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

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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 Minimal Standard Model group $G_{\rm MSM} \equiv SU(3)_{\rm QCD} \otimes SU(2)_{\rm Weak} \otimes U(1)_Y \to G_{\rm MSM} \otimes U(1)_{L_\mu - L_\tau}$. The new gauge boson Z' could affect the cooling mechanism of core-collapse supernove (SNe). The production of Z' in a SN might over contribute to the energy loss depending on the coupling magnitude $g_{Z'}$ between Z' and μ, τ leptons. Consequently, the SN neutrino production 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 with a benchmark SN simulation SFHo18.8 (Thomas Janka *et al.*) and put constraints on the $g_{Z'}$ in this new gauged $U(1)_{L_\mu - L_\tau}$ model. Although such constraints were 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 $g_{Z'}$ 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 $m_{Z'} \lesssim 2$ eV. For $m_{Z'} \lesssim 2$ eV, the so-called trapping limit shall disappear completely. We stress that the plateau behavior in a large coupling limit should also occur for other BSM models that introduce new light bosons.

The $U(1)_{L_\mu - L_\tau}$ Model

The $U(1)_{L_\mu - L_\tau}$ model is a model constructed by extending the standard model of fundamental particles by a new gauge boson Z'. The Lagrangian of this model is given by

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

where l_1 and l_2 are the electroweak doublets for left-handed leptons $(\mu_L, \nu_{\mu,L})$ and $(\tau_L, \nu_{\tau,L})$ respectively.

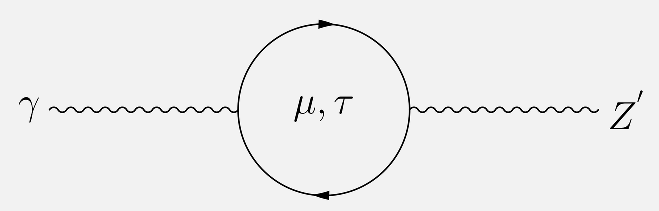

Fig. 1: Feynman diagram that indicates the kinetic mixing ϵ in Eq. (1).

The new gauge boson Z' is only allowed to interact with leptons μ, $\nu_{\mu,L}$, τ and $\nu_{\tau,L}$ in tree level, as indicated in the second line of Eq. (1). The kinetic mixing between Z' and the standard model photon γ in the first line of Eq. (1) arises due to integrating out the μ and τ loops in Fig. 1.

The SFHo18.8 SN Simulation

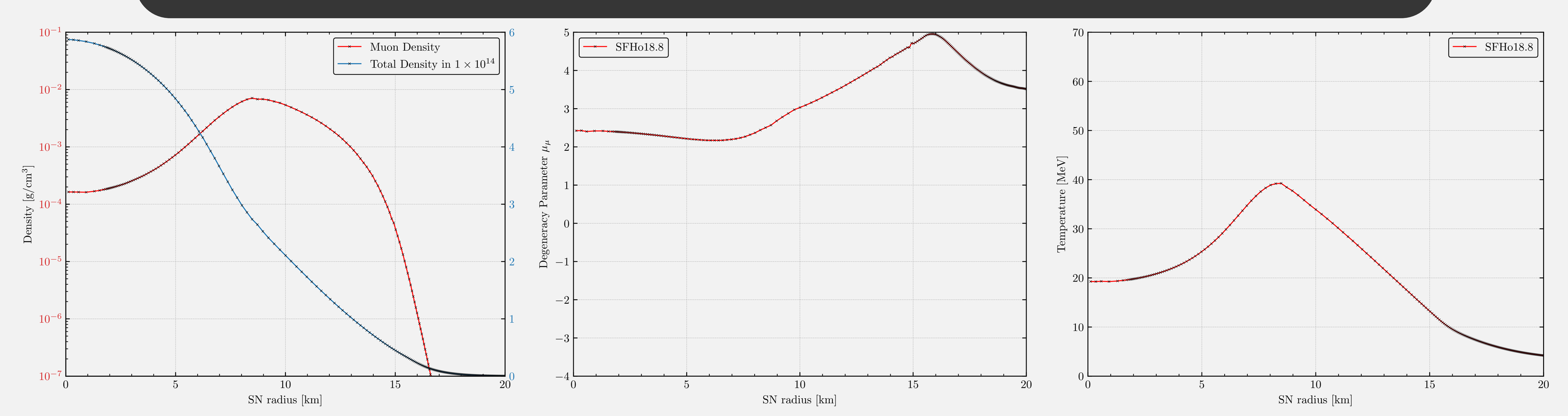

Fig. 2: Some of the SFHo18.8 simulation data provided by Thomas Janka *et al.* [3]

Luminosity of The Dark Boson Z'

The new gauge boson Z' luminosity within the neutrino sphere R_ν in a SN is given by

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

where $d\dot{\epsilon}/d\omega$ and $\lambda_{\rm att}$ are the *differential emissivity* and the *attenuation length* of Z' emission (see Fig. 4) and re-absorption processes respectively. $\bar{\mathcal{A}}$ is the average of the *attenuation factor* over a polar angle θ, with $y = \cos\theta$.

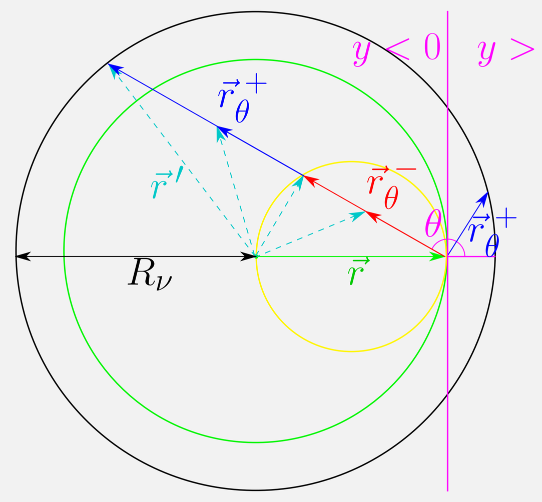

Fig. 3: Geometric interpretation of those integrals in Eq. (4).

$$\bar{\mathcal{A}} = \frac{1}{2}\int_{-1}^{1} \exp\left(-\int_0^{r_\theta^{\rm Max}} \frac{1}{\lambda_{\rm att}(\omega, T)} dr_\theta\right) dy \tag{3}$$

$$\begin{aligned} &= \frac{1}{2}\int_0^1 \exp\left(-\int_r^{R_\nu} \frac{1}{\lambda_{\rm att}} \frac{r'}{\sqrt{r^2(y^2-1)+r'^2}} dr'\right) dy \\ &+ \frac{1}{2}\int_{-1}^0 \exp\left(-\int_{r\sqrt{1-y^2}}^{r} \frac{1}{\lambda_{\rm att}} \frac{r'}{\sqrt{r^2(y^2-1)+r'^2}} dr' \right. \\ &\left. - \int_{r\sqrt{1-y^2}}^{R_\nu} \frac{1}{\lambda_{\rm att}} \frac{r'}{\sqrt{r^2(y^2-1)+r'^2}} dr'\right) dy \end{aligned} \tag{4}$$

The dark Z' luminosity is constrainted by the Raffelt's criterion $L_{\rm R}$, which is a rough estimation on the enery rate carried away by SN neutrinos at $t_{\rm pb} = 1$ s.

$$\text{Raffelt's criterion}: \; L_{Z'} < L_{\rm R} = 3 \times 10^{52} \text{ [erg/s]} \tag{5}$$

Reaction Channels

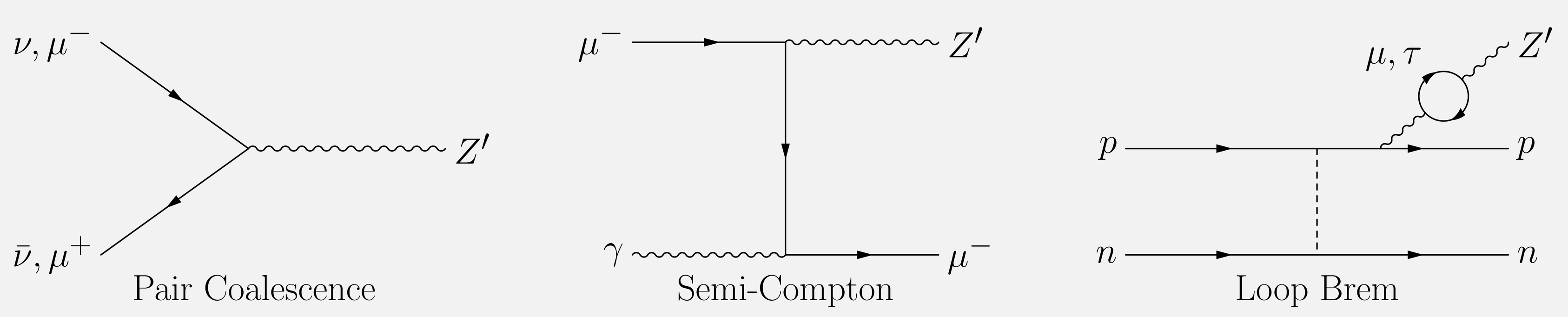

Fig. 4: Dominant Z' emission processes in a core-collapse supernova.

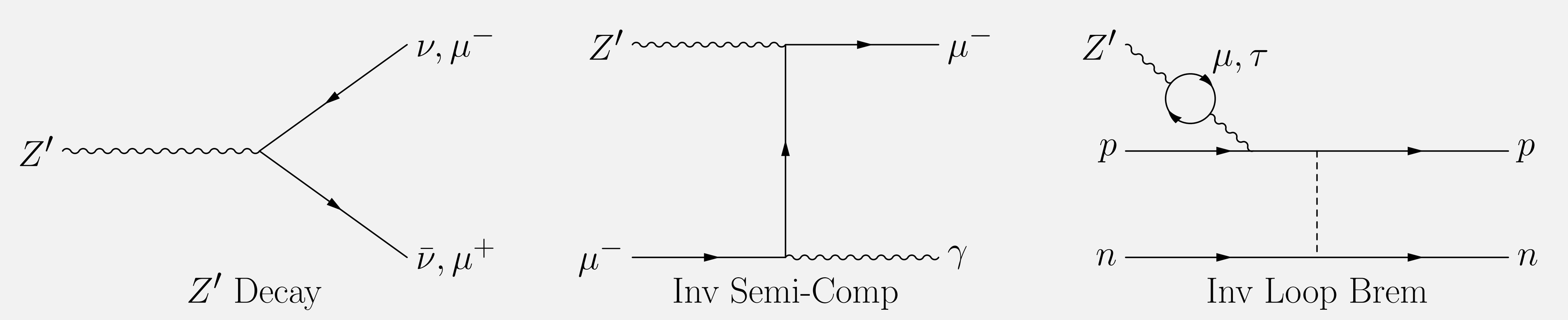

Fig. 5: Dominant Z' re-absorption processes in a core-collapse supernova.

Result

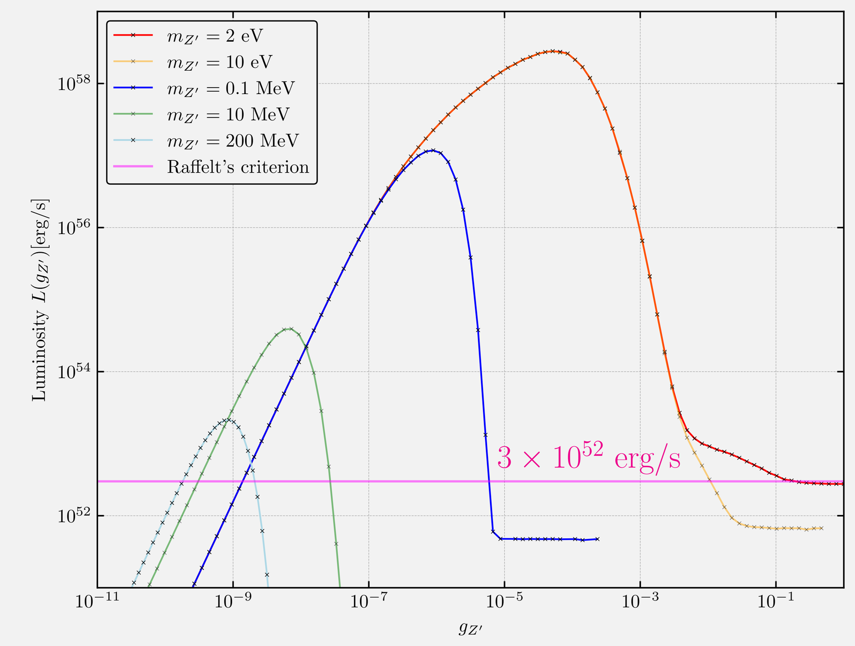

Fig. 6: Z' Luminosity $L_{Z'}(m_{Z'}, g_{Z'})$

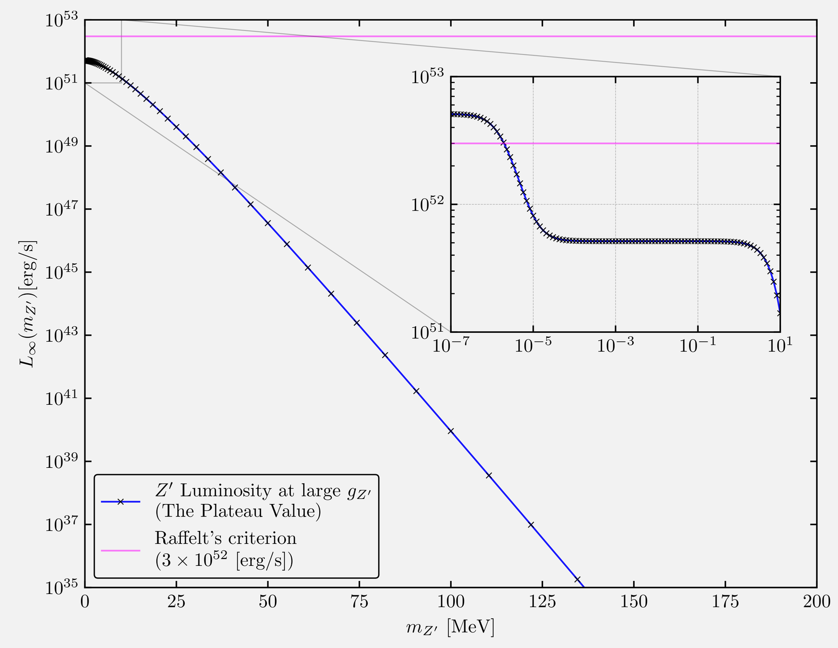

Fig. 7: The plateau value $L_{Z'}(m_{Z'}, \infty)$.

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 $m_{Z'}$ as shown on Fig. 6. On the other hand, the plateau value increases as $m_{Z'}$ decreases on figure 6. Moreover, it gets greater than the Raffelt bound 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 trapping limit) anymore. Thus, the plateau phenomenon stringent the model substantially when $m_{Z'} < 2$ eV.

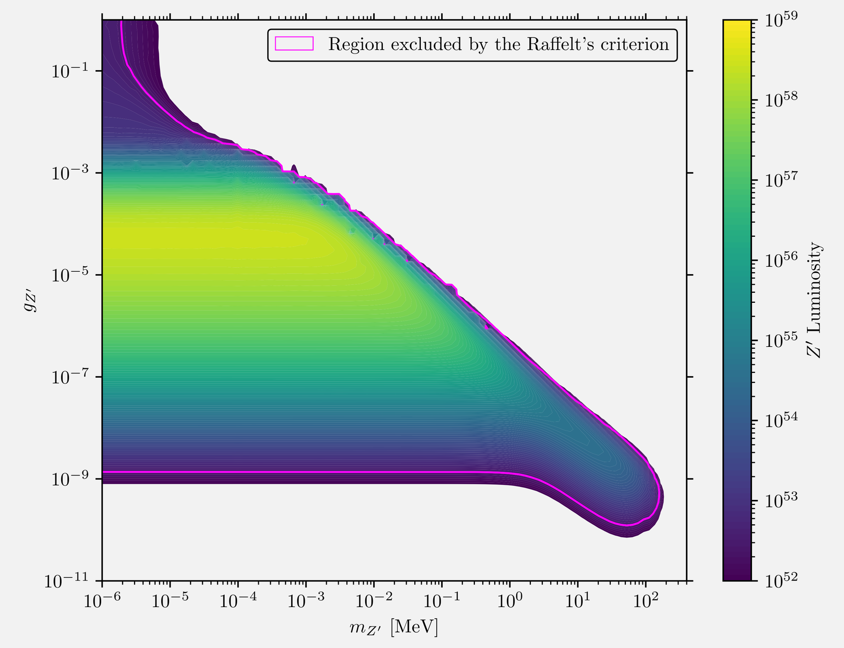

Fig. 8: Region excluded by L_R.

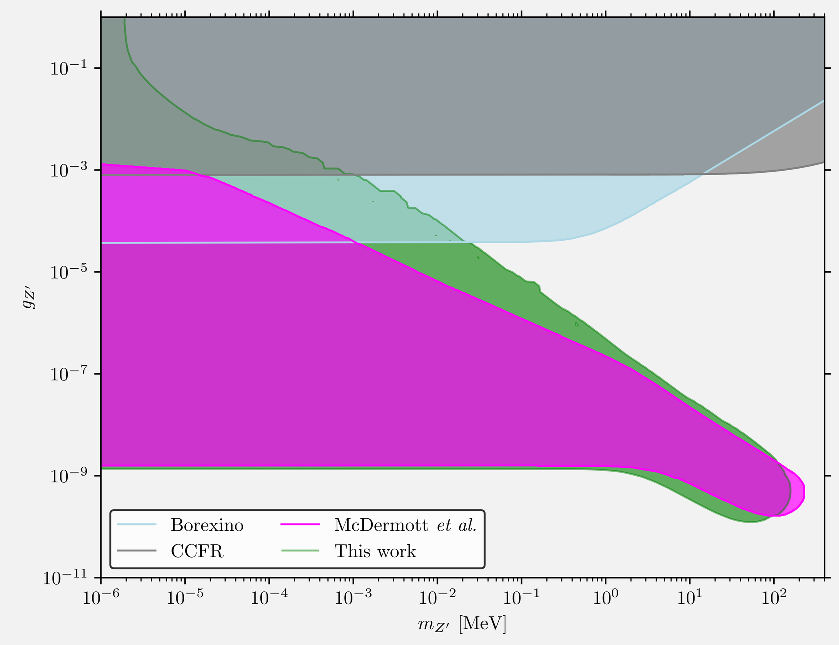

Fig. 9: Comparison with previous works.

The region enclosed by the magenta line on Fig. 8 represents an excluded region that corresponds to Z' luminosity $L_{Z'} > L_{\rm Raffelt}$. 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.* [5] ($R_{\rm far} = 100$km $> R_\nu = 25$ km, the region shaded in magenta colour on figure 9), the production and absorption processes have been treated on an equal footing in our work, i.e., $R_{\rm far} = R_\nu = 25$ km, in the numerical calculation on the attenuation factor (see Eq. (3) and (4)). Results in a plateau phenomenon as indicated on Figs 6 and 7. Consequently, the excluded region will be extended accordingly, and the trapping limit shall disappear when $m_{Z'} \lesssim 2$ eV.

Conclusion

We used Raffelt's criterion (see Eq. (5)) to put constraints on the parameter space $(m_{Z'}, g_{Z'})$ of the $U(1)_{L_\mu - L_\tau}$ model (Fig. 8 and 9) and made comparison to the previous work (McDermott *et al.* [5]). Results in a plateau phenomenon as indicated on Figs 6 and 7. The trapping limit shall disappear as a consequence of the plateau phenomenon when $m_{Z'} \lesssim 2$ eV.

The plateau phenomenon purely comes from the competition between the production and the reabsorption rates, therefore, we expect the plateau should also occur in a large coupling limit for other BSM models that introduce new light boson.

Main References

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