Neutrino-Dark Matter Connections in Gauge Theories

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ABSTRACT

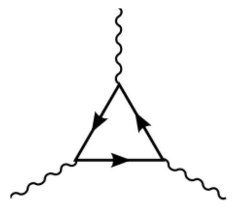
- We discuss the connection between the origin of neutrino masses and the properties of dark matter candidates in minimal gauge extensions of the Standard Model where **neutrinos are predicted to be Dirac fermions.**
- We find that the upper bound on the **effective number of relativistic species provides a strong constraint**.
- In the theories where lepton number is a local gauge symmetry spontaneously broken at the low scale, the existence of dark matter is predicted from the condition of anomaly cancellation.
- Applying the cosmological bound on the dark matter relic density, **we find an upper bound on the symmetry breaking scale in the multi-TeV region.** Therefore, we can test these simple gauge theories for neutrino masses at current or future experiments.

$U(1)_{B-L}$ gauge extension

Promote *B-L* to a local symmetry

Anomaly cancellation:

$$3\nu_R \Rightarrow U(1)_{B-L}$$

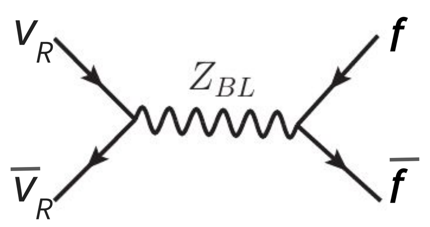


***B-L* symmetry unbroken**

$$\cancel{\tfrac{1}{2} M_R \nu_R^T C \nu_R}$$

What about the Majorana mass term?

This symmetry forbids the Majorana mass term, and hence, neutrinos are predicted to be **Dirac fermions**



These interactions bring ν_R into thermal equilibrium in the early universe and they contribute to the **effective number of relativistic especies** N_{eff}

In order to find when the right-handed neutrino decoupling temperature we set the interaction rate equal to the Hubble expansion rate:

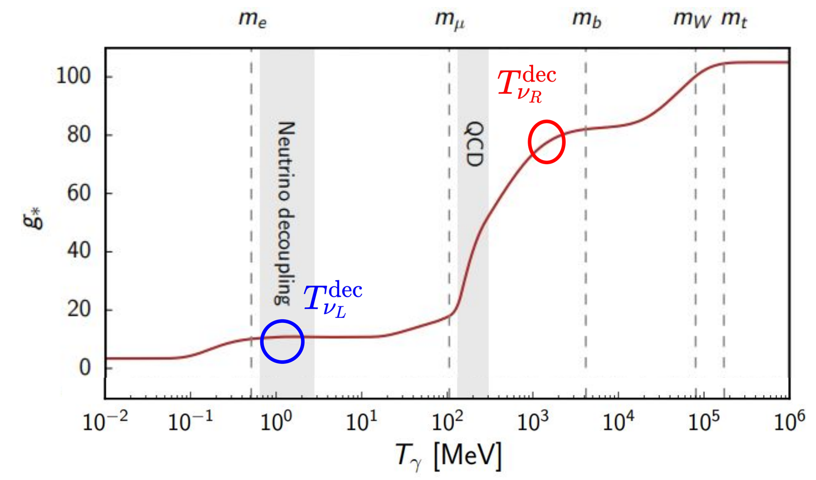
$$\boxed{\Gamma(T_{\nu_R}^{\rm dec}) = H(T_{\nu_R}^{\rm dec})}$$

$$\Gamma_{\nu_R}(T) = n_{\nu_R}(T)\langle\sigma(\bar{\nu}_R\nu_R \to \bar{f}f)\, v_M\rangle = \frac{g_{\nu_R}^2}{n_{\nu_R}(T)}\int \frac{d^3\vec{p}}{(2\pi)^3} f_{\nu_R}(p)\int\frac{d^3\vec{k}}{(2\pi)^3} f_{\nu_R}(k)\sigma_f(s)v_M$$

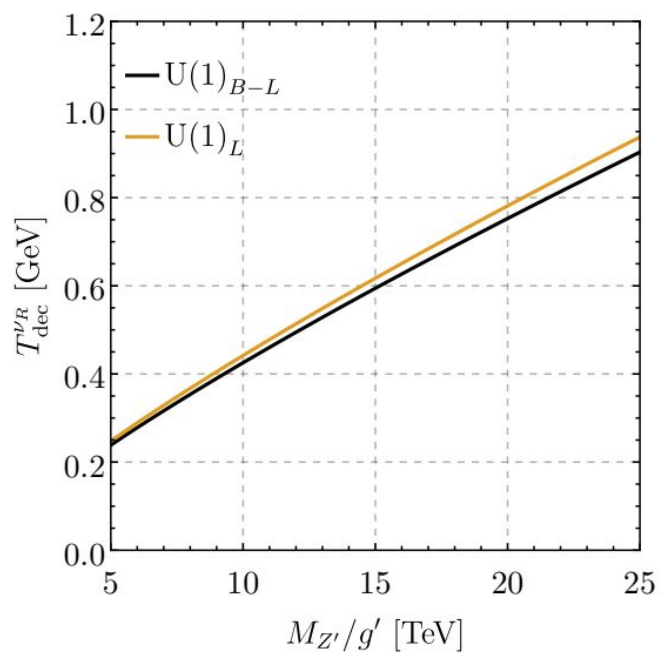
$$H(T) = \sqrt{\frac{8\pi G_N \rho(T)}{3}} = \sqrt{\frac{4\pi^3 G_N}{45}\left(g(T) + 3\frac{7}{8}g_{\nu_R}\right)}\, T^2$$

$$\Delta N_{\rm eff} = N_{\rm eff} - N_{\rm eff}^{\rm SM} = N_{\nu_R}\left(\frac{T_{\nu_R}}{T_{\nu_L}}\right)^4 = N_{\nu_R}\left(\frac{g(T_{\nu_L}^{\rm dec})}{g(T_{\nu_R}^{\rm dec})}\right)^{\frac{4}{3}}$$

$\mathcal{O}$(MeV)
$\mathcal{O}$(GeV)



[Simons Observatory: Science Goal and Forecasts 2019] [Borsany et al 2016]



The decoupling temperature of the right-handed neutrinos ν_R as a function of $M_{Z'}/g'$

See FIG. 1

$$\Delta N_{\rm eff} < 0.285 \text{ at 95\% CL} \Longrightarrow \boxed{\frac{M_{Z_{BL}}}{g_{BL}} > 10.33 \text{ TeV}}$$

[Planck 2018]

Stronger than the LEP & LHC bound for large couplings and/or $M_Z > 4$ TeV

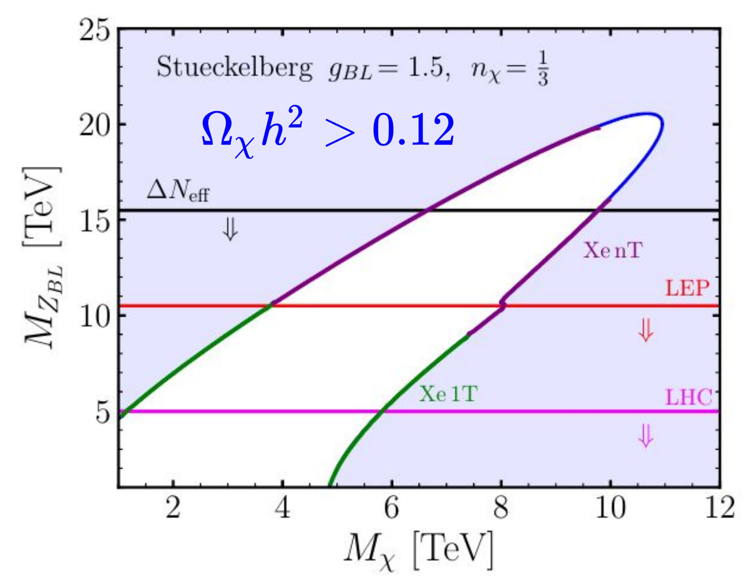
Dark Matter: Introduce vector-like fermion with *B-L* charge

$$\chi \sim (1, 1, 0, n)$$

Green line: Excluded by Xenon-1T

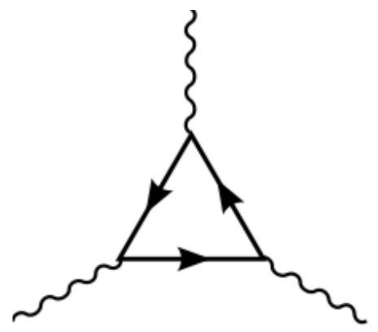
Purple line: Projection for Xenon-nT

We find that this bound on Delta N _eff gives the strongest bound on the model



$U(1)_L$ gauge extension

- Promote lepton number to a local symmetry
- Need to add new fermions to cancel anomalies



$\mathcal{A}_1\,(SU(3)^2\otimes U(1)_L)$, $\mathcal{A}_2\,(SU(2)^2\otimes U(1)_L)$, $\mathcal{A}_3\,(U(1)_Y^2\otimes U(1)_L)$, $\mathcal{A}_4\,(U(1)_Y\otimes U(1)_L^2)$, $\mathcal{A}_5\,(U(1)_B)$, $\mathcal{A}_6\,(U(1)_L^3)$.

In the SM the non-zero values are:

$$\mathcal{A}_2 = -\mathcal{A}_3 = 3/2$$

Fermions and their representation added to cancel anomalies:

Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_L$
$\Psi_L = \begin{pmatrix}\Psi_L^0\\ \Psi_L^-\end{pmatrix}$	1	2	$-\frac{1}{2}$	$-\frac{3}{2}$
$\Psi_R = \begin{pmatrix}\Psi_R^0\\ \Psi_R^-\end{pmatrix}$	1	2	$-\frac{1}{2}$	$\frac{3}{2}$
η_R^-	1	1	-1	$-\frac{3}{2}$
η_L^-	1	1	-1	$\frac{3}{2}$
χ_R^0	1	1	0	$-\frac{3}{2}$
χ_L^0	1	1	0	$\frac{3}{2}$

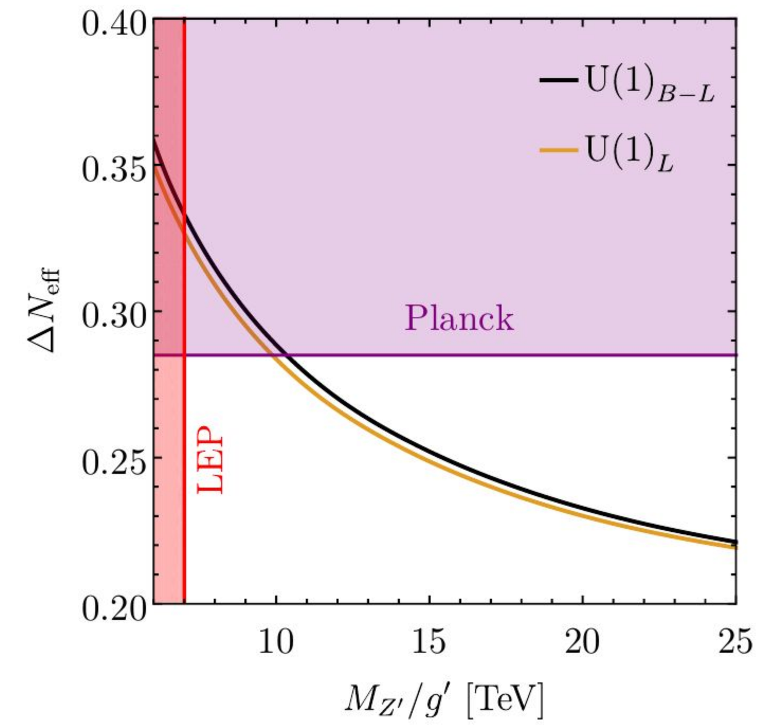
Dark Matter

[Duerr, Fileviez Perez & Wise 2013]

- Neutral fermion required for anomaly cancellation
- Automatically stable from remnant $U(1) \longrightarrow Z_2$ symmetry

DM Candidate

FIG. 1

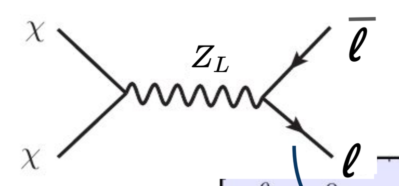


$\Delta N_{\rm eff} < 0.285$

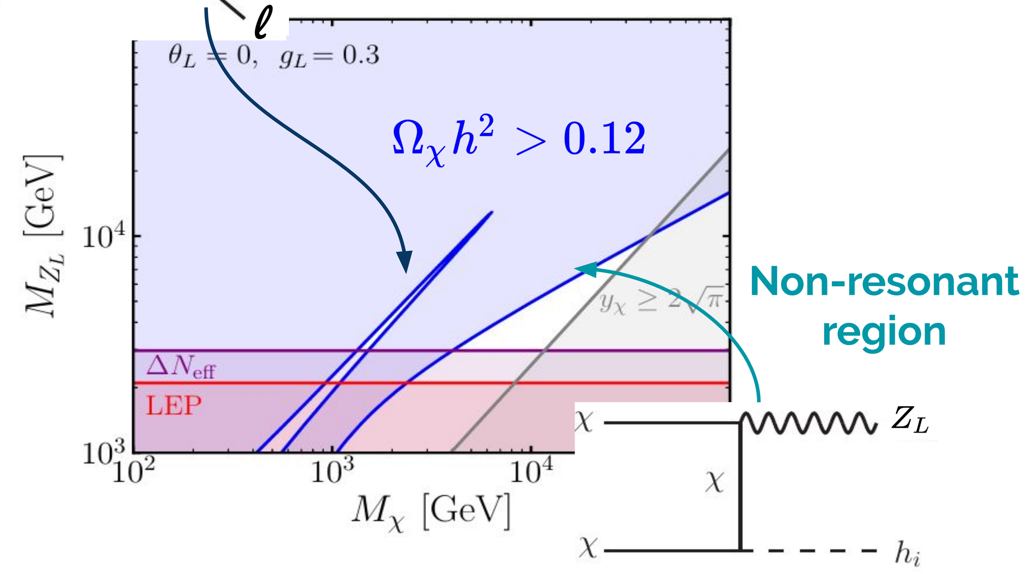
[Planck 2018]

We find that this bound on ΔN_{eff} gives the following bound for the $U(1)_L$ model:

$$\boxed{\frac{M_{Z_L}}{g_L} > 9.87 \text{ TeV}}$$



$$M_\chi \approx M_{Z_L}/2$$



CONCLUSIONS

- $U(1)_{B-L}$ minimal gauge extension of SM that links dark matter and neutrinos
- In this model, lepton number violating processes must lie below the multi-TeV scale (could be reached at the LHC)
- $U(1)_L$ dark matter is predicted from gauge anomaly cancellation
- Unbroken $U(1)_{B-L}$ and $U(1)_L$ neutrinos are Dirac. Next generation CMB will fully test these theories (with thermal DM.)
- Not overproducing $\Omega h^2 \leq 0.12$ implies an upper bound on all these theories < 35 TeV