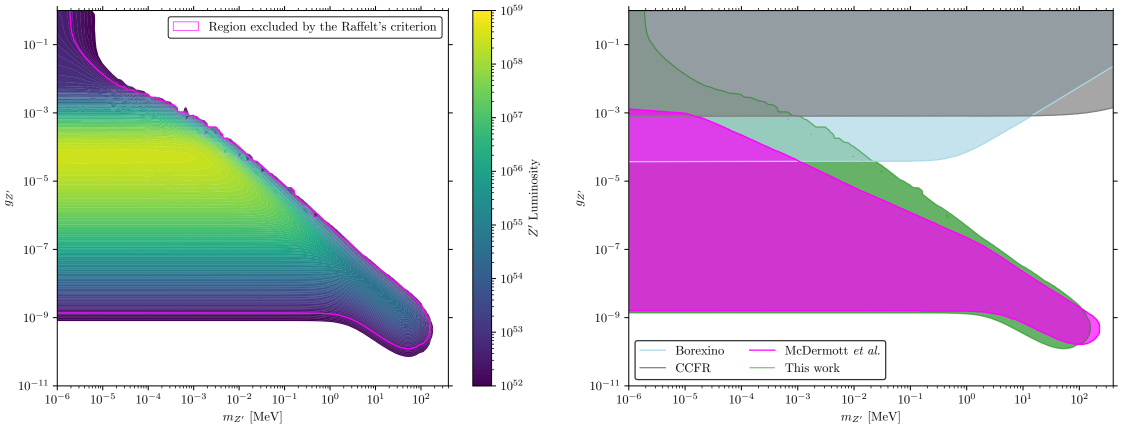

Figure 3: (Left) The luminosity contour plot corresponds to $L_{Z'} > 10^{52}$ [erg/s]. The region corresponds to $L_{Z'} > L_{\text{Raffelt}} = 3 \times 10^{52}$ [erg/s] is enclosed by the magenta line. (Right) The excluded parameter region done by previous works and other experiments. Our result is shaded in red colour.

trapping limit) anymore. Thus, the plateau phenomenon puts a stringent constraint on the model when $m_{Z'} < 2$ eV. This stunning result can be visualized in figure 3.

On the left panel of figure 3, we present a more comprehensive calculation of the luminosity contour diagram by scanning through the parameter space $(m_{Z'}, g_{Z'})$ in formula (3). The region enclosed by the magenta line represents an excluded region that corresponds to Z' luminosity $L_{Z'} > L_{\text{Raffelt}}$. It can be seen that the upper magenta curve tends to a vertical line when $m_{Z'}$ approaches ~ 2 eV from above, which exclude all the parameter space g'_Z and the trapping limit shall disappear due to the plateau phenomenon. As a comparison to the previous work done by McDermott *et al.* (the region shaded in magenta colour on the right panel of figure 3), our work (shaded in red) literally extended the trapping limit gradually as $m_{Z'}$ decreases down to ~ 2 eV. Furthermore, for $m_{Z'} < 2$ eV, the plateau value in figure 2 is already greater than the Raffelt bound, resulting in the vanishing of the trapping limit. It can be seen that the extended region overlaps the excluded regions put by the neutrino trident experiment in CCFR [7], as well as the muon anomalous magnetic moment measurement in Borexino [6], thus our work has indeed verified the disallowance of this overlapped parameter region.

Besides that, we get pretty much agreements with McDermott's result. Supernova neutrinos give new constraints on the $U(1)_{L_\mu - L_\tau}$ model and have a huge potential in providing constraints for other new long-living weak interacting hypothetical particles.

References

[1] Georg G. Raffelt, *"Stars as Laboratories for Fundamental Physics"*, (1996).

[2] Xiao-Gang He, G. C. Joshi, H. Lew, and R. R. Volkas, *"Simplest Z′ Model"*, Phys. Rev. Lett. **44**, 2118 (1991)

[3] Robert Bollig, William DeRocco, Peter W. Graham, and Hans-Thomas Janka, *"Muons in Supernovae: Implications for the Axion-Muon Coupling"*, Phys. Rev. Lett. **125**, 051104 (2020);

[4] Jae Hyeok Chang, Rouven Essig, Samuel D. McDermott, *"Revisiting Supernova 1987A Constraints on Dark Photons"*, J. High Energy Phys. **107** (2017)

[5] Djuna Croon, Gilly Elor, Rebecca K. Leane and Samuel D. McDermott, *"Supernova Muons: New Constraints on Z Bosons, Axions and ALPs"*, J. High Energy Phys. **107** (2021)

[6] D.W.P. Amaral , D.G. Cerdeño, P. Foldenauer and E. Reid, *"Solar neutrino probes of the muon anomalous magnetic moment in the gauged $U(1)_{L_\mu - L_\tau}$"*, J. High Energy Phys. **155** (2020)

[7] Wolfgang Altmannshofer, Stefania Gori, Maxim Pospelov, and Itay Yavin, *"Neutrino Trident Production: A Powerful Probe of New Physics with Neutrino Beams"*, Phys. Rev. Lett. **113**, 091801 (2014)