Neutrino-dark matter connections in gauge theories

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with Pavel Fileviez Perez and Clara Murgui

[arXiv: 1905.06344] PRD 100 (2019) 035041

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PHENO 2020 - Pittsburgh

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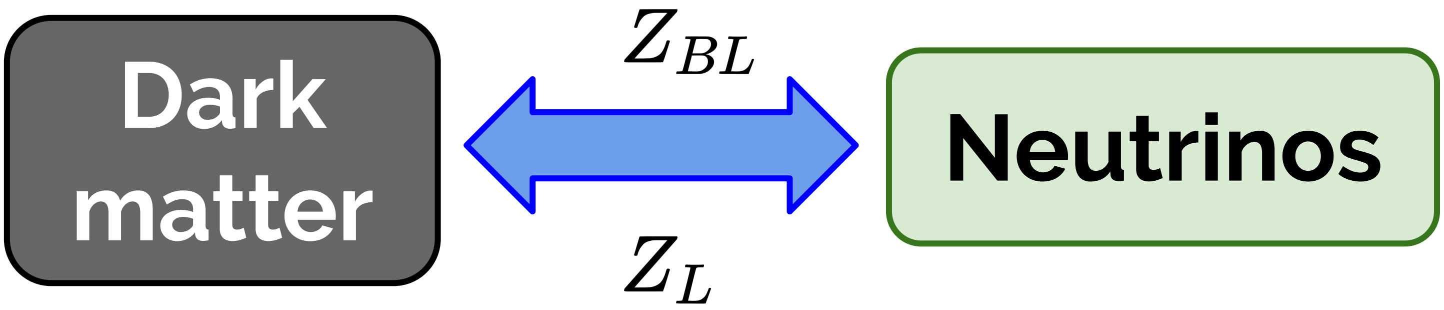
Aim of the talk

In order to explain non-zero neutrino masses, we need to go beyond the SM

Discuss the phenomenology of extensions of the SM where dark matter and neutrinos are linked by new interaction



1. Unbroken $U(1)_{B-L}$

Dirac neutrinos and Dirac DM

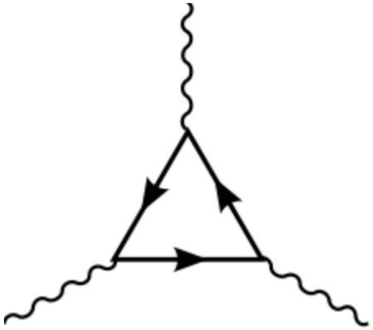
[Fileviez Perez, Murgui, ADP 2019]

Dirac neutrinos

Promote *B-L* to a local symmetry

Anomaly cancellation:

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



***B-L* symmetry unbroken**

$$-\frac{1}{2}M_R\nu_R^T C\nu_R$$

What about the Majorana mass term?

This symmetry forbids the Majorana mass term

Dirac Neutrinos

$$\mathrm{U}(1)_{B-L}$$

In order to give mass to the *B-L* gauge boson we can :

1) Unbroken *B-L*: Stueckelberg mechanism Z_{BL}

2) Spontaneous symmetry breaking of *B-L* Z_{BL}

$$S_{BL} \sim (1, 1, 0, q_{BL})$$

$$|q_{BL}| > 2$$

To forbid Majorana mass term

Dirac Neutrinos

$\mathrm{U}(1)_{B-L}$

In order to give mass to the *B-L* gauge boson we can :

1) Unbroken *B-L*: Stueckelberg mechanism Z_{BL}

2) Spontaneous symmetry breaking of *B-L* Z_{BL}

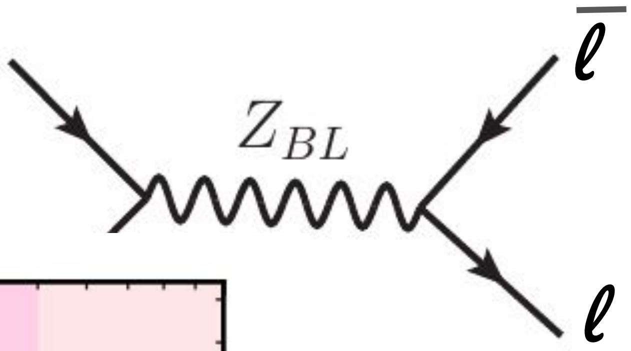
$$S_{BL} \sim (1, 1, 0, q_{BL}) \qquad |q_{BL}| > 2$$

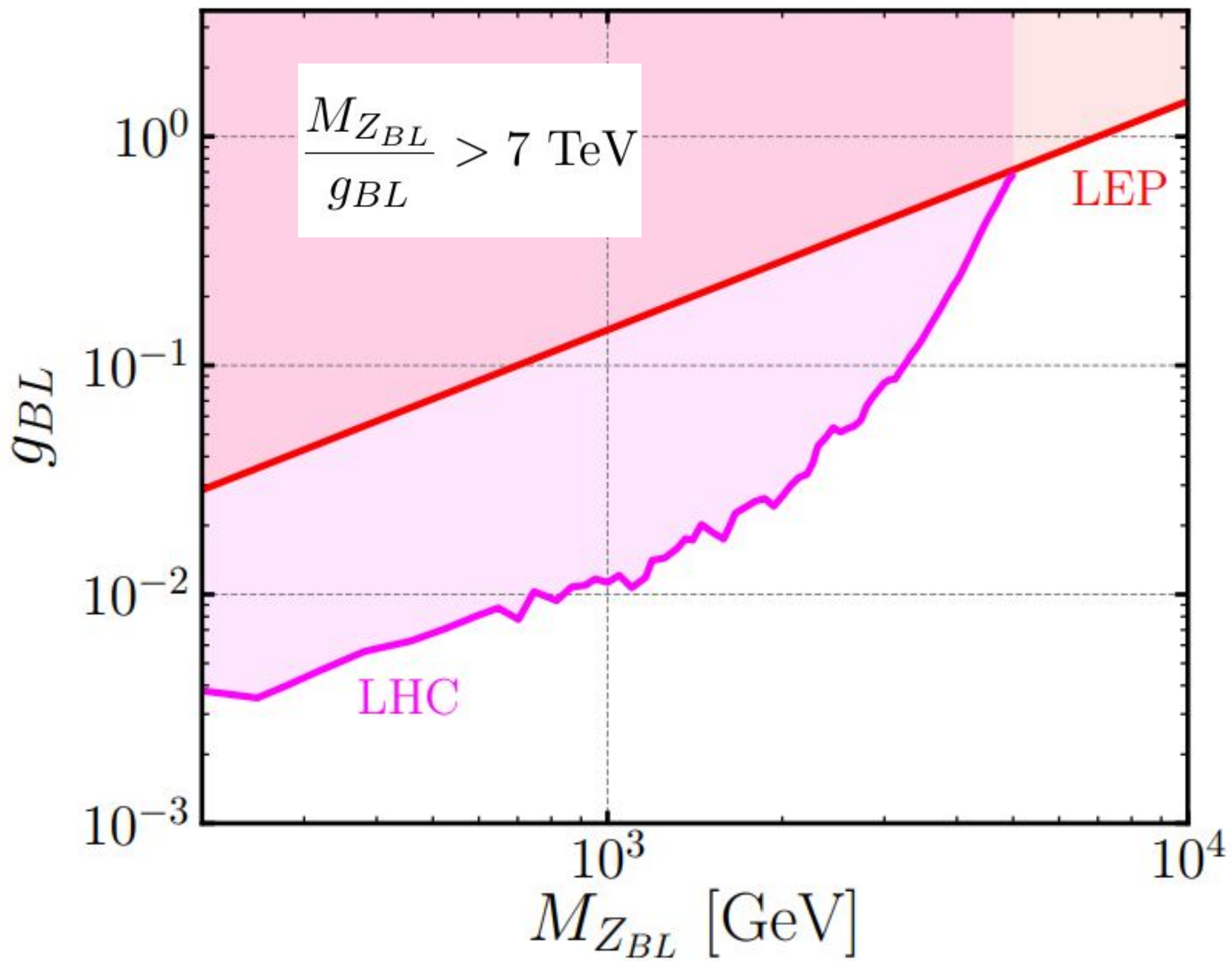
Dirac neutrinos:

$$\nu = \nu_L + \nu_R$$

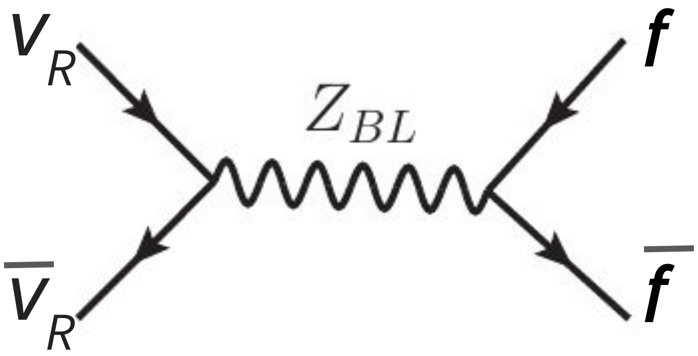
$$m_\nu \leq 0.1 \ \ \mathrm{eV}$$

B - *L* as a local symmetry





[ATLAS 2017] [Alioli, Farina, Pappadopulo, and Ruderman 2018]



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

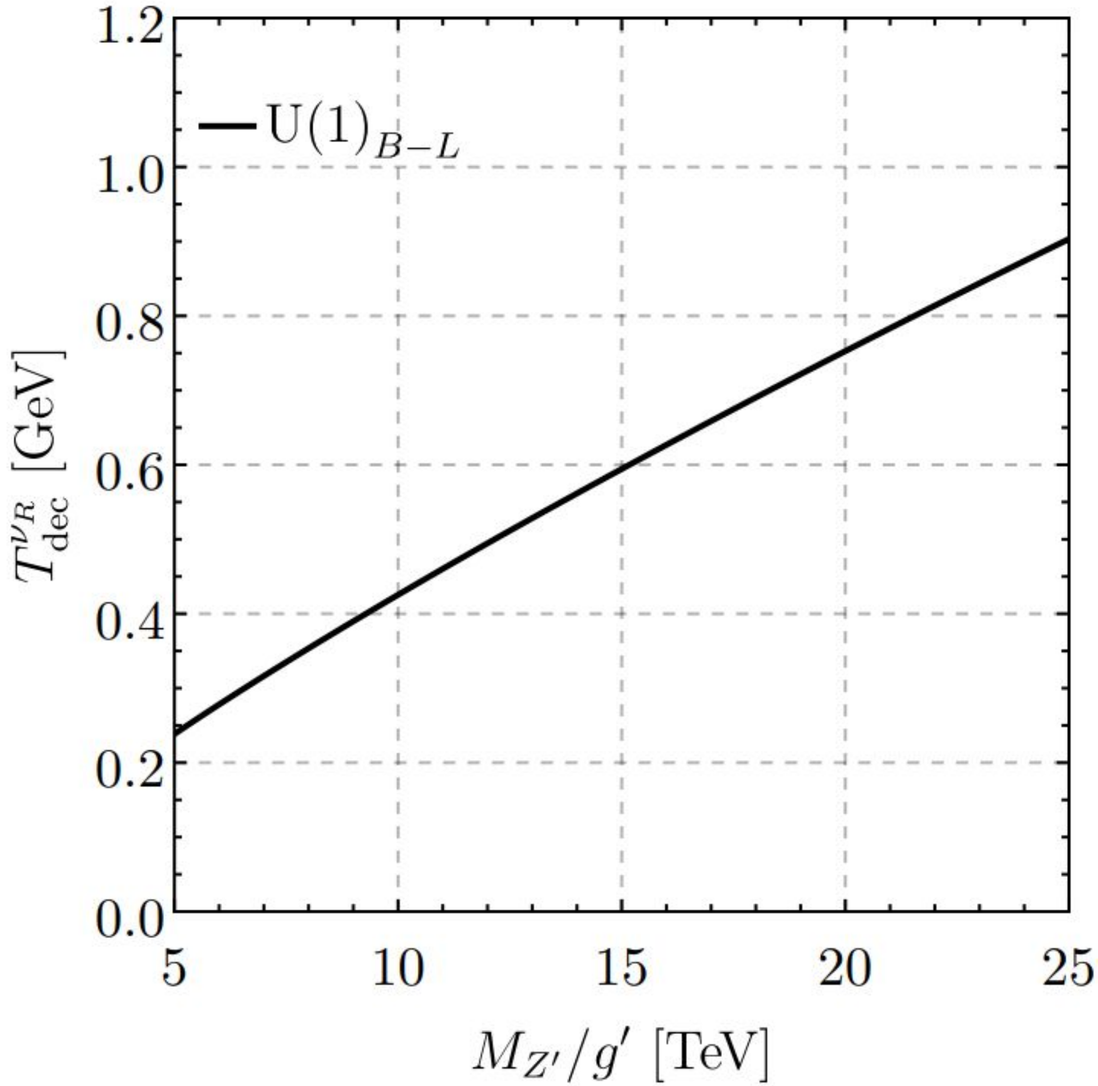
$$\Gamma(T_{\nu_R}^{\text{dec}}) = H(T_{\nu_R}^{\text{dec}})$$

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

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

Decoupling T for ν_R

$\mathrm{U}(1)_{B-L}$



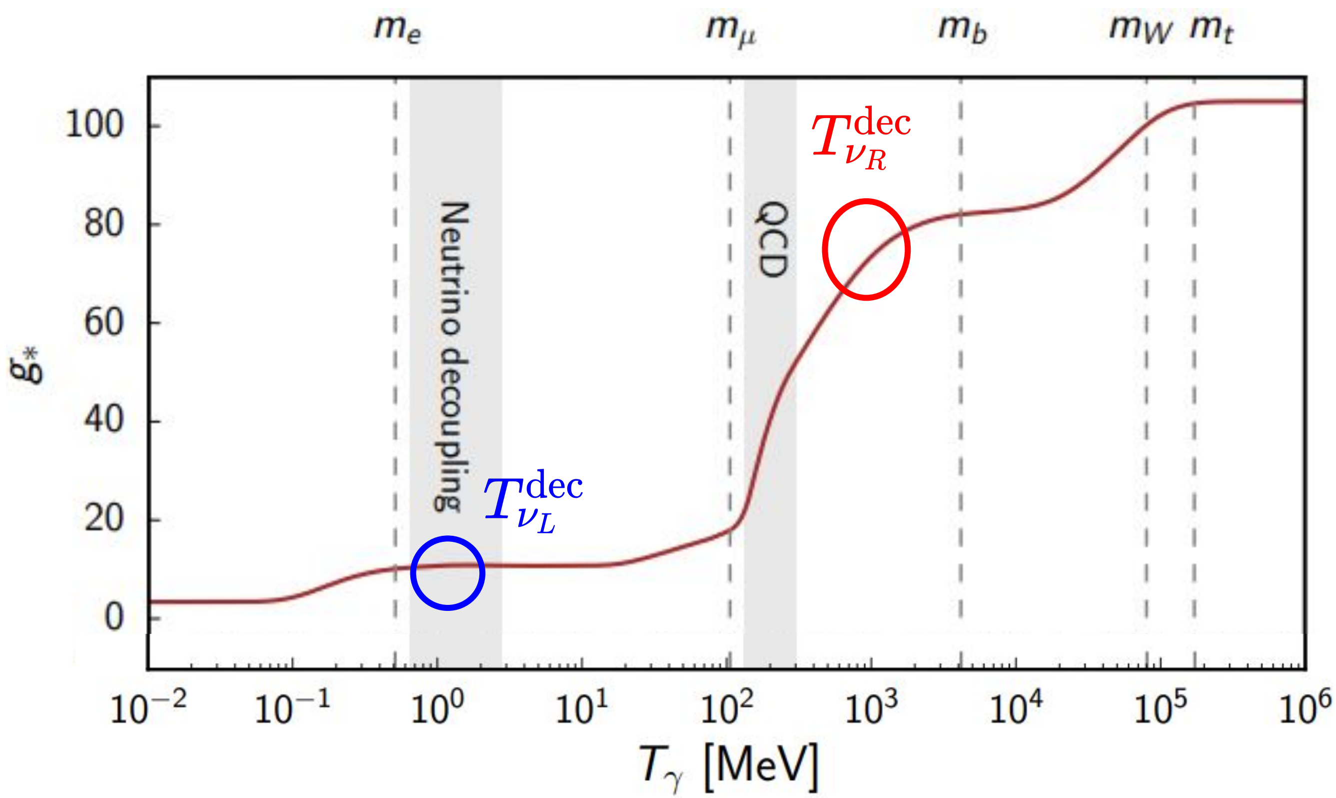
[Fileviez Perez, Murgui, ADP 2019]

N_{eff}

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

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

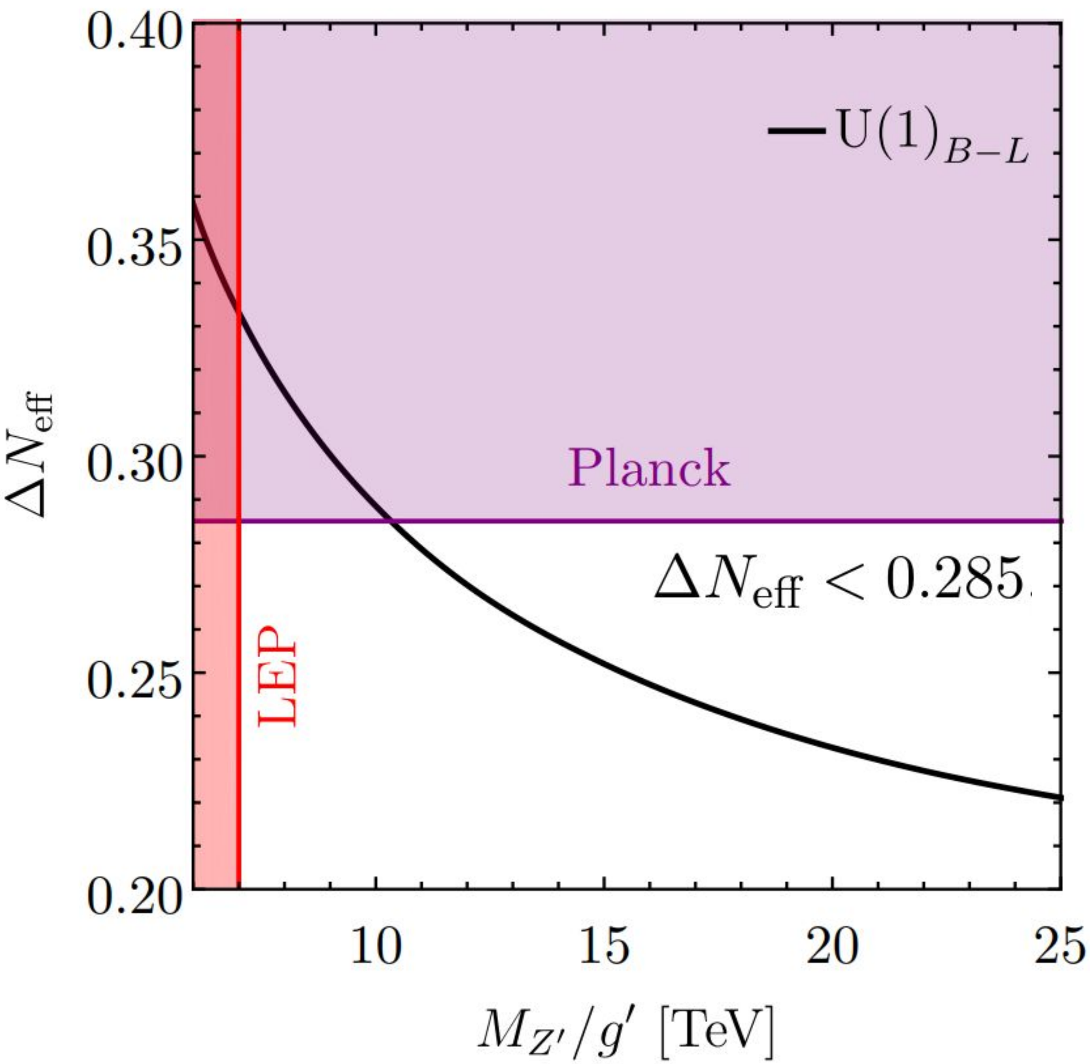
$\mathcal{O}(\text{GeV})$



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

N_{eff}

$\mathrm{U}(1)_{B-L}$



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

at 95% CL

[Planck 2018]

$$\frac{M_{Z_{BL}}}{g_{BL}} > 10.33 \text{ TeV}$$

Stronger than the LEP & LHC bound for large couplings and/or $M_{Z'} > 4$ TeV

[Fileviez Perez, Murgui, ADP 2019]

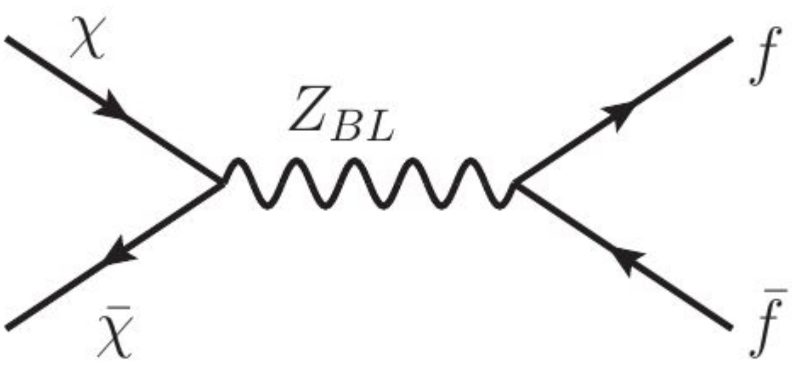
Dirac fermion as dark matter

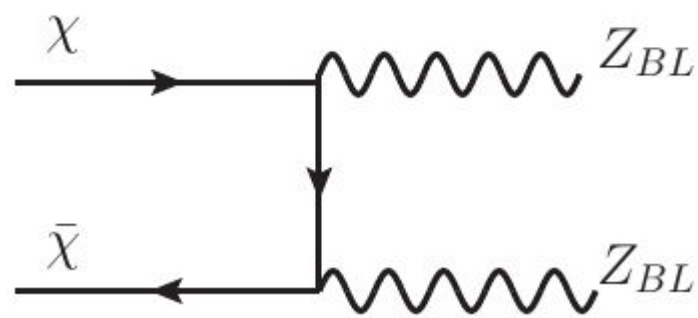
Introduce vector-like fermion with *B-L* charge

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

***n* ≠ 1** since n=1 allows mixing with neutrinos and decay

Non-renormalizable operators forbid *n* odd

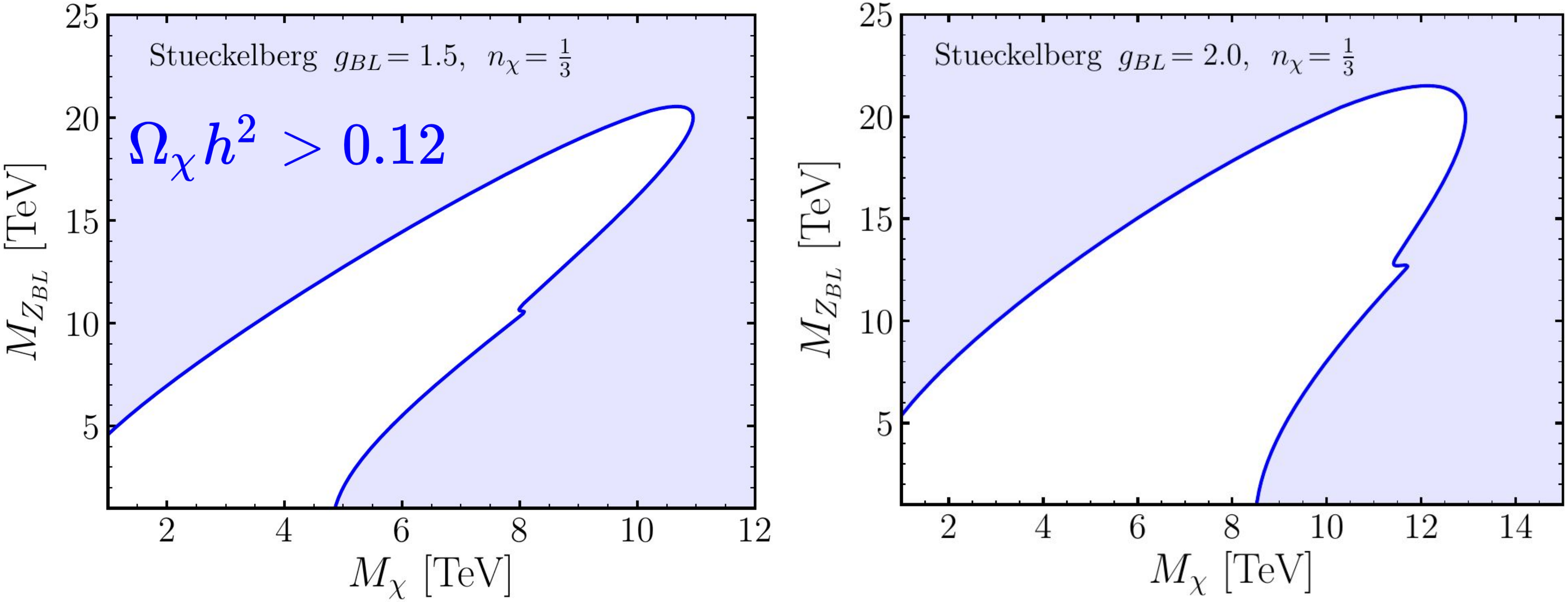




Dark Matter

$\mathrm{U}(1)_{B-L}$

$\Omega_\chi h^2 = 0.1200 \pm 0.0012$ [Planck 2018]



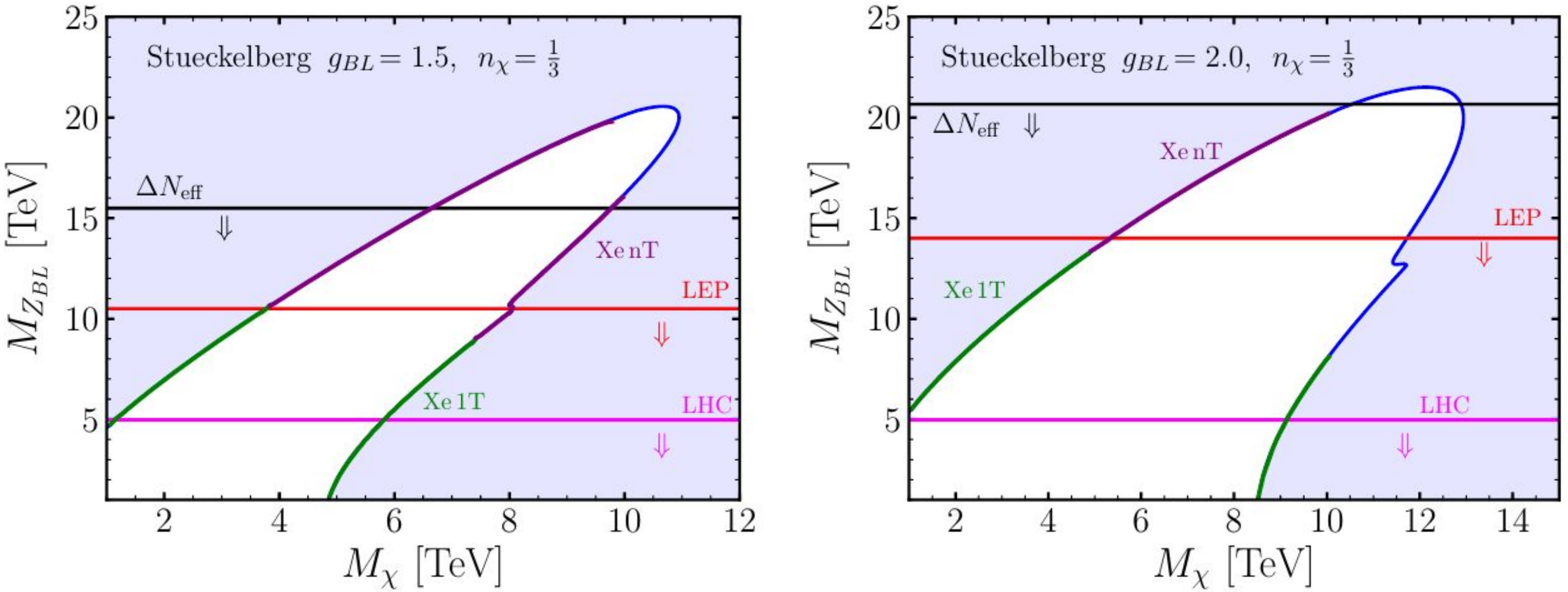
$$M_{Z_{BL}} \leq 22 \text{ TeV} \qquad M_\chi \leq 13 \text{ TeV}$$

Note: Partial wave unitarity requires $M_{DM} < 240$ TeV weaker bound [Griest & Kamionkowski 1990]

Dark Matter

$\mathrm{U}(1)_{B-L}$

$\Omega_\chi h^2 = 0.1200 \pm 0.0012$ **[Planck 2018]**



$\Delta N_{eff} < 0.285$ gives the strongest bound

2. $U(1)_L$

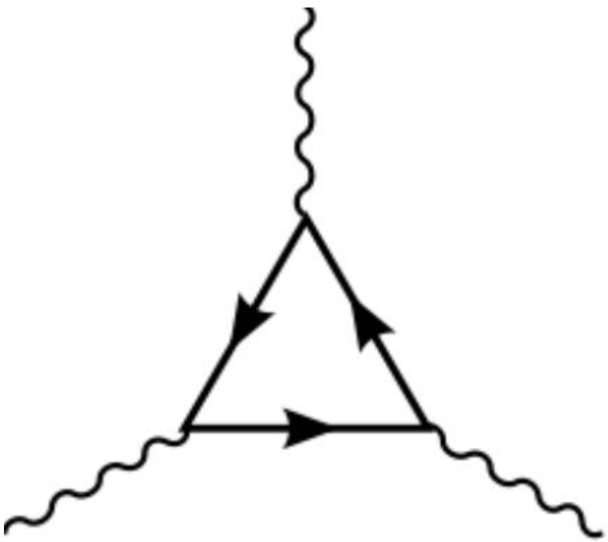
Dirac neutrinos and Majorana DM

[Fileviez Perez, Murgui, ADP 2019]

Gauging lepton number

$\mathrm{U}(1)_L$

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



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

In the SM the non-zero values are:

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

Anomaly-free model

$U(1)_L$

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	$\frac{3}{2}$

[Duerr, Fileviez Perez & Wise 2013]

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

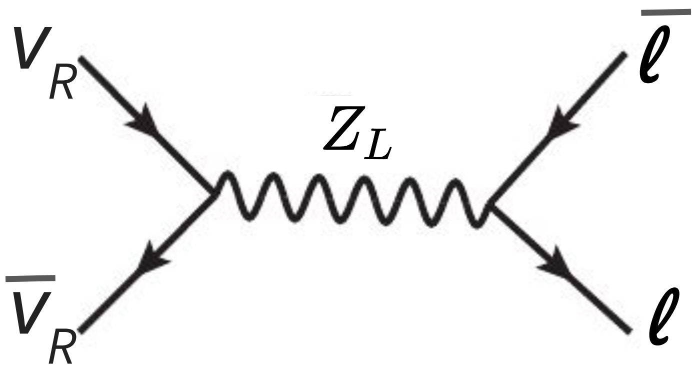
⟶ DM Candidate

Dirac neutrinos

$\mathrm{U}(1)_L$

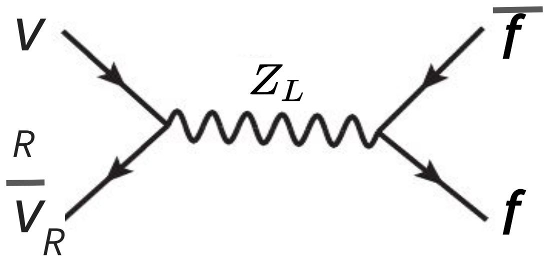
- Lepton number broken by 3 units: $\Delta L = \pm 3$ interactions

→ **Dirac neutrinos**

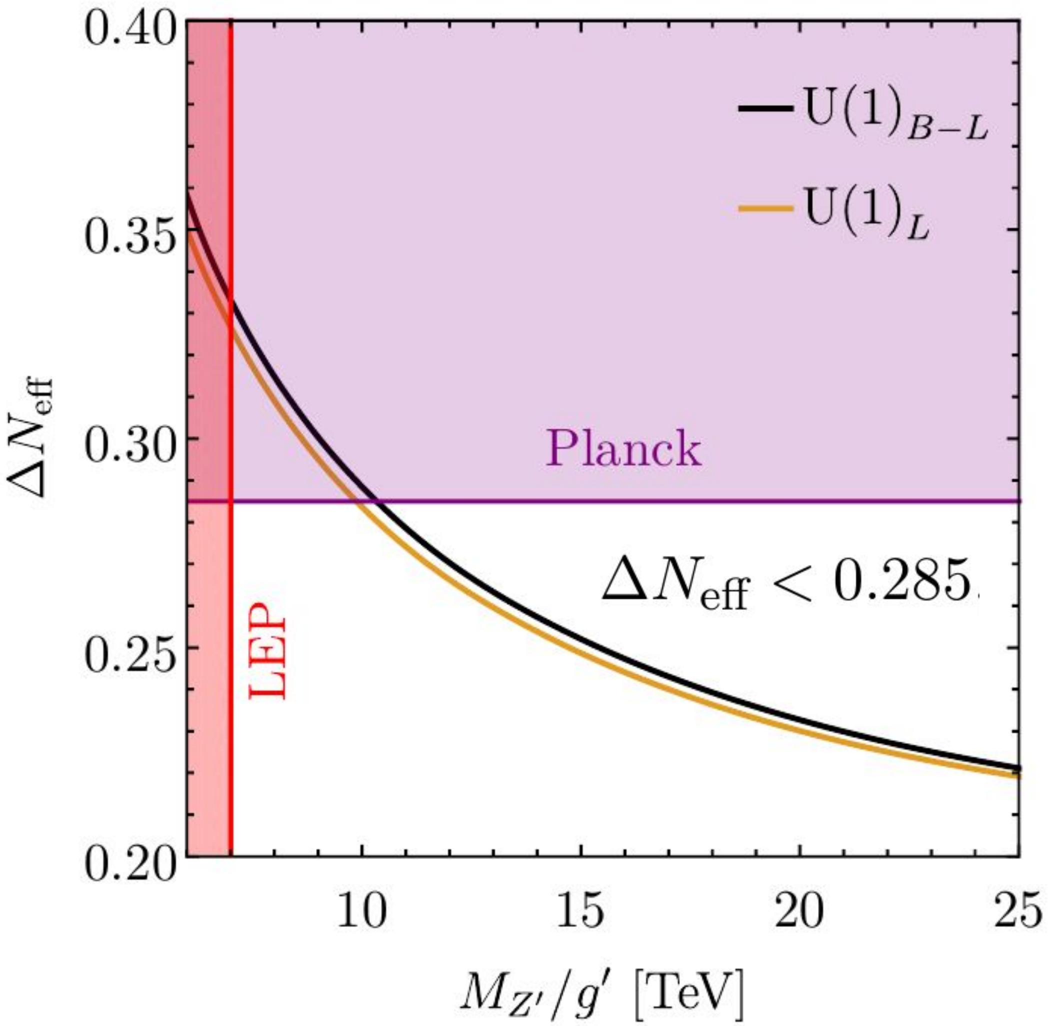


Constraints from N_{eff} also apply to this scenario!

N_{eff}



$U(1)_L$



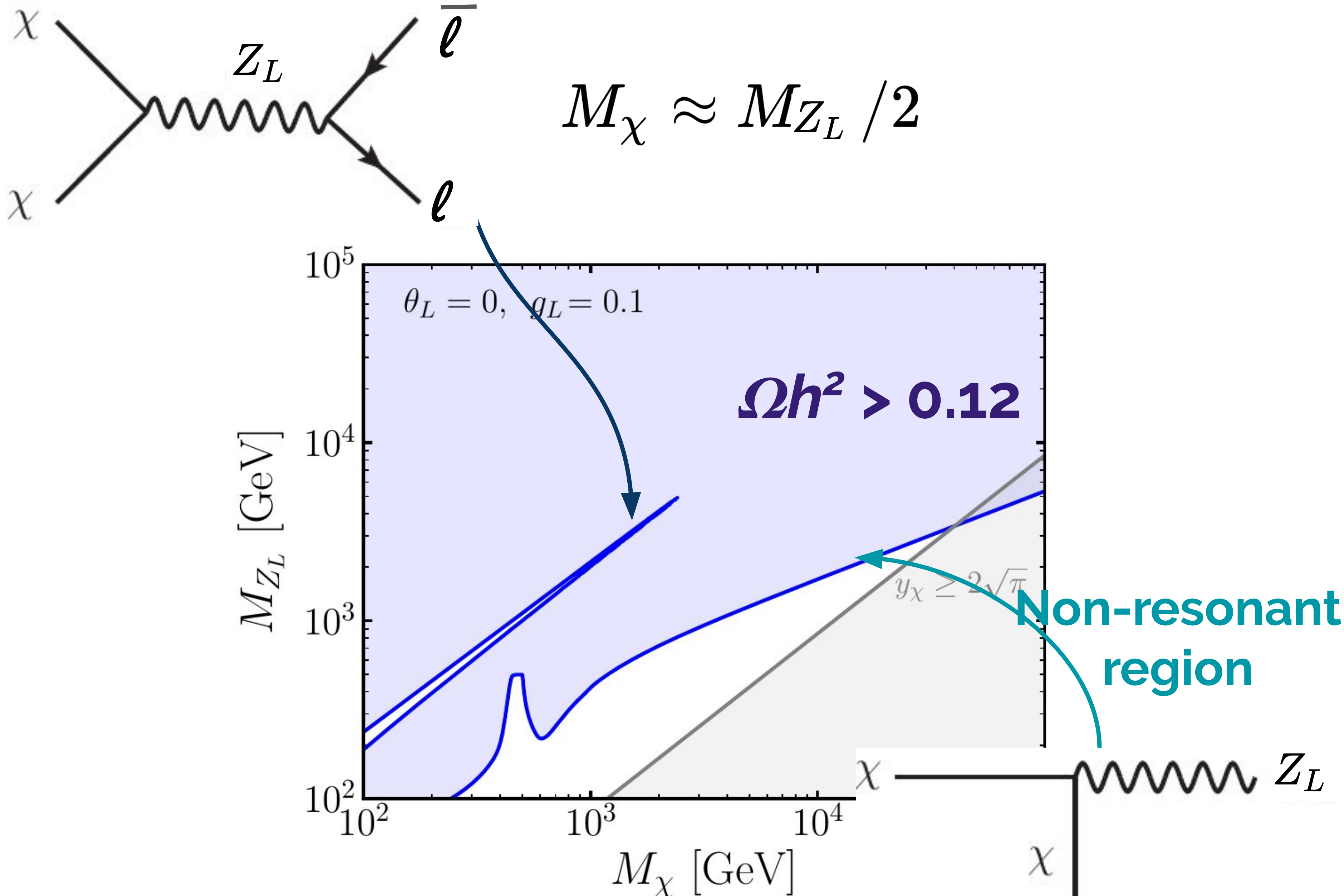
$$\Delta N_{\rm eff} < 0.285$$

[Planck 2018]

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

[Fileviez Perez, Murgui, ADP 2019]

Stronger than the LEP bound: $\frac{M_{Z_L}}{g_L} > 7 \text{ TeV}$



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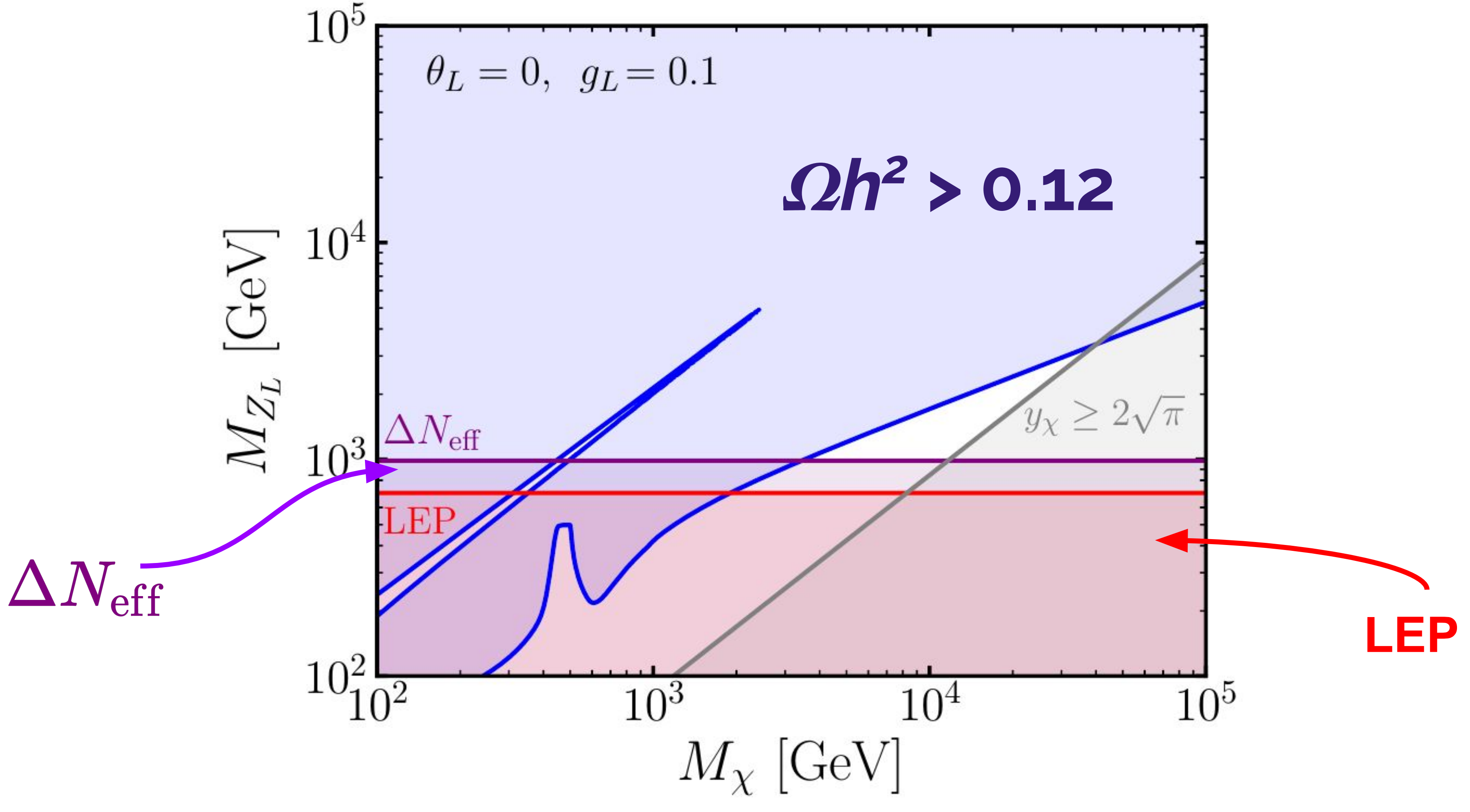
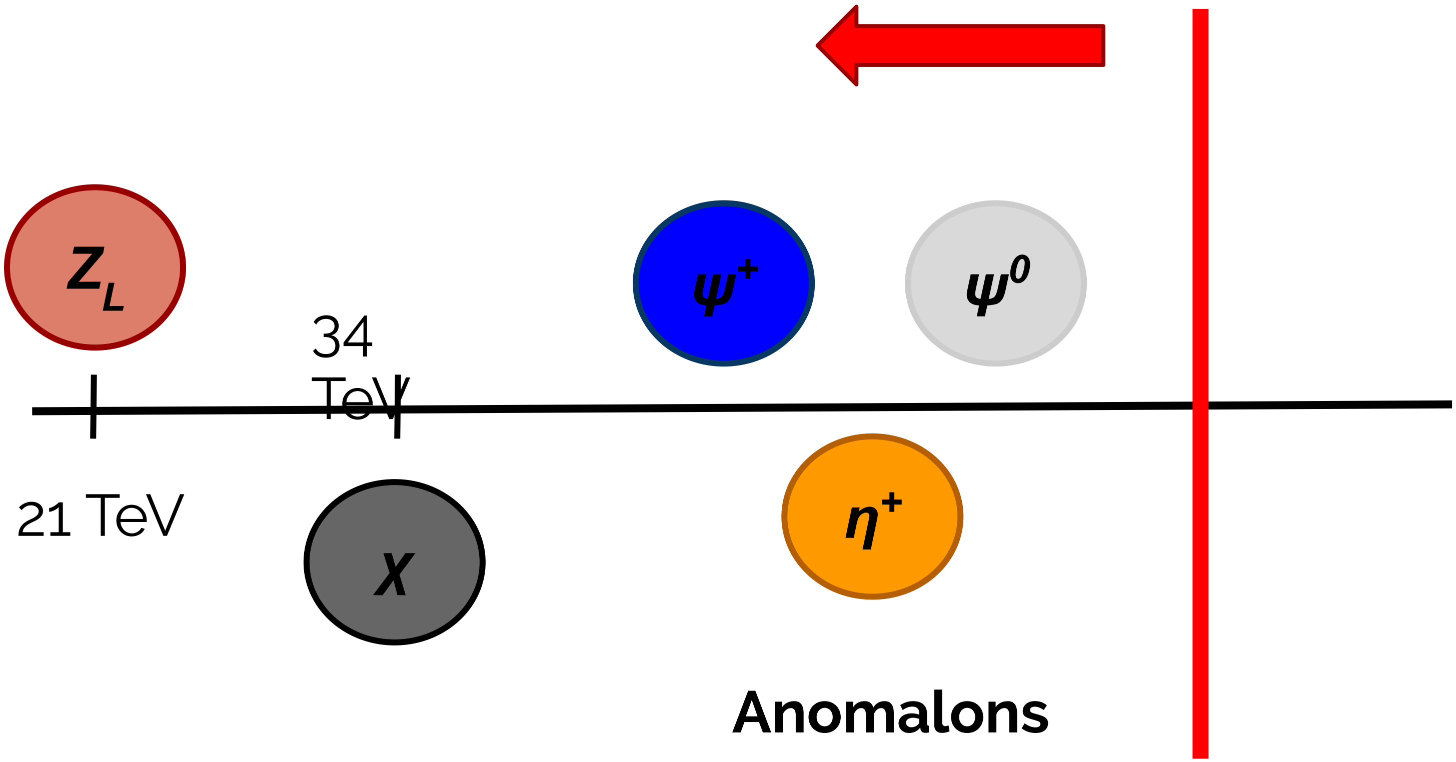
- Z_L does not couple to quarks
- Direct detection constraints can be avoided with $\sin\theta < 0.1$



Upper bound on lepton number breaking scale

Perturbativity $g_L \leq \frac{\sqrt{2\pi}}{3} \approx 0.84$ and $\Omega h^2 \leq 0.12$

All masses connected to $\langle v \rangle_L$ and hence there is an upper bound for the full model



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Next generation CMB experiments

- Telescope array in the Atacama Desert, Chile
- Funded
- Observing 2020's

$$\Delta N_{\rm eff} < 0.12 \ \text{ at } 95\% \, \text{CL}$$

[Simons Observatory: Science Goal and Forecasts 2019]

Projection for CMB Stage-IV:

$$\Delta N_{\rm eff} < 0.06 \quad \text{at } 95\% \, \text{CL}$$

[CMB-S4 Science Book 2016]

- Array of ground-based telescopes in South Pole and Chile
- Joint NSF and DOE project
- Observing late 2020s

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

Thank you!


рахмат
danke
謝謝
ngiyabonga
teşekkür ederim
Баярлалаа
spas
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kia ora
barka
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tapadh leat
спасибо
faafetai lava
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merci

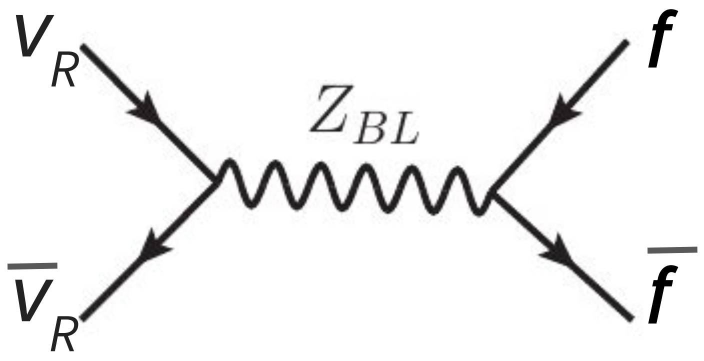
Back-up

Model II

Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
$\Psi_L = \begin{pmatrix} \Psi_L^+ \\ \Psi_L^0 \end{pmatrix}$	1	2	$\frac{1}{2}$	$\frac{3}{2}$
$\Psi_R = \begin{pmatrix} \Psi_R^+ \\ \Psi_R^0 \end{pmatrix}$	1	2	$\frac{1}{2}$	$-\frac{3}{2}$
$\Sigma_L = \frac{1}{\sqrt{2}} \begin{pmatrix} \Sigma_L^0 & \sqrt{2}\Sigma_L^+ \\ \sqrt{2}\Sigma_L^- & -\Sigma_L^0 \end{pmatrix}$	1	3	0	$-\frac{3}{2}$
χ_L^0	1	1	0	$-\frac{3}{2}$

[Ohmer, Fileviez Perez, Patel 2014]

N_{eff}



$\mathrm{U}(1)_{B-L}$

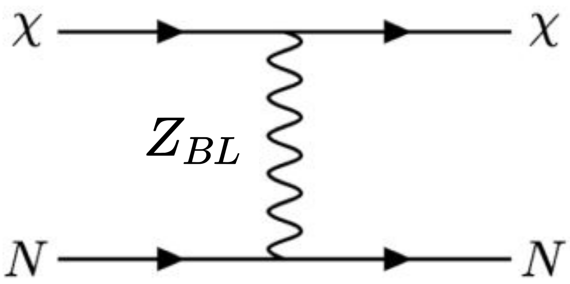
$$\Gamma(T_{\nu_R}^{\mathrm{dec}}) = H(T_{\nu_R}^{\mathrm{dec}})$$

$$\sigma_{\bar{\nu}_R \nu_R \to \bar{f} f} = \frac{g'^4}{12\pi\sqrt{s}} \frac{1}{(s - M_{Z'}^2)^2 + \Gamma_{Z'}^2 M_{Z'}^2} \sum_f N_f^C n_f^2 \sqrt{s - 4M_f^2}\,(2M_f^2 + s)$$

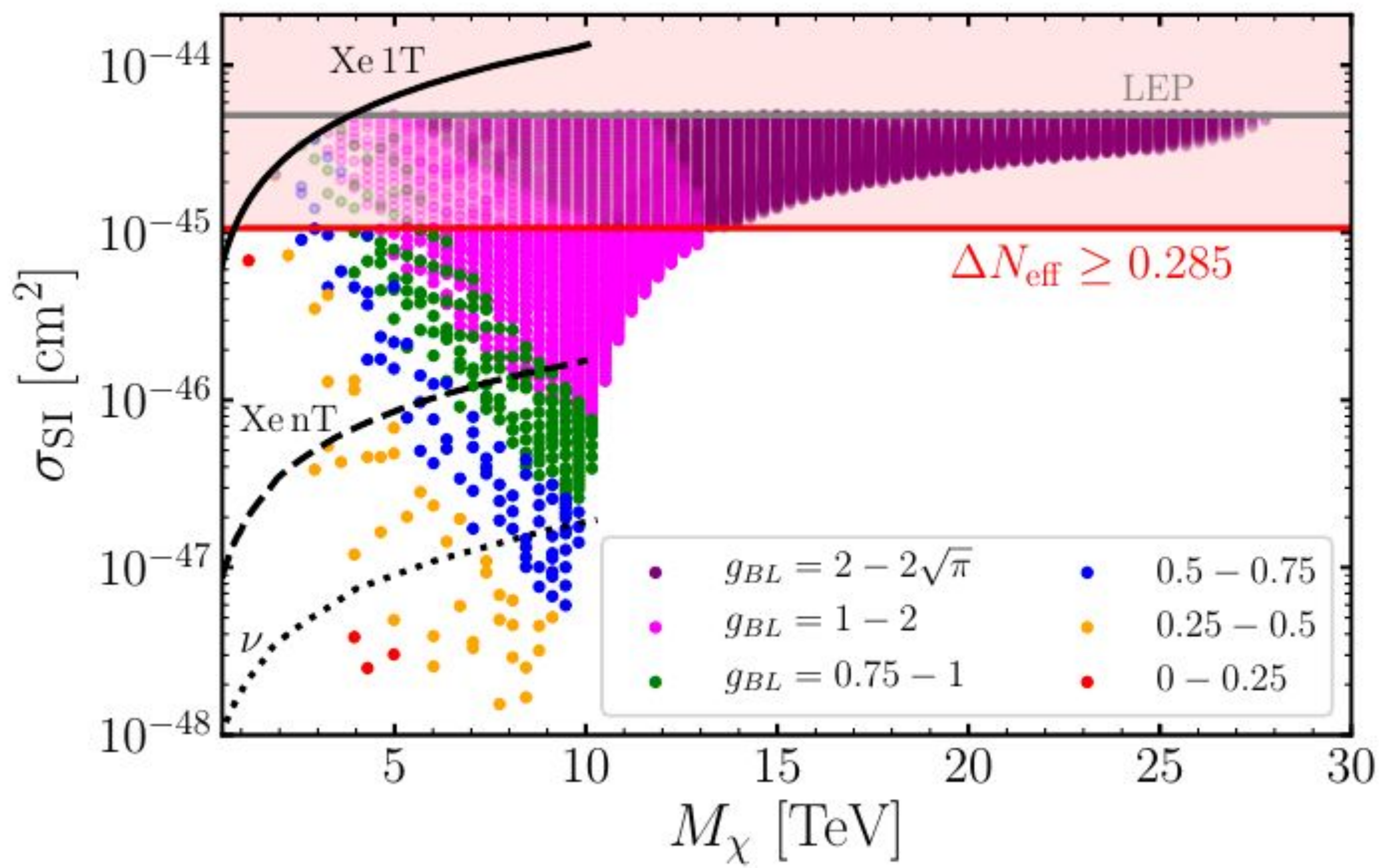
$$T_{\nu_R}^{\mathrm{dec}} \ll M_{Z'} \qquad \Gamma_{\nu_R}(T) = \frac{49\pi^5 T^5}{97200\xi(3)} \left(\frac{g'}{M_{Z'}}\right)^4 \sum_f N_f^C n_f^2,$$

Dark Matter - direct detection

$\mathrm{U}(1)_{B-L}$



$$\sigma_{\rm SI} = \frac{m_N^2 M_\chi^2}{\pi (m_N + M_\chi)^2} \frac{n_\chi^2 g_{BL}^4}{M_{Z_{BL}}^4},$$



N_{eff}

$$N_{\rm eff} = 2.99^{+0.34}_{-0.33} \quad \Rightarrow \quad \Delta N_{\rm eff} < 0.285,$$

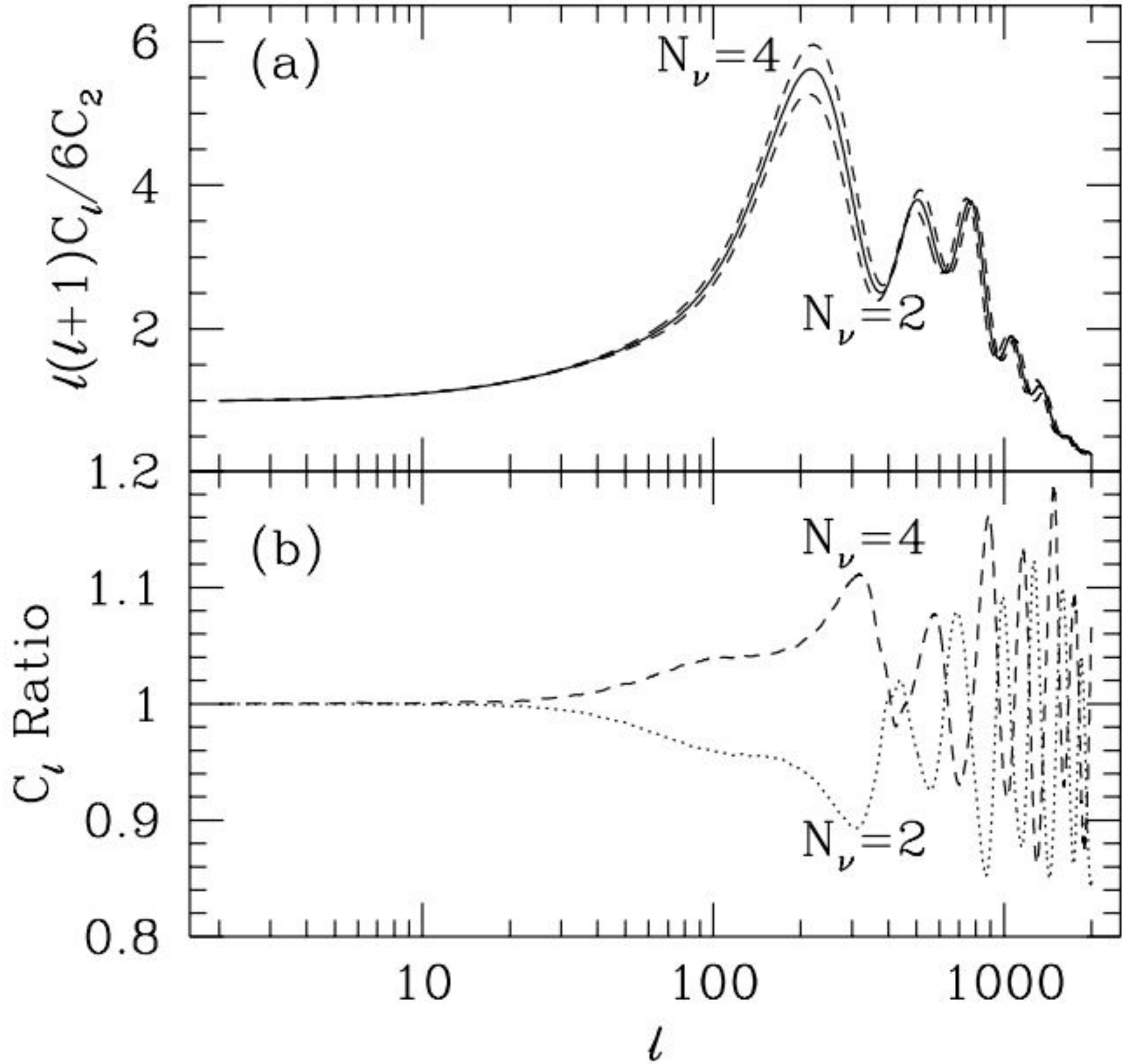
[Planck 2018]

Projection for CMB Stage-IV:

$$\Delta N_{\rm eff} < 0.06 \quad \textbf{at } 95\%\,\textbf{CL}$$

[CMB-S4 Science Book 2016]

N_{eff}



[Hu et al 1995]

N_{eff}

$\mathrm{U}(1)_{B-L}$

As long as V_R reached thermal equilibrium in early Universe, ΔN_{eff} goes asymptotically to

$$\Delta N_{\mathrm{eff}} \to 0.021$$

In other words, as long as $T_{reheating} > T_{equil}$ there will be a non-zero contribution to ΔN_{eff}

ΔN_{eff} can be sensitive to a high scale Z_{BL}!