Neutrino-dark matter connections in gauge theories

Alexis Plascencia

with Pavel Fileviez Perez and Clara Murgui

[arXiv: 1905.06344] PRD 100 (2019) 035041

[arXiv: 2008.09116] JHEP 03 (2021) 185

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

"Neutrinos as a Portal to New Physics and Astrophysics" - KITP, March 11, 2022

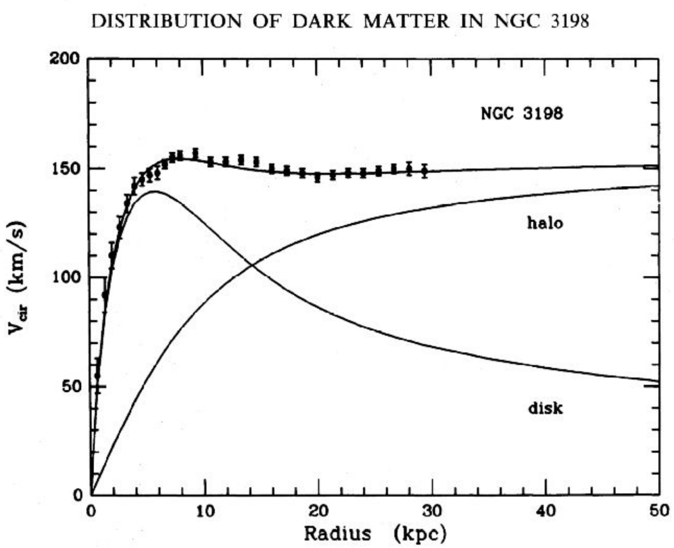
Aim of the talk

Discuss minimal gauge extensions of the SM that predict dark matter and neutrino masses.

These theories must live at the low scale and can be fully probed in the near future.

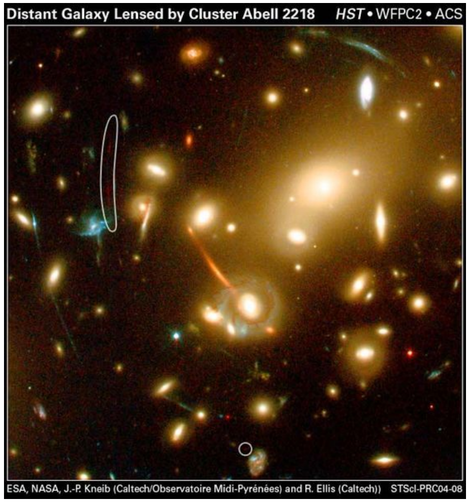
Dark Matter

Rotation curves

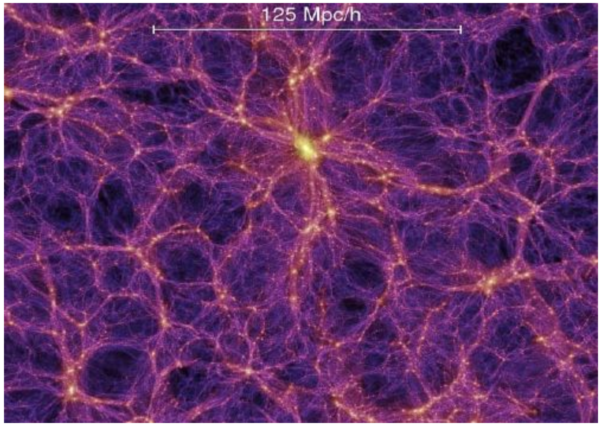


Bullet cluster

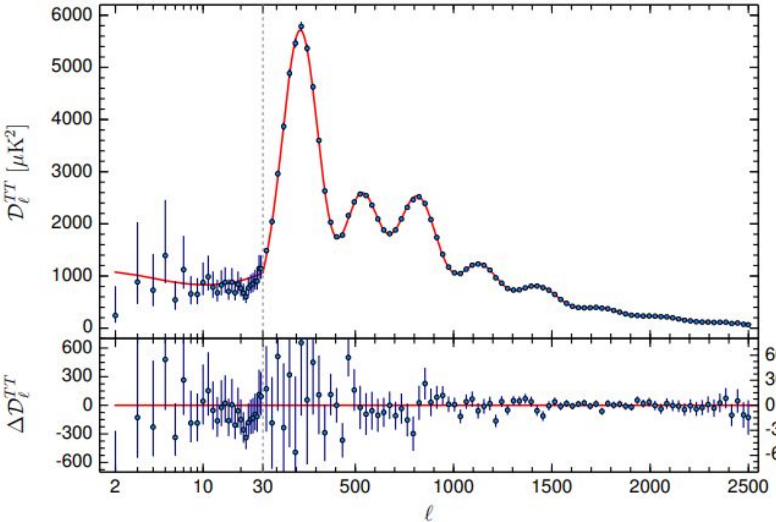
Gravitational lensing



Structure formation



CMB



Neutrino masses

NuFIT 4.1 (2019)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK-atm	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.62 \to 36.27$
	$\sin^2\theta_{23}$	$0.582^{+0.015}_{-0.019}$	$0.428 \to 0.624$	$0.582^{+0.015}_{-0.018}$	$0.433 \to 0.623$
	$\theta_{23}/^\circ$	$49.7^{+0.9}_{-1.1}$	$40.9 \to 52.2$	$49.7^{+0.9}_{-1.0}$	$41.2 \to 52.1$
	$\sin^2\theta_{13}$	$0.02240^{+0.00065}_{-0.00066}$	$0.02044 \to 0.02437$	$0.02263^{+0.00065}_{-0.00066}$	$0.02067 \to 0.02461$
	$\theta_{13}/^\circ$	$8.61^{+0.12}_{-0.13}$	$8.22 \to 8.98$	$8.65^{+0.12}_{-0.13}$	$8.27 \to 9.03$
	$\delta_{\rm CP}/^\circ$	217^{+40}_{-28}	$135 \to 366$	280^{+25}_{-28}	$196 \to 351$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.525^{+0.033}_{-0.031}$	$+2.431 \to +2.622$	$-2.512^{+0.034}_{-0.031}$	$-2.606 \to -2.413$

The Standard Model needs to be extended to account for non-zero neutrino masses

$$m_\nu \neq 0$$

New Gauge Symmetries at the Low Scale

- Anomalous symmetries, predict a new sector needed for Anomaly Cancellation

- Predict a DM candidate from Anomaly Cancellation

- The new symmetry breaking scale must be low to be in agreement with Cosmology

New Gauge Symmetries at the Low Scale

- Anomalous symmetries, predict a new sector needed for Anomaly Cancellation
- Predict a DM candidate from Anomaly Cancellation
- The new symmetry breaking scale must be low to be in agreement with Cosmology
- New gauge boson couples to neutrinos and dark matter
- Predict new CP-violating interactions. Can be complementary tested by CMB data, dark matter and EDM experiments

$U(1)_L$

Dirac neutrinos and Majorana DM

[Fileviez Perez, Murgui, ADP 1905.06344]

Gauging Lepton Number

- Lepton number is an accidental global symmetry in the SM
- Anomalous in the Standard Model

$$\underbrace{\mathrm{U}(1)_L}_{\text{Local gauge symmetry}} \qquad \langle S_L \rangle \neq 0$$

Local gauge symmetry

gauge boson: Z_L

- Spontaneous breaking of lepton number
- Consistent UV completion of leptophilic models of DM

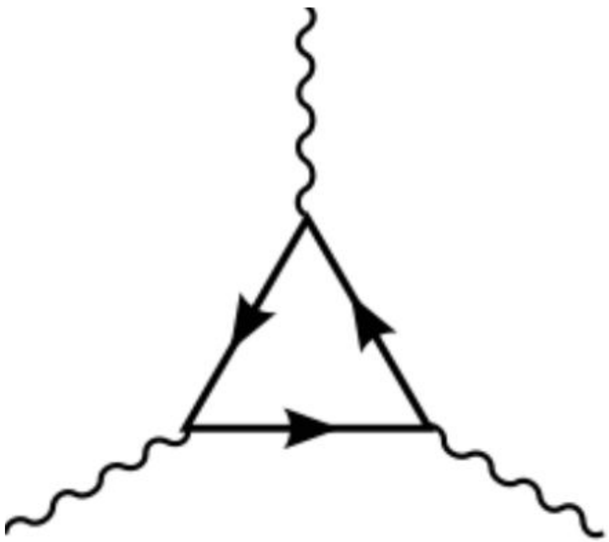
[Pais 1973]

[Fileviez Perez, Wise 2011]

Gauging Lepton Number

$\mathrm{U}(1)_L$

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



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

In the SM the non-zero values are:

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

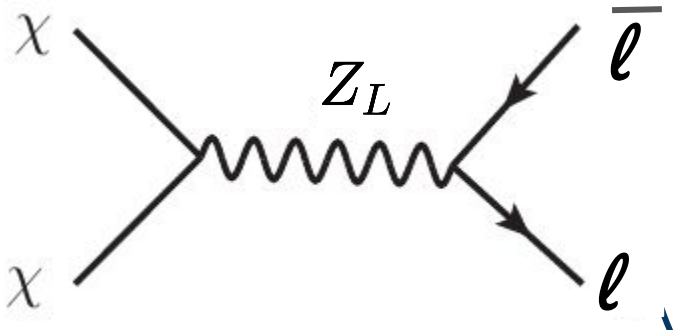
Anomaly-free model

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

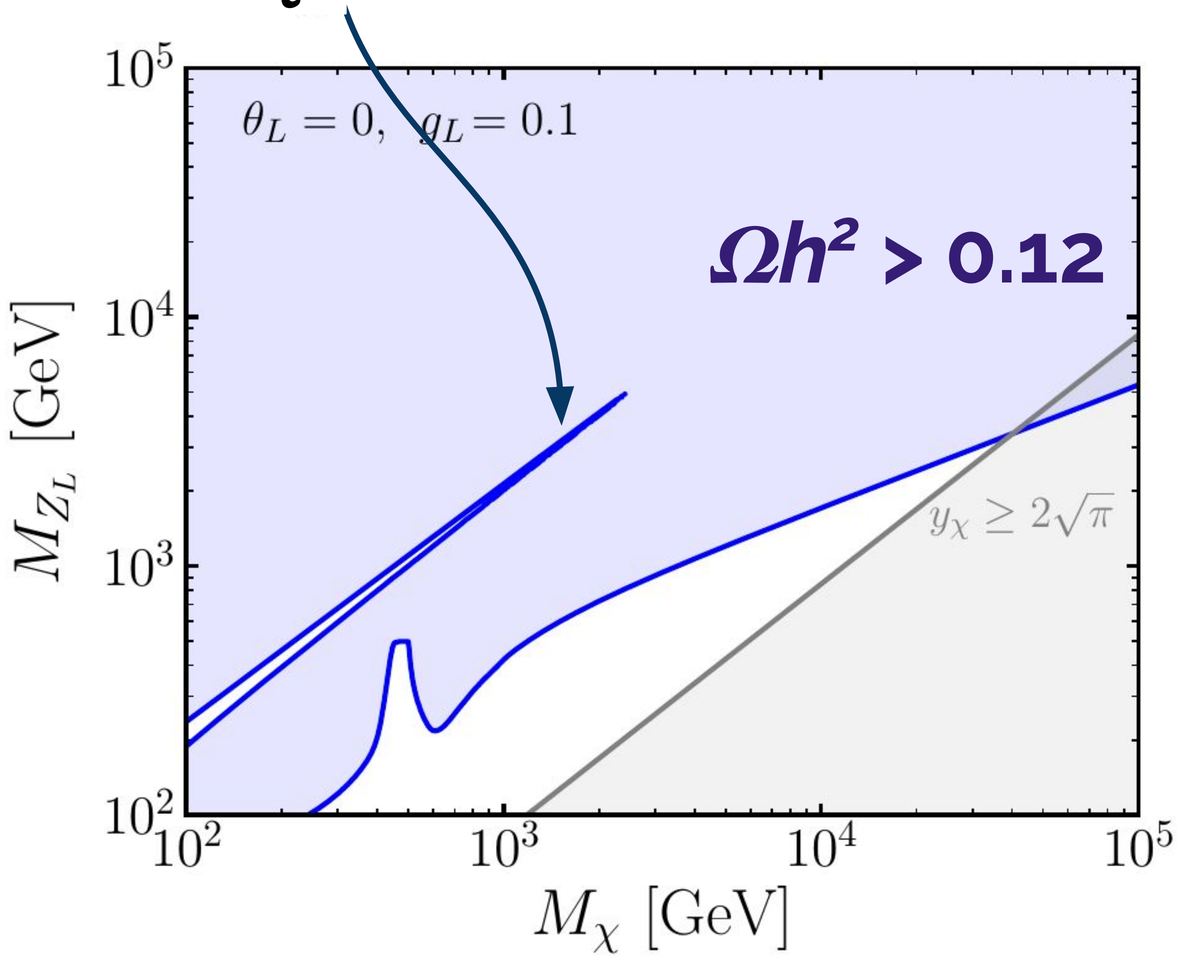
[Fileviez Perez, Ohmer, Patel 1403.8029]

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

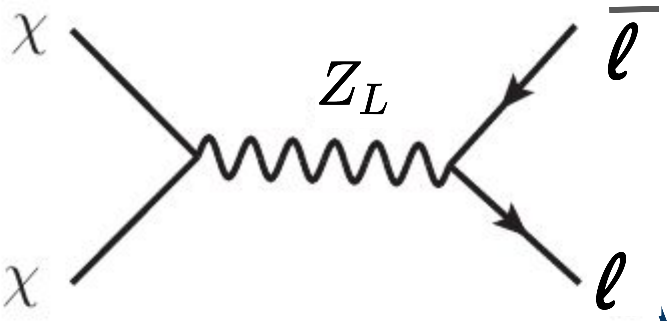
→ DM Candidate 



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



[Fileviez Perez, Murgui, ADP 1905.06344]



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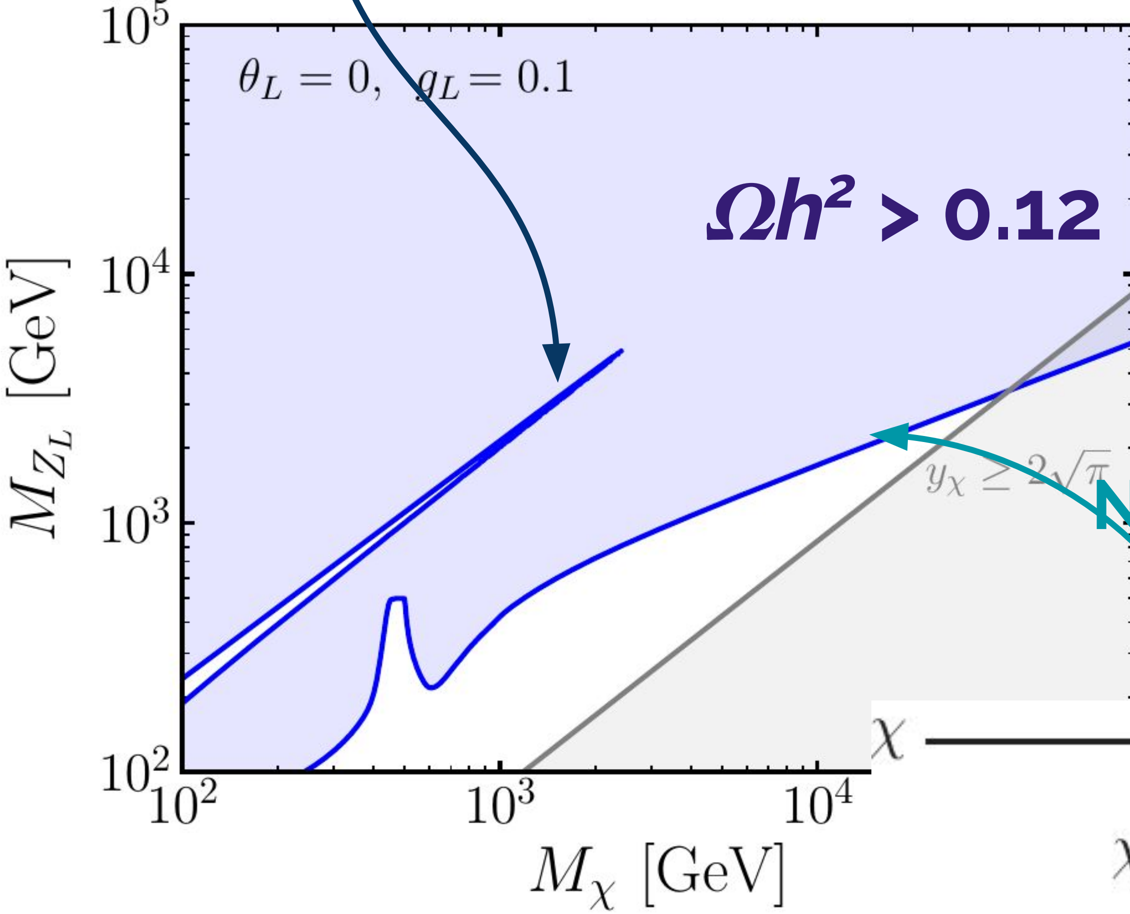
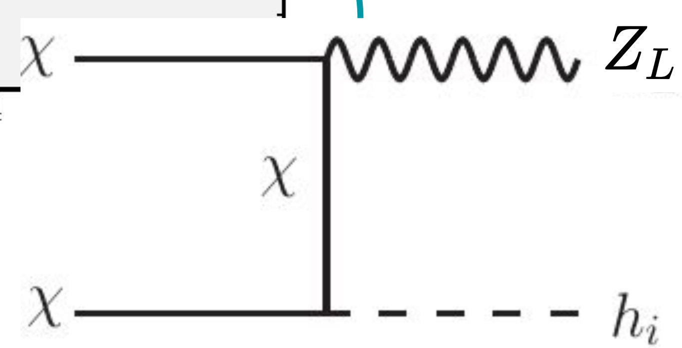
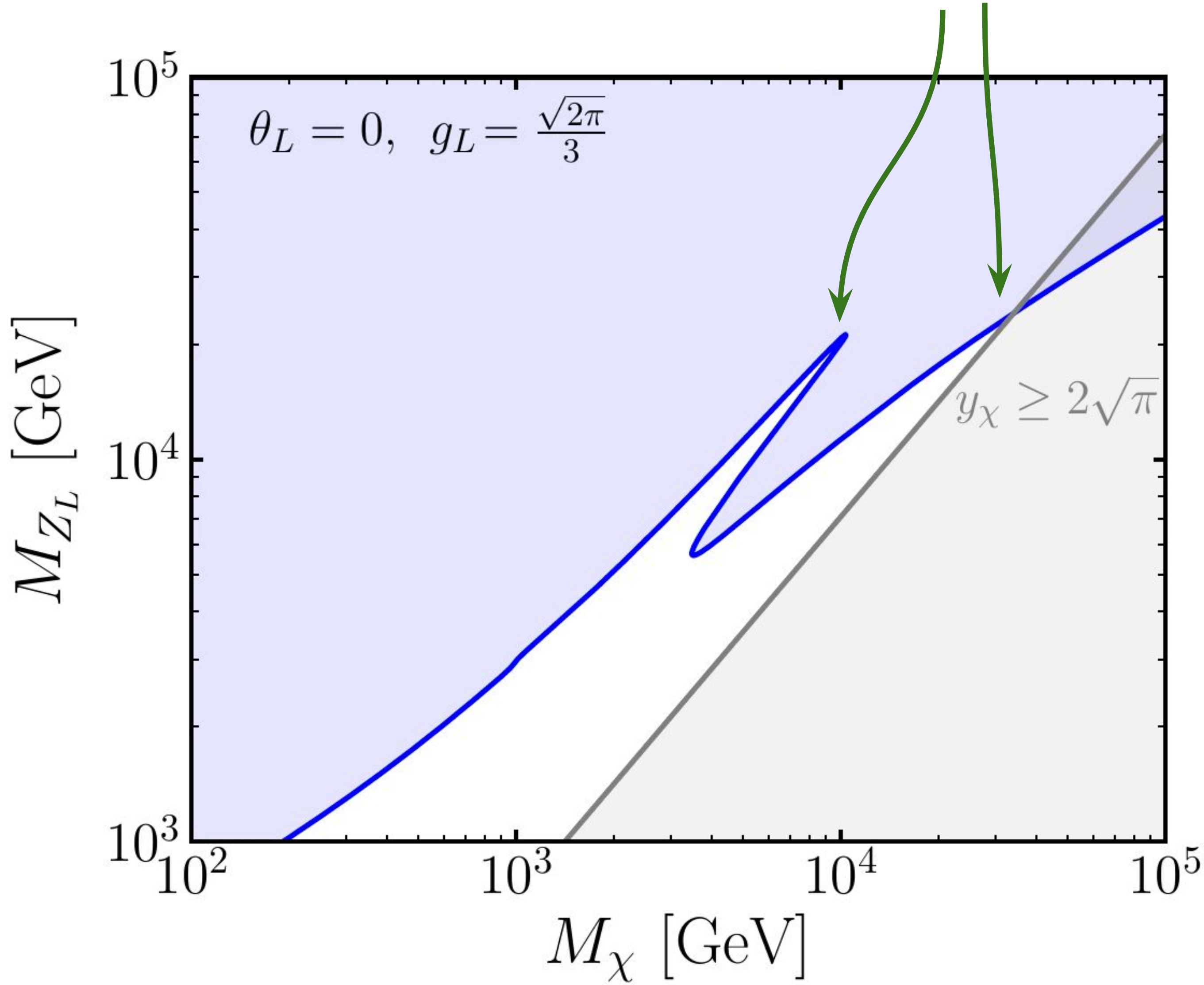




Alexis Plascencia

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

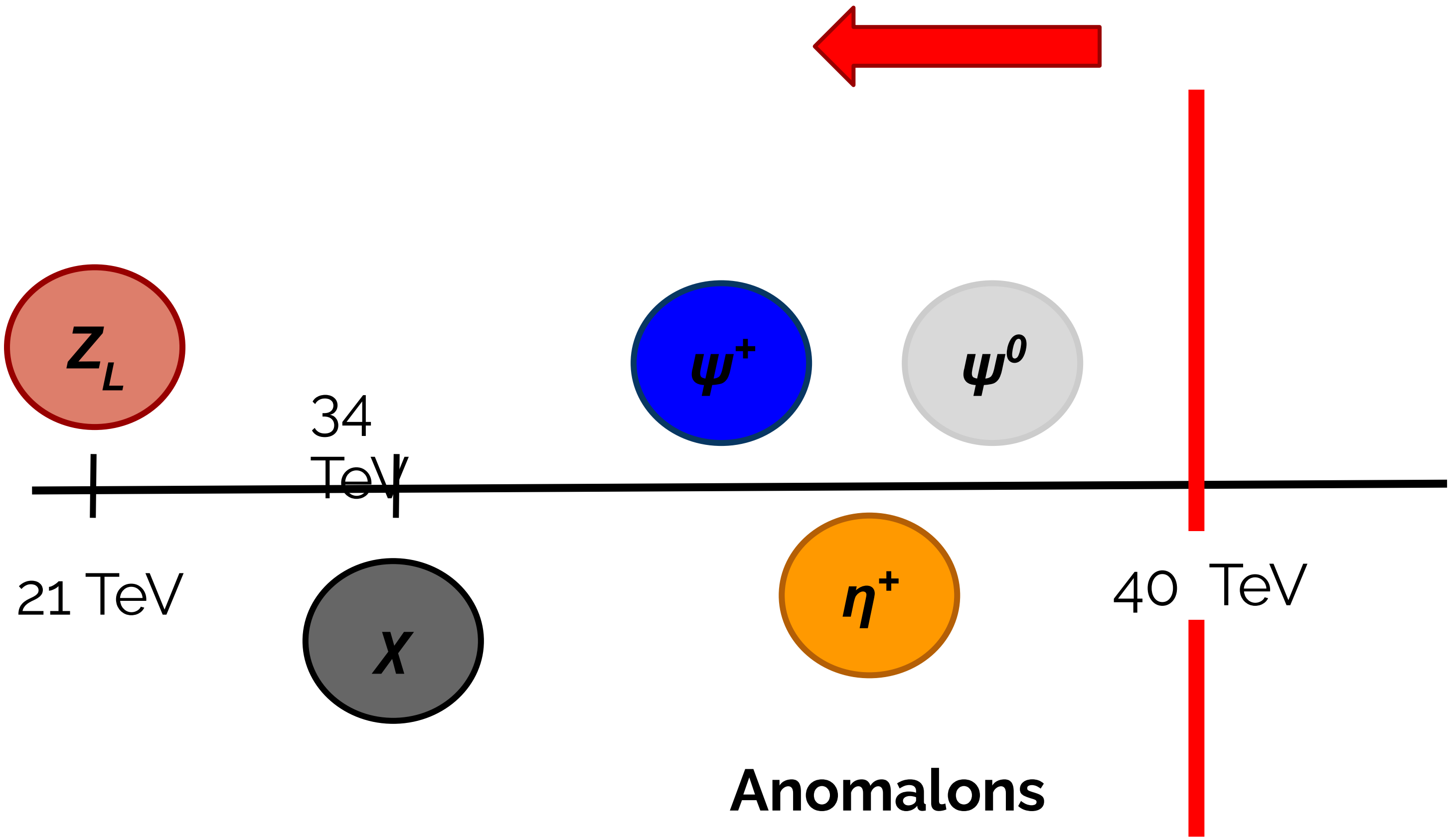
Give an upper bound on the scale



Upper bound on lepton number breaking scale

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

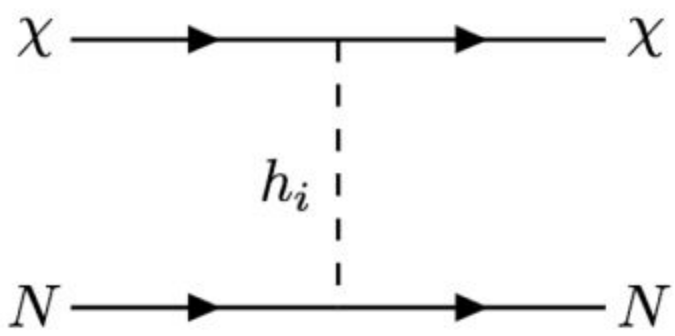
There is a *no decoupling* effect within the New Sector



Direct Detection

$\mathrm{U}(1)_L$

Z_L does not couple to quarks



suppressed by Higgs mixing

$\theta < 0.3$ for $M_{H2} > 200$ GeV

For lighter M_{H2} stronger bound

Direct detection constraints can be avoided with $\sin\theta < 0.1$

Bounds from cosmology

- In the early Universe, weak interactions keep neutrinos in thermal equilibrium with the plasma

$$\nu + \bar{\nu} \leftrightarrow e^- + e^+ \qquad \nu + e^\pm \leftrightarrow \nu + e^\pm \qquad \nu + \nu \leftrightarrow \nu + \nu$$

- As the rate of these interactions becomes smaller than the Hubble expansion rate, neutrinos decouple and propagate freely in the Universe

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- After neutrinos decouple, electron-positron annihilation heats up the photon plasma, and hence, the neutrino temperature is a bit smaller than the one of photons

$$T_\nu = \left(\tfrac{4}{11}\right)^{1/3} T_\gamma$$

N_{eff} effective number of relativistic species

$$N_{\rm eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_{\rm rad}-\rho_\gamma}{\rho_\gamma}\right) \qquad N_{\rm eff} = 3\left(\frac{11}{4}\right)^{4/3}\left(\frac{T_\nu}{T_\gamma}\right)^4$$

T= 2-3 MeV (t=0.1 s) weak interactions cannot keep neutrinos in thermal equilibrium with electrons and positrons

$$N_{\rm eff}^{\rm SM} = 3.045$$ **[Salas & Pastor 2016]**

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$$N_{\rm eff}^{\rm SM} = 3.045$$ **[Salas & Pastor 2016]**

Deviation from 3 comes from- non-instantaneous decoupling, finite temperature corrections, etc... **Review: [Dolgov 2002]**

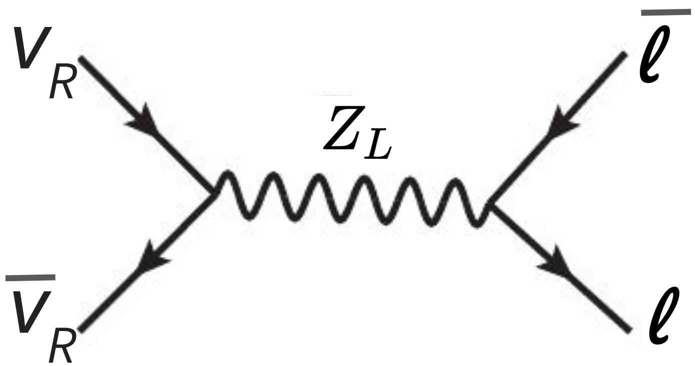
$$N_{\rm eff} = 2.99^{+0.34}_{-0.33} \quad \Rightarrow \quad \Delta N_{\rm eff} < 0.285,$$

[Planck 2018] $\text{at } 95\%\,\text{CL}$

N_{eff} effective number of relativistic species

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

→ **Dirac neutrinos**

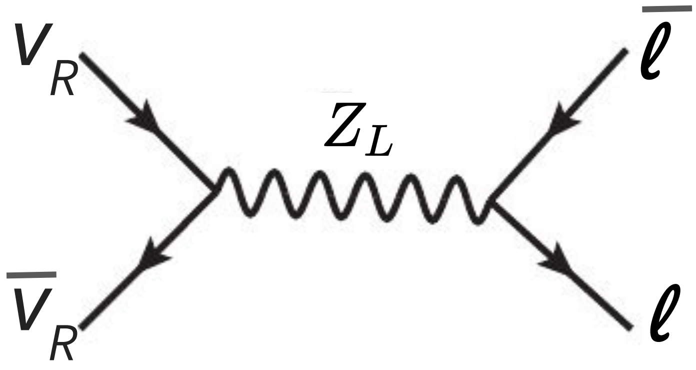


These interactions bring ν_R into thermal equilibrium in the early universe and they contribute to N_{eff}

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

N_{eff}

$\mathrm{U}(1)_L$

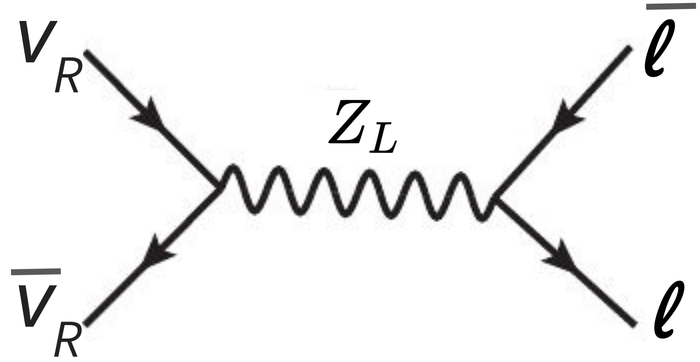


$$\Gamma(T^{\rm dec}_{\nu_R}) = H(T^{\rm dec}_{\nu_R})$$

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

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

N_{eff}



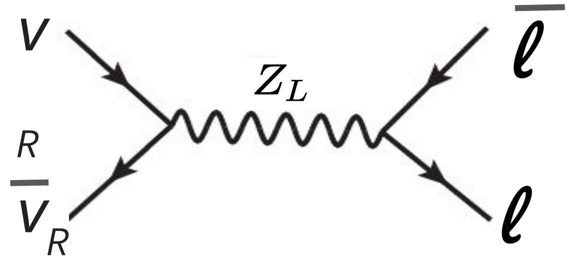
$\mathrm{U}(1)_L$

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

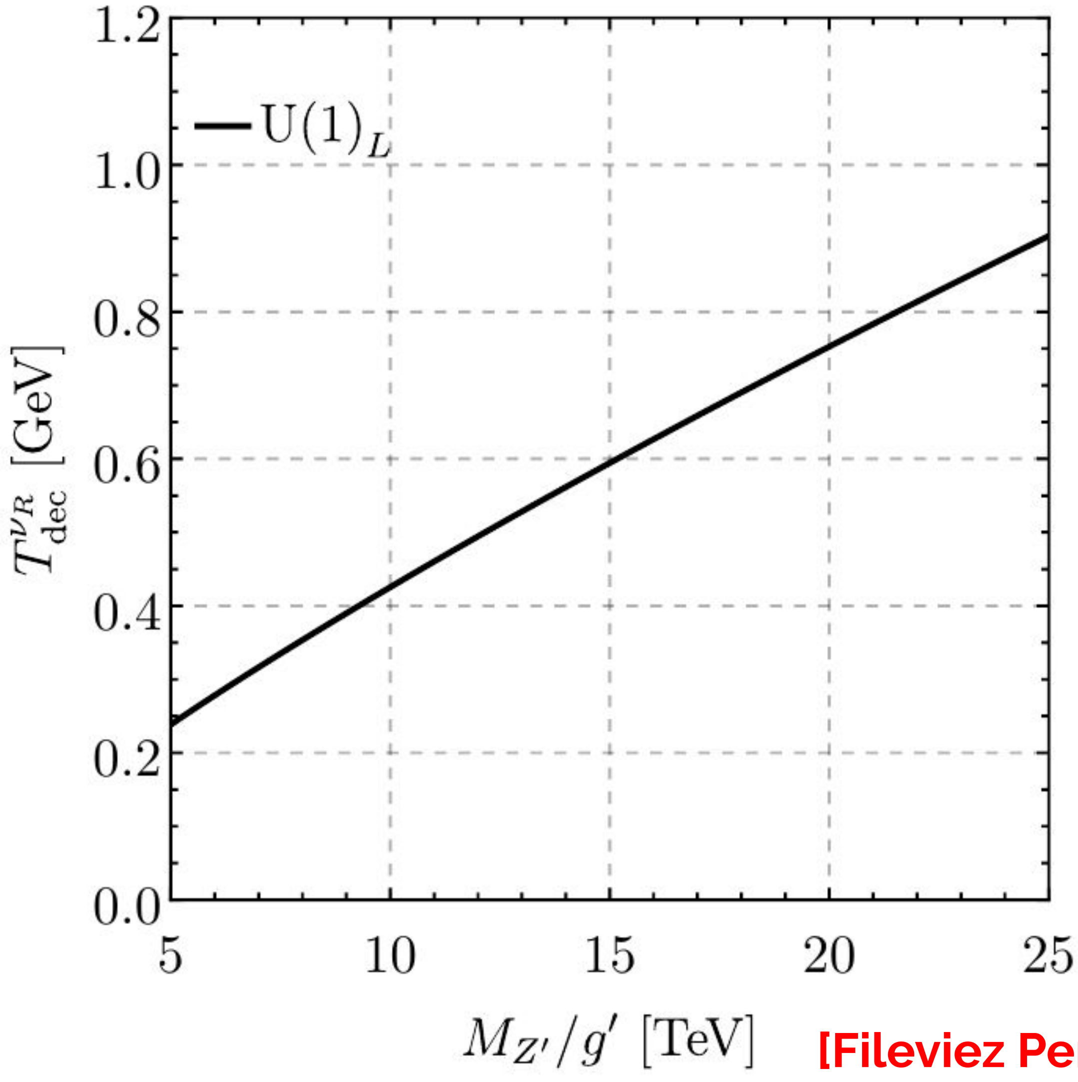
$$\sigma_{\bar{\nu}_R \nu_R \to \bar{f} f} = \frac{g'^4}{12\pi\sqrt{s}} \frac{1}{(s - M_{Z'}^2)^2 + \Gamma_{Z'}^2 M_{Z'}^2} \sum_f N_f^C n_f^2 \sqrt{s - 4M_f^2}\,(2M_f^2 + s)$$

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

N_{eff}



$\mathrm{U}(1)_L$



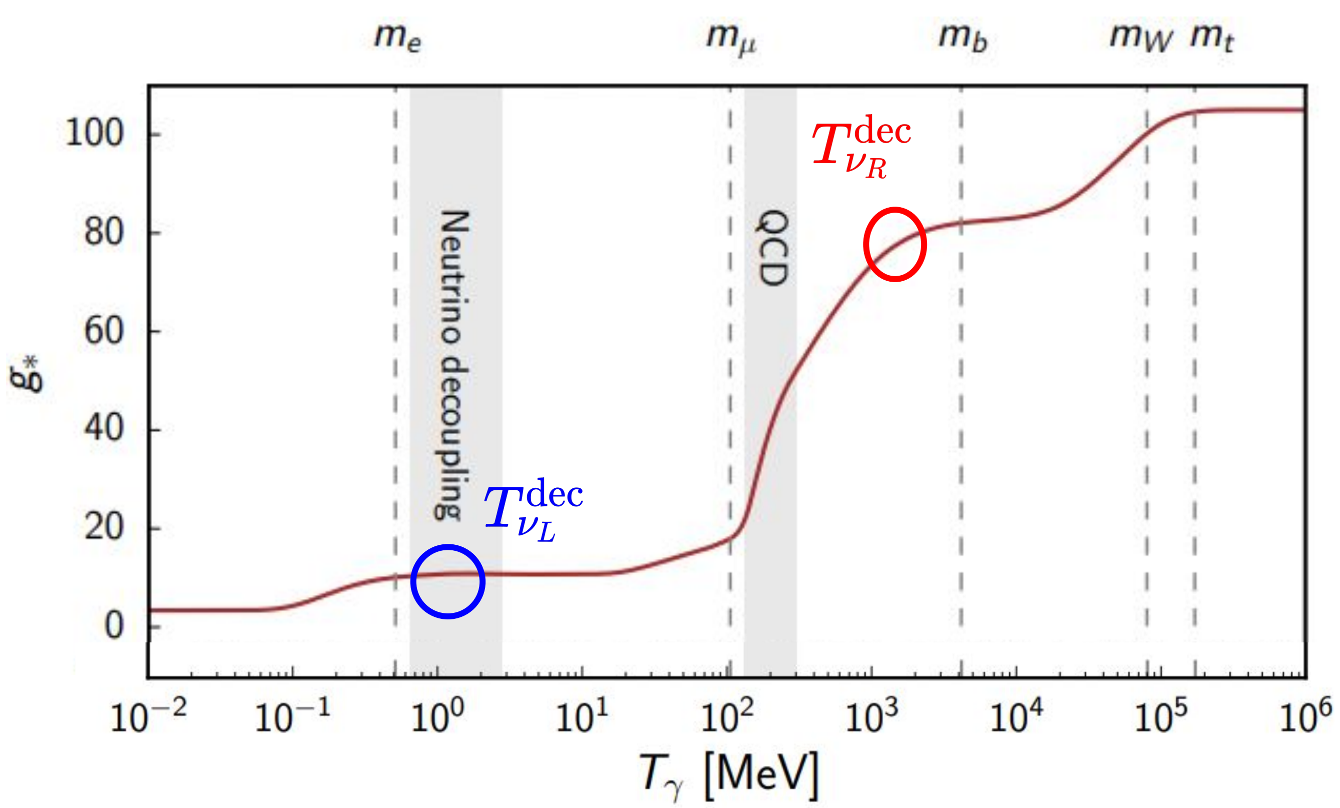
[Fileviez Perez, Murgui, ADP 2019]

N_{eff}

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

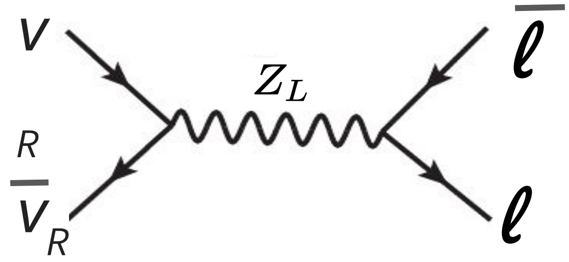
$$\Delta N_{\rm eff} = N_{\rm eff} - N_{\rm eff}^{\rm SM} = N_{\nu_R}\left(\frac{T_{\nu_R}}{T_{\nu_L}}\right)^4 = N_{\nu_R}\left(\frac{g(T_{\nu_L}^{\rm dec})}{g(T_{\nu_R}^{\rm dec})}\right)^{\frac{4}{3}}$$

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

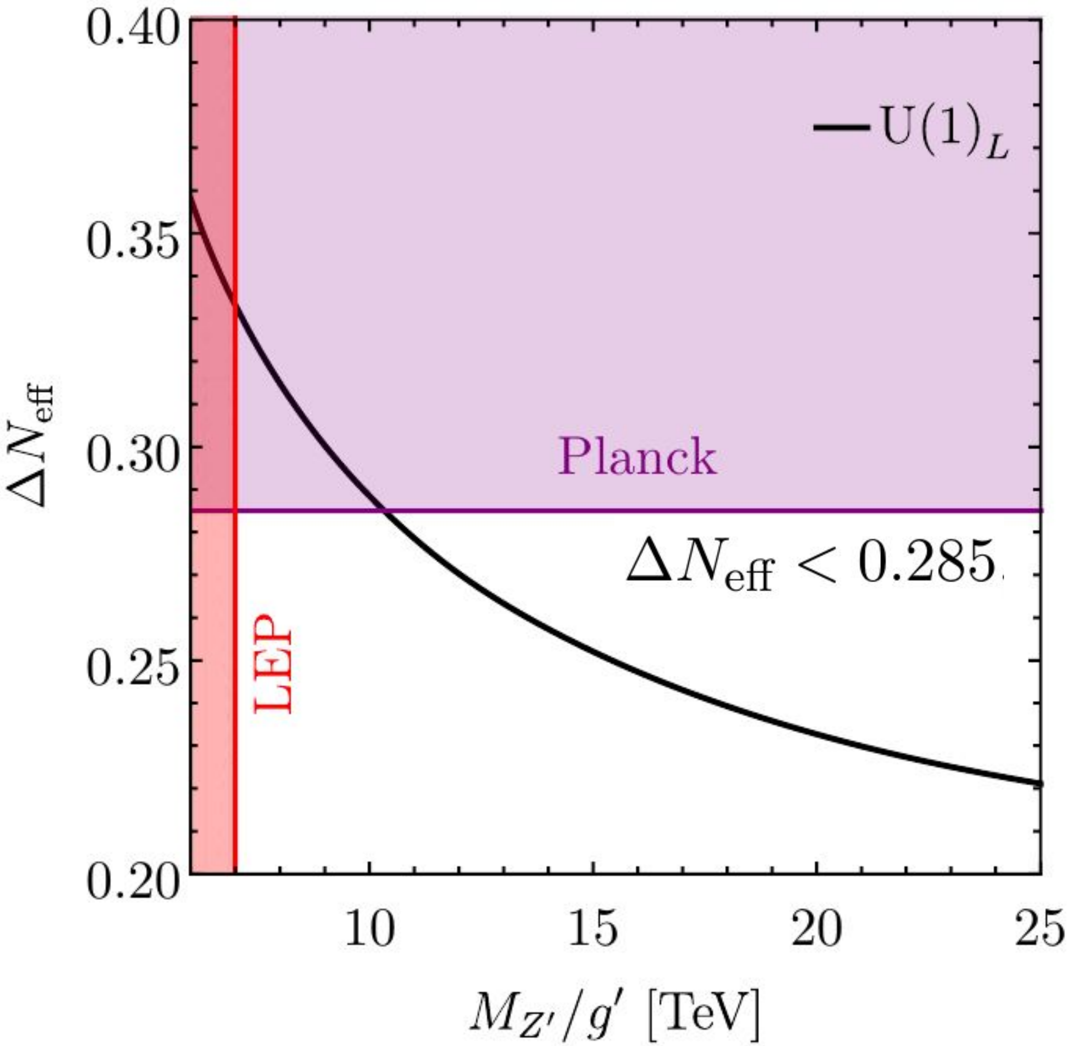


[Simons Observatory: Science Goal and Forecasts 2019] **[Borsany et al 2016]**

N_{eff}



$\mathrm{U}(1)_L$



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

at 95% CL
[Planck 2018]

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

Stronger than the LEP bound

[Fileviez Perez, Murgui, ADP 2019]

N_{eff}

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

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

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_L **!**

Other scenarios that contribute to N_{eff}

For Majorana neutrinos; if very light (*eV*) right-handed neutrinos are thermalized

[Dasgupta, Kopp 1310.6337]
[Hannestad, Hansen, Tram 1310.5926]
[Mirizzi, Mangano, Pisanti, Saviano 1410.1385]
[Cherry, Friedland, Shoemaker 1605.06506]
and others…

or for the thermalization of light (*MeV*) dark matter interacting with neutrinos, electrons or photons

[Ho, Scherrer 1208.4347]
[Boehm, Dolan, McCabe 1303.6270]
[Escudero 1812.05605]
and others…

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]

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]

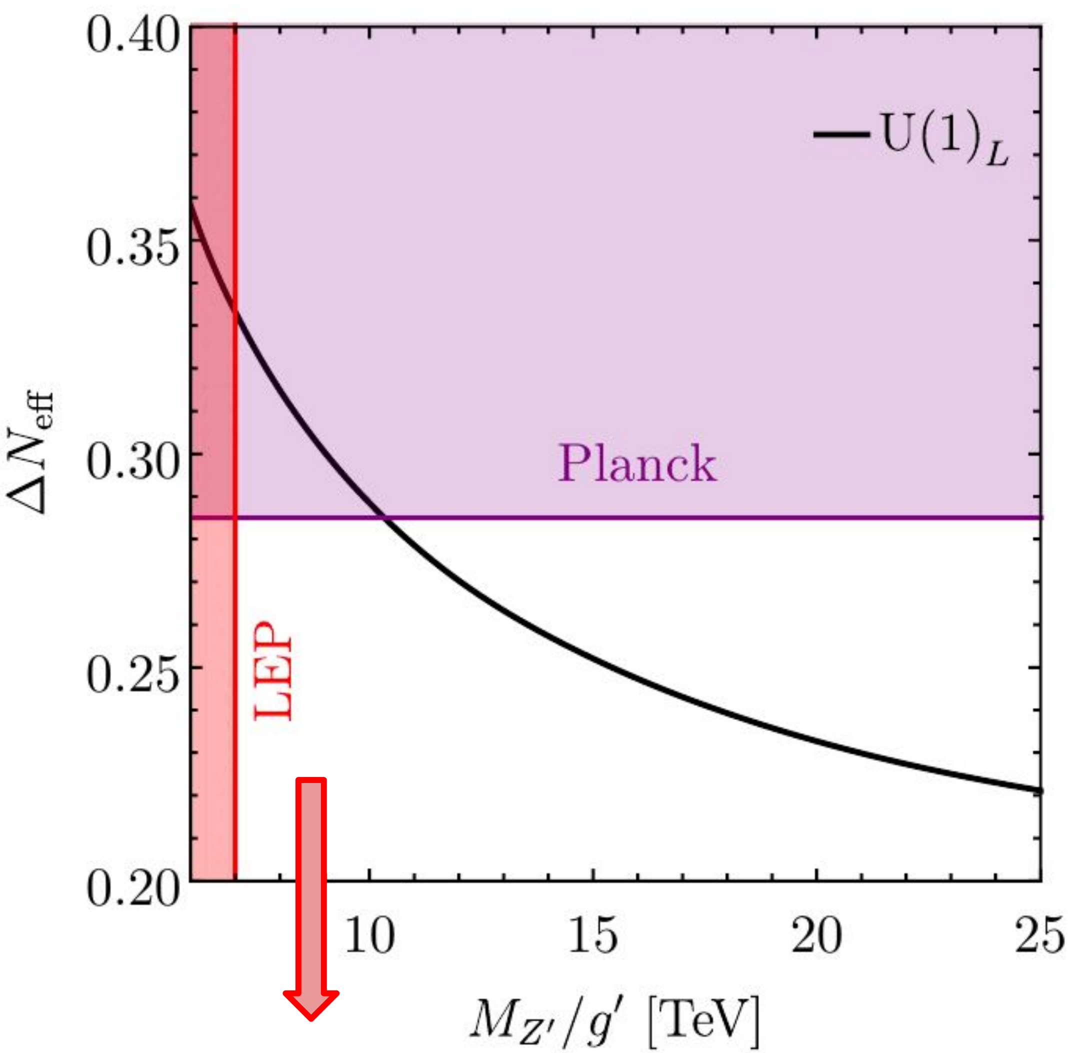
Projection for CMB Stage-IV:

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

[CMB-S4 Science Book 2016]

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

N_{eff} gives strongest bound

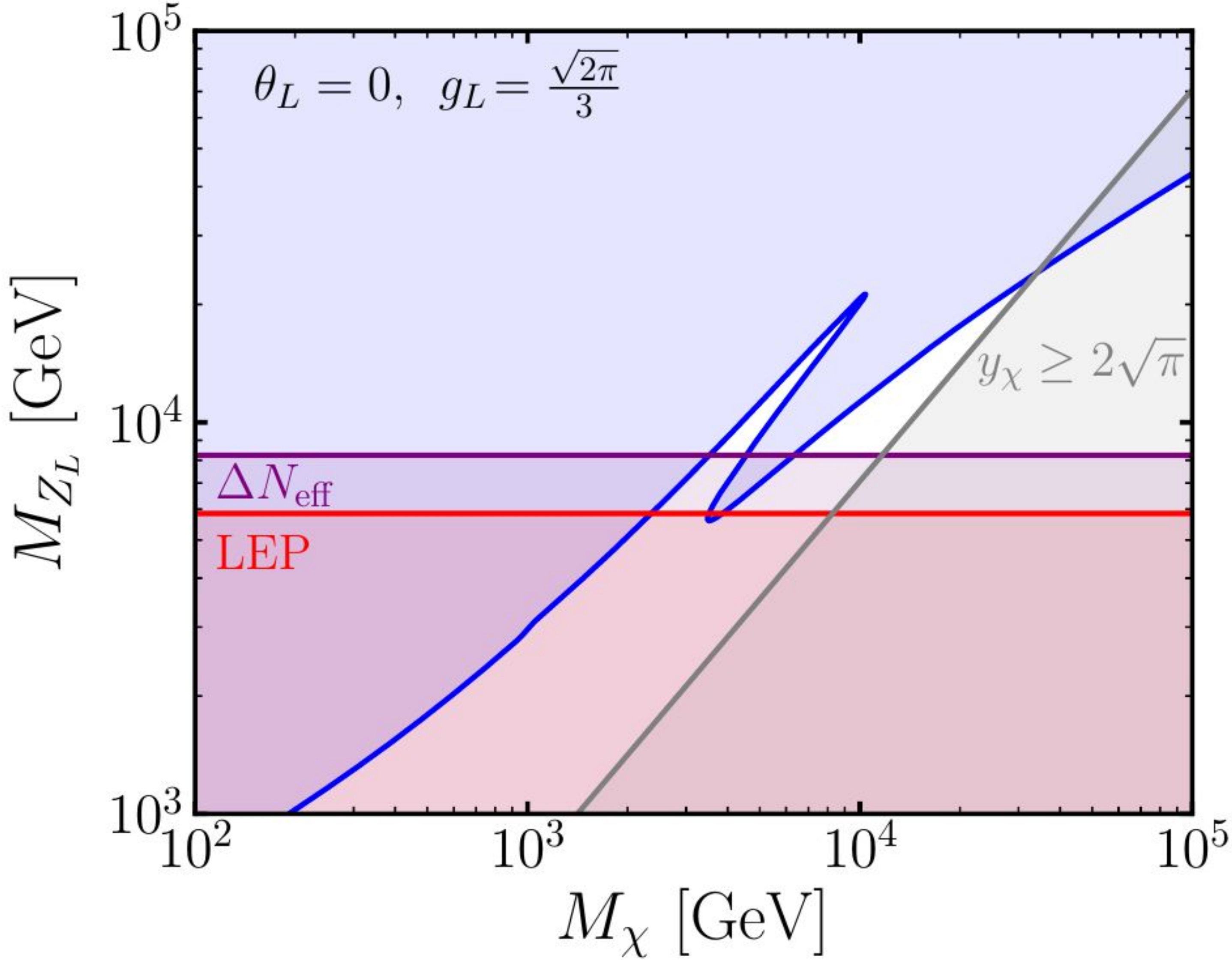


Next generation CMB experiments could fully probe the parameter space that also explains dark matter

CMB-S4

$$\Delta N_{\rm eff} < 0.06$$

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



EDM

CP Violation and Electric Dipole Moments

[Fileviez Perez, ADP 2008.09116]

CP violation and electron EDM

$$-\mathcal{L} \supset y_1 \bar{\Psi}_R H \chi_L + y_2 H^\dagger \Psi_L \chi_L + y_3 H^\dagger \Sigma_L \Psi_L + y_4 \bar{\Psi}_R \Sigma_L H$$

$$+ \; y_\Psi \bar{\Psi}_R \Psi_L S_L^* + \frac{y_\chi}{\sqrt{2}} \chi_L \chi_L S_L + y_\Sigma \mathrm{Tr}(\Sigma_L \Sigma_L) S_L + \mathrm{h.c.}$$

$$-\mathcal{L} \supset \begin{pmatrix} \overline{\Sigma_R^+} & \overline{\Psi_{2R}^+} \end{pmatrix} \mathcal{M}_C \begin{pmatrix} \Sigma_L^+ \\ \Psi_{1L}^+ \end{pmatrix} + \mathrm{h.c.}$$

$$\mathcal{M}_C = \begin{pmatrix} \sqrt{2} y_\Sigma v_L & \frac{y_3 v}{\sqrt{2}} \\ \frac{y_4 v}{\sqrt{2}} & \frac{y_\Psi v_L}{\sqrt{2}} \end{pmatrix}$$

$$\boxed{\phi = \arg(y_3^* y_4^* \mu_\Sigma \mu_\Psi)}$$

[Fileviez Perez, ADP 2008.09116]

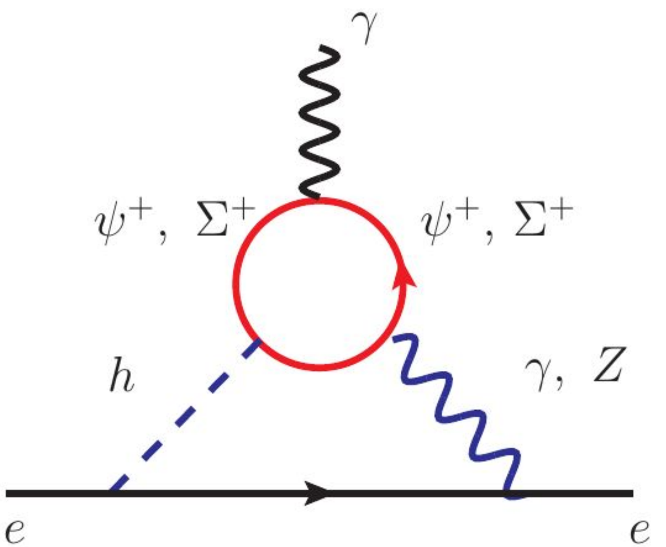
CP violation and electron EDM

Two-loop **Barr-Zee** diagrams with the charged anomaly-canceling fermions in the loop

$$d_e^{\gamma h} = \frac{\alpha^2 \cos\theta_B\, Q_e\, m_e}{8\pi^2 s_W\, m_h^2\, m_W} \sum_{i=1}^{2} M_{\chi_i^\pm}\, \mathrm{Im}[C_h^{ii}]\, I_{\gamma h}^i(M_{\chi_i^\pm})$$

$$C_h^{ij} = \frac{1}{\sqrt{2}} \cos\theta_B \left[y_3 (V_R^{1i})^* V_L^{2j} + y_4 (V_R^{2i})^* V_L^{1j} \right] + \frac{1}{\sqrt{2}} \sin\theta_B \left[y_\Psi (V_R^{2i})^* V_L^{2j} + 2 y_\Sigma (V_R^{1i})^* V_L^{1j} \right]$$

$$I_{\gamma h}^i(M_{\chi_i^\pm}) = \int_0^1 \frac{dx}{x} j\left(0, \frac{M_{\chi_i^\pm}^2}{m_h^2} \frac{1}{x(1-x)}\right)$$

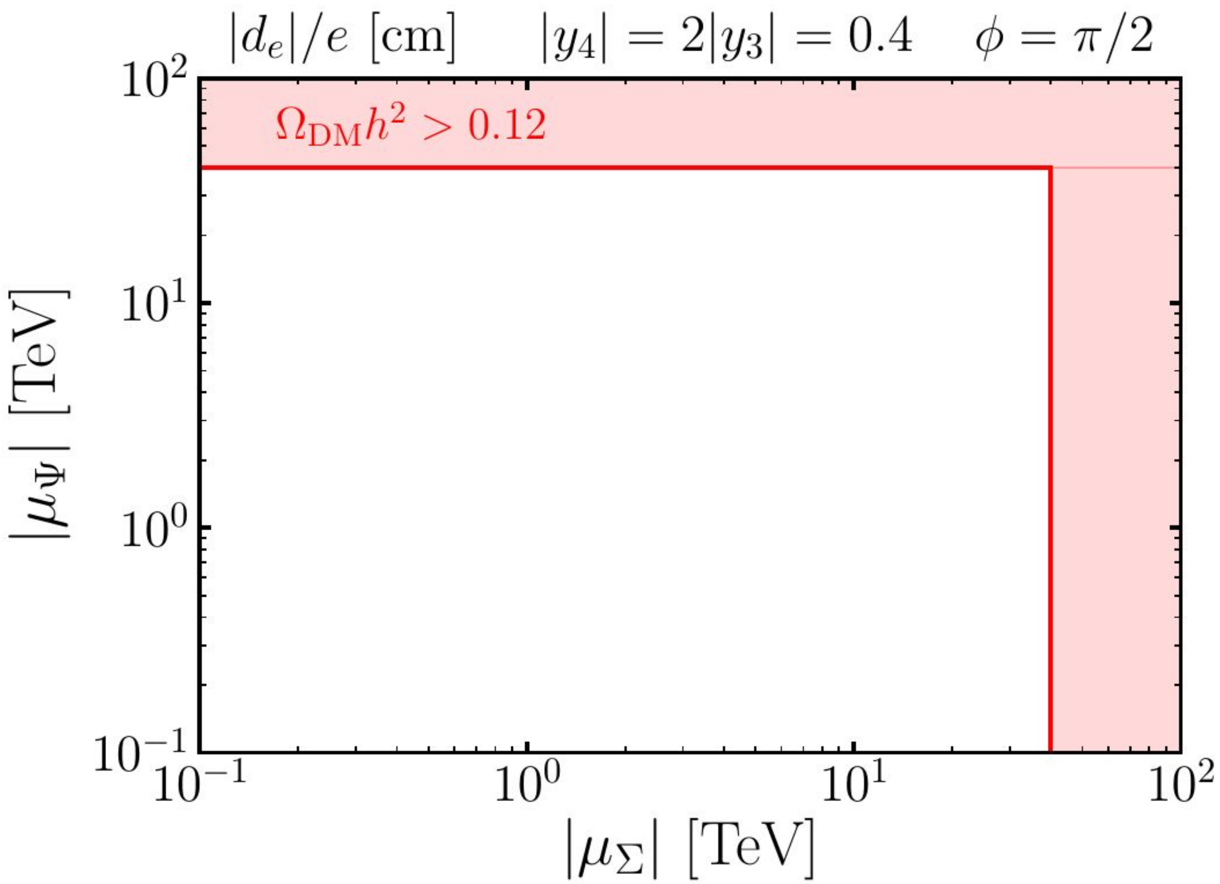


[Fileviez Perez, ADP 2008.09116]

[Barr, Zee 1990]
[Nakai, Reece 1612.08090]

Electron EDM

$$\phi = \arg(y_3^* y_4^* \mu_\Sigma \mu_\Psi) = \pi/2$$

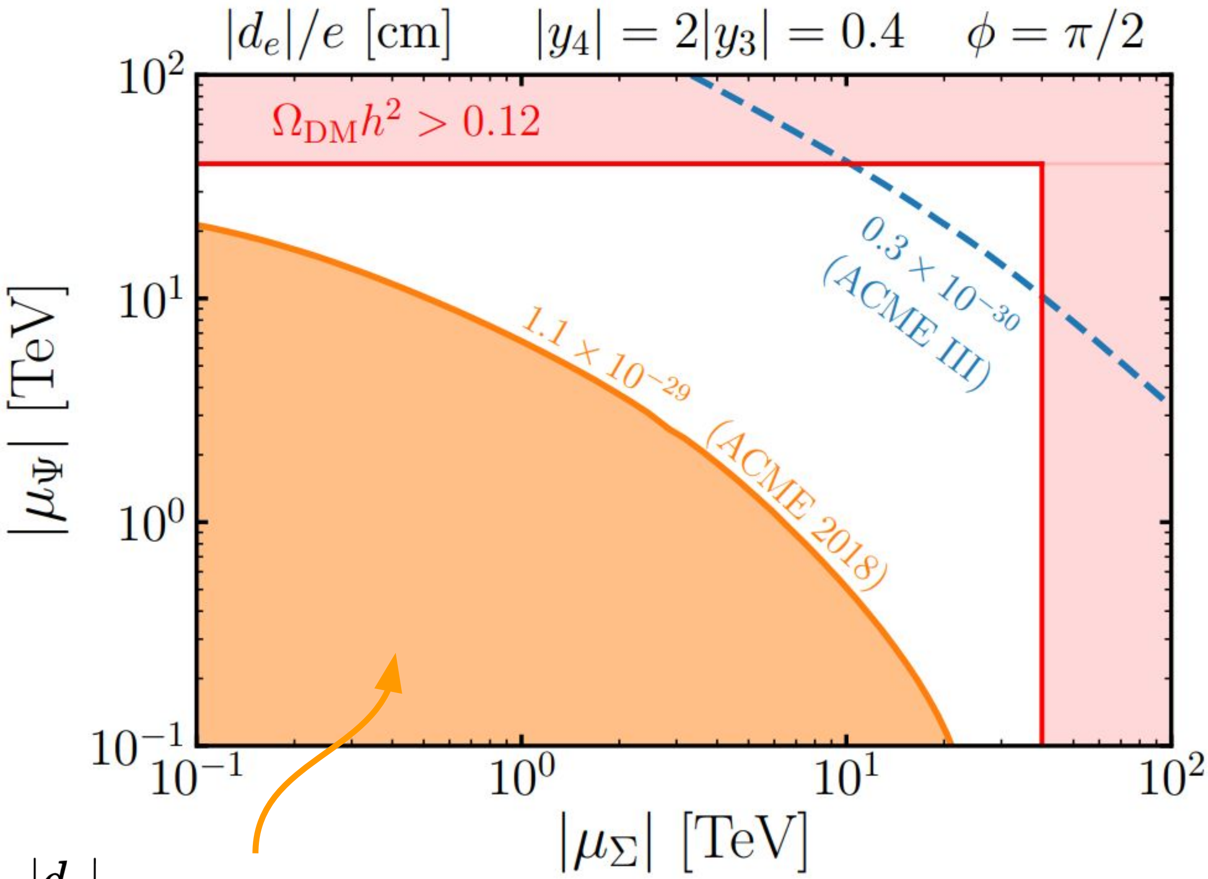


DM relic density requires:

$$|\mu_\Sigma|, |\mu_\Psi| < 40 \text{ TeV}$$

Electron EDM

$$\phi = \arg(y_3^* y_4^* \mu_\Sigma \mu_\Psi) = \pi/2$$



$$\frac{|d_e|}{e} < 1.1 \times 10^{-29} \text{ cm}$$

[ACME, Nature 2018]

DM relic density requires:

$$|\mu_\Sigma|, |\mu_\Psi| < 40 \text{ TeV}$$

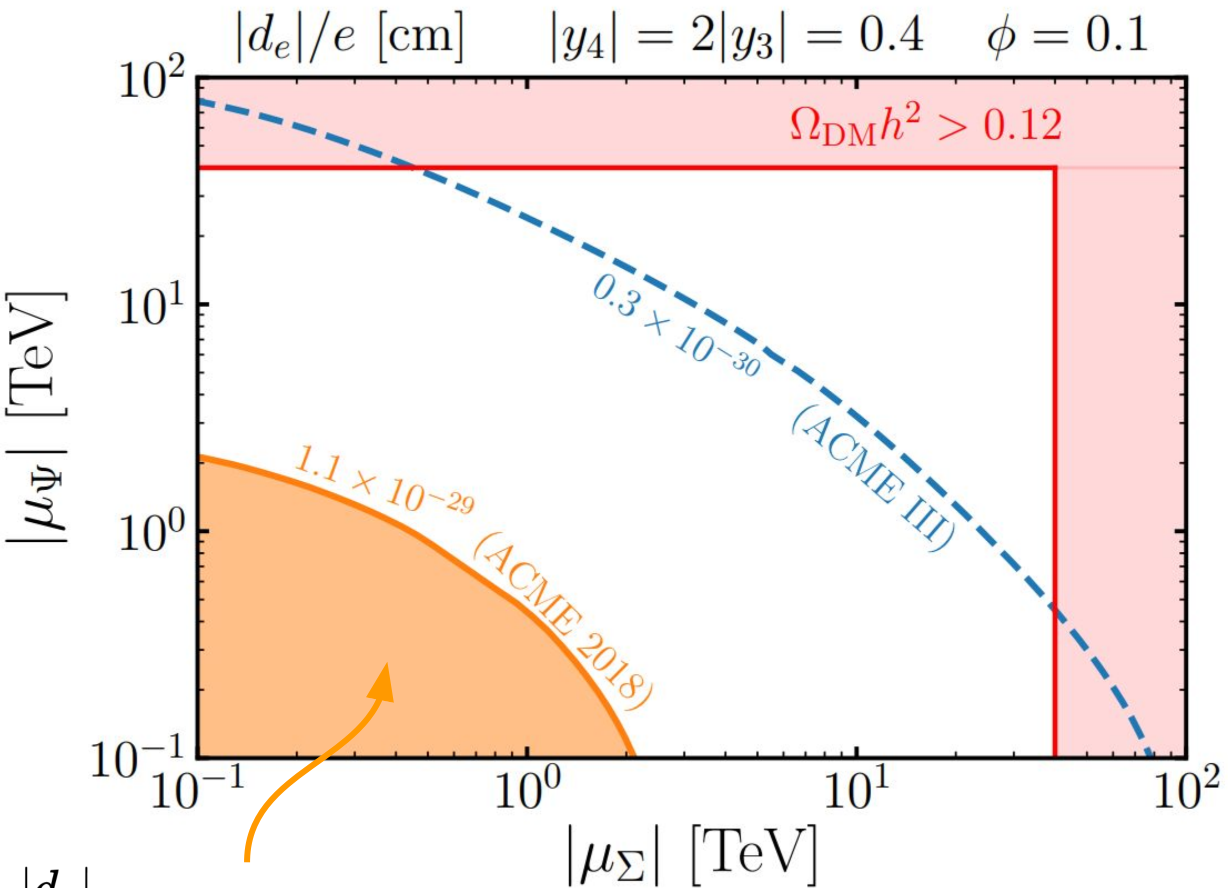
ACME bound implies:

$$|\mu_\Sigma|, |\mu_\Psi| > 20 \text{ TeV}$$

[Fileviez Perez, ADP 2008.09116]

Electron EDM

$$\phi = \arg(y_3^* y_4^* \mu_\Sigma \mu_\Psi) = 0.1$$



DM relic density requires:

$$|\mu_\Sigma|, |\mu_\Psi| < 40 \text{ TeV}$$

ACME bound implies:

$$|\mu_\Sigma|, |\mu_\Psi| > 2 \text{ TeV}$$

$$\frac{|d_e|}{e} < 1.1 \times 10^{-29} \text{ cm}$$

[ACME, Nature 2018]

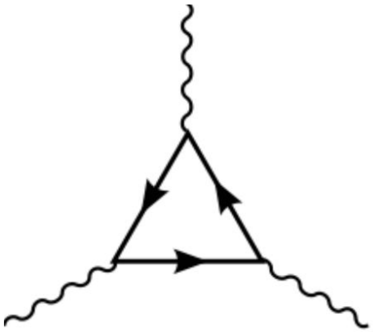
[Fileviez Perez, ADP 2008.09116]

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

Dirac neutrinos and Dirac DM

[Fileviez Perez, Murgui, ADP 1905.06344]

Dirac Neutrinos



Anomaly cancellation:

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

If *B-L* is conserved, then, the Majorana mass term is forbidden

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

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

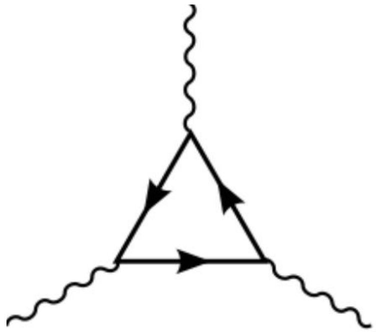
2) Spontaneous symmetry breaking of *B-L* Z_{BL}

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

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

To forbid Majorana mass term

Dirac Neutrinos



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2) Spontaneous symmetry breaking of *B-L* ***Z*$_{BL}$**

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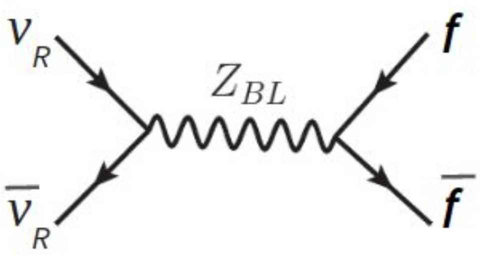
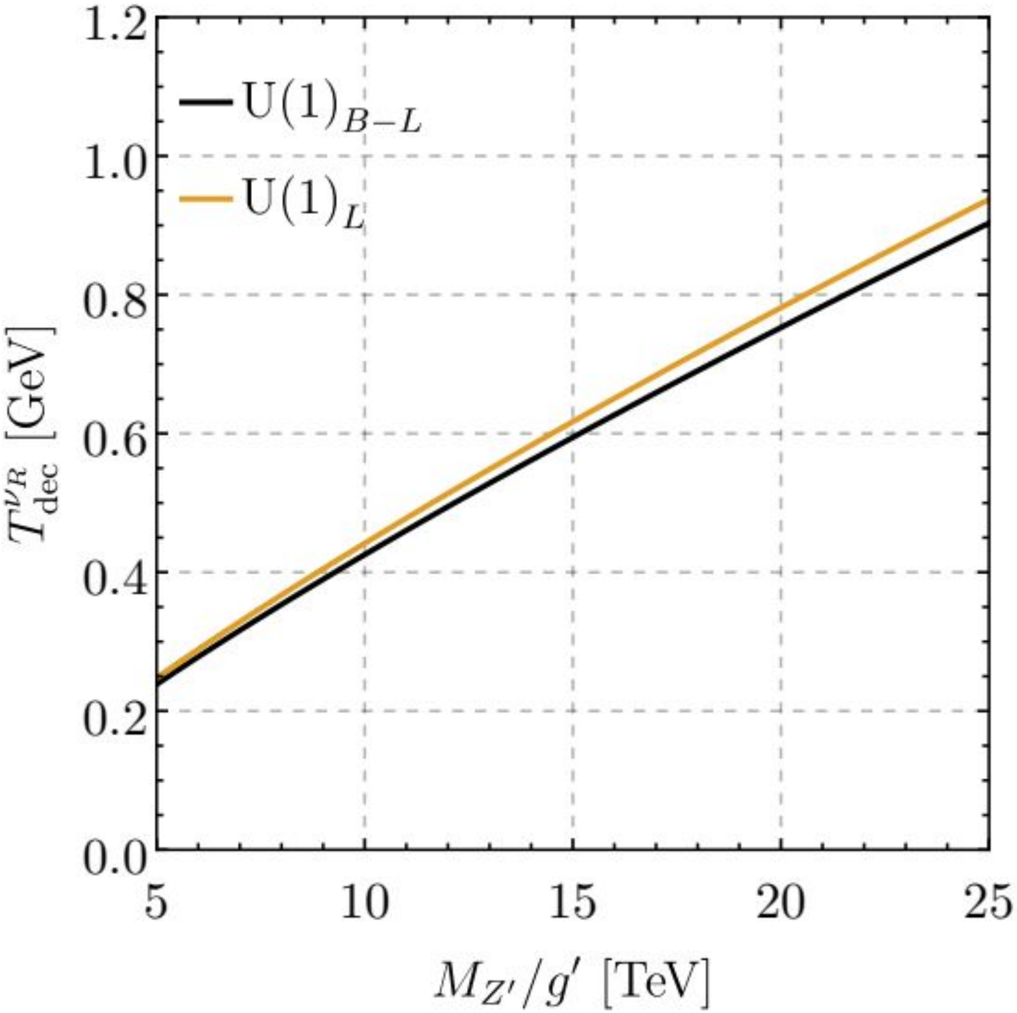
Decoupling T for ν_R

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



Thermalizes the right-handed neutrinos in the Early Universe

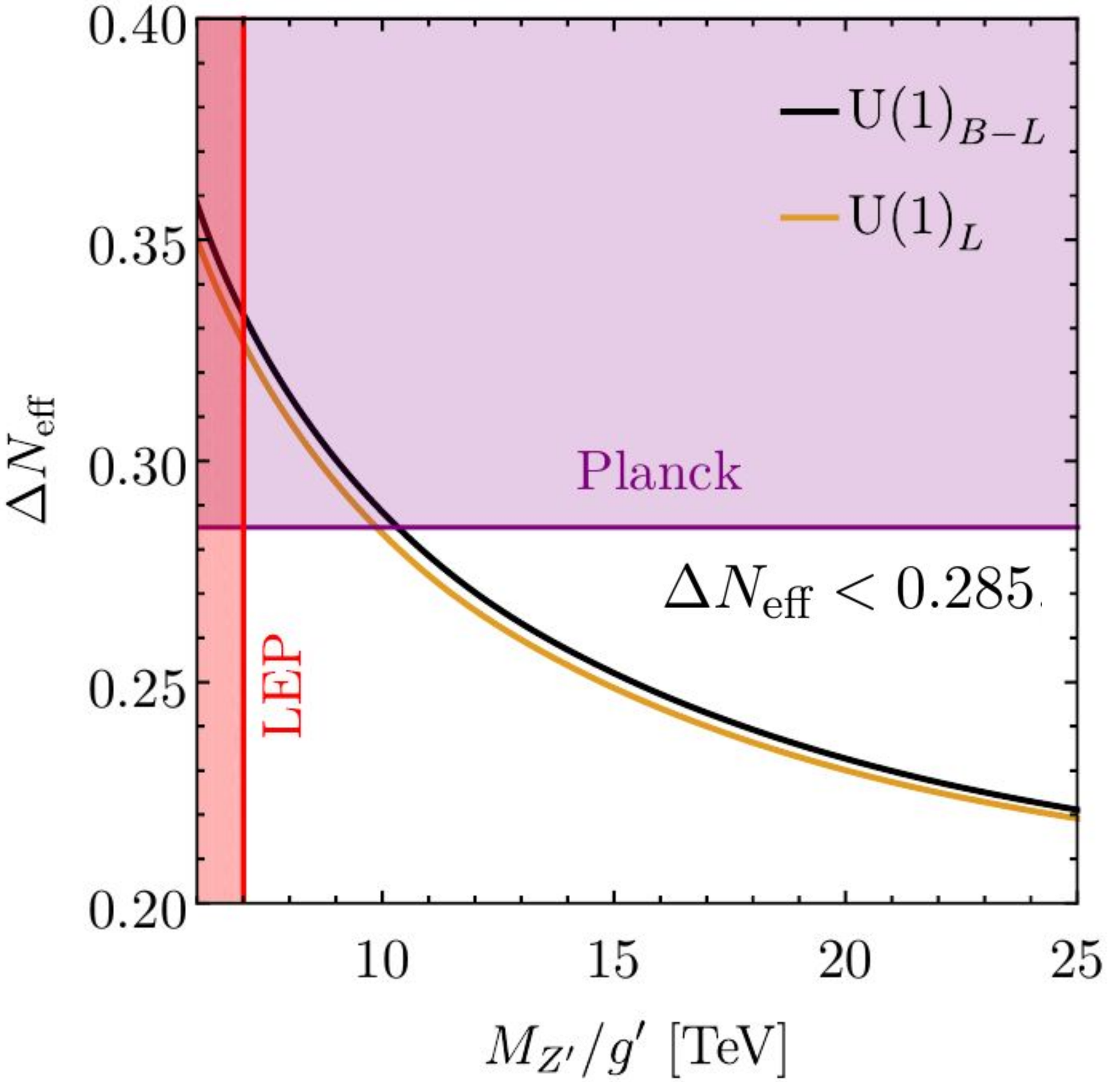


Alexis Plasce

[Fileviez Perez, Murgui, ADP 2019]

N_{eff}

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



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

at 95% CL
[Planck 2018]

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

Stronger than the LEP & LHC bound

[Fileviez Perez, Murgui, ADP 2019]

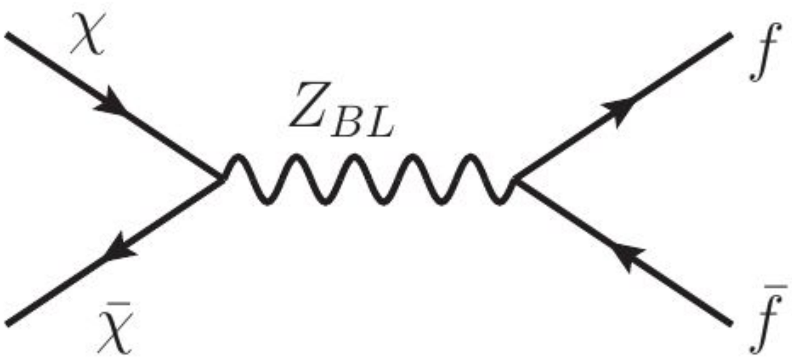
Dirac fermion as dark matter

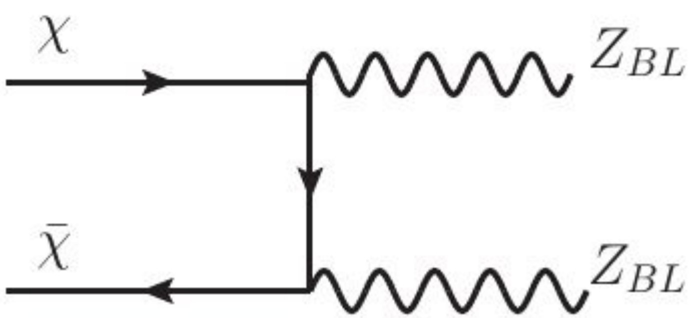
Introduce vector-like fermion with *B-L* charge

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

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

Non-renormalizable operators forbid *n* odd

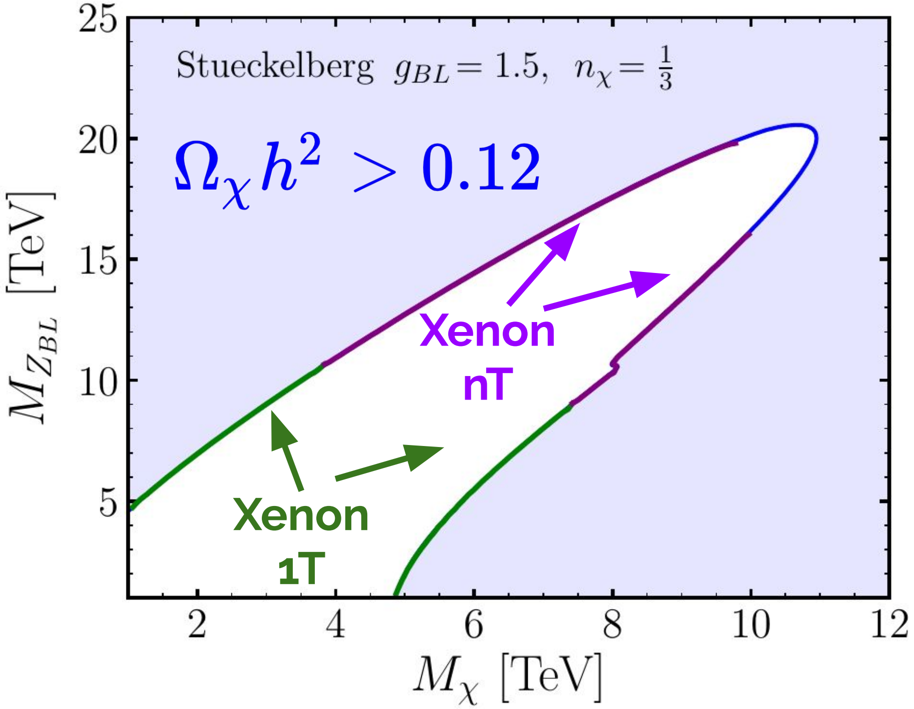


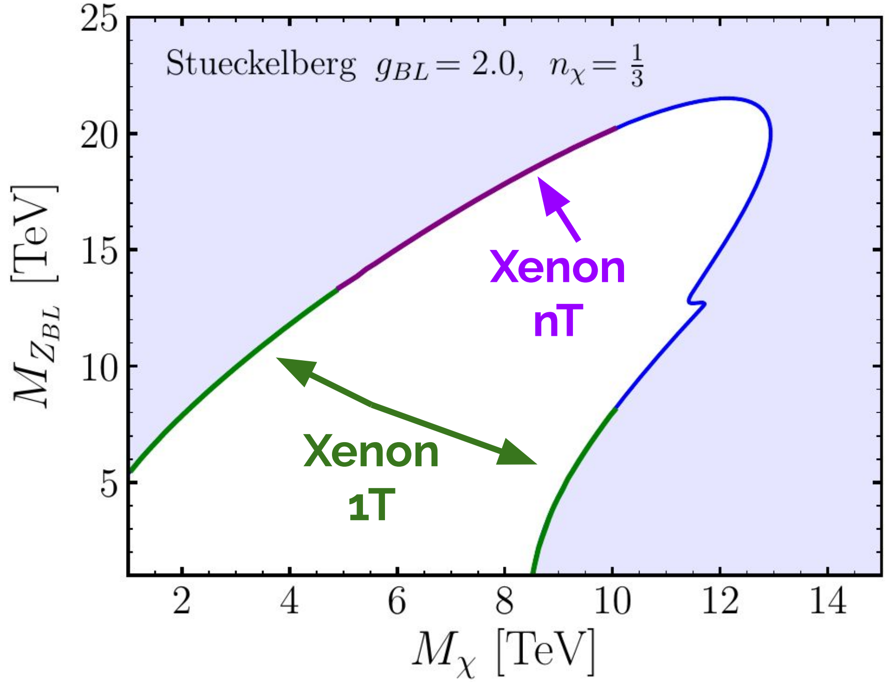


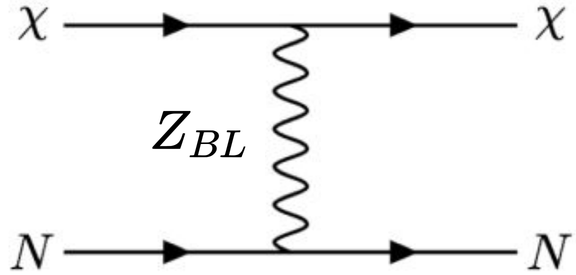
Dark Matter

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

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

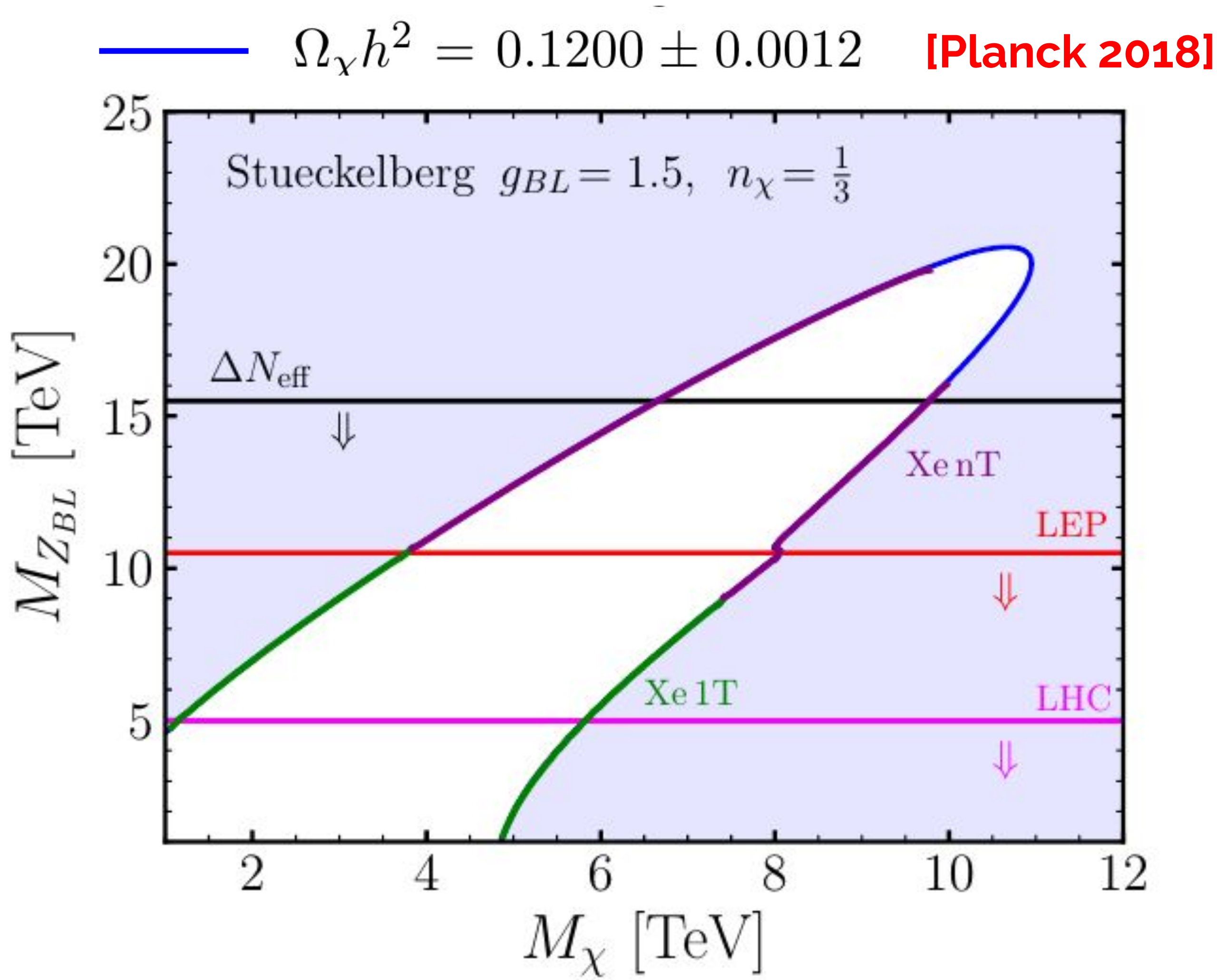






Dark Matter

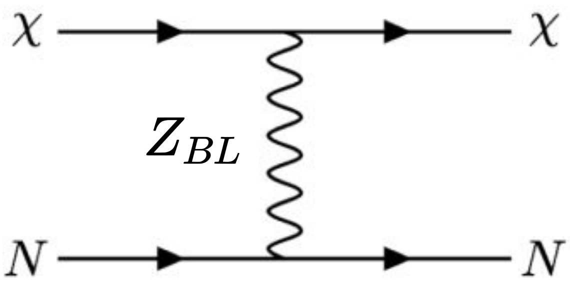
$\mathrm{U}(1)_{B-L}$



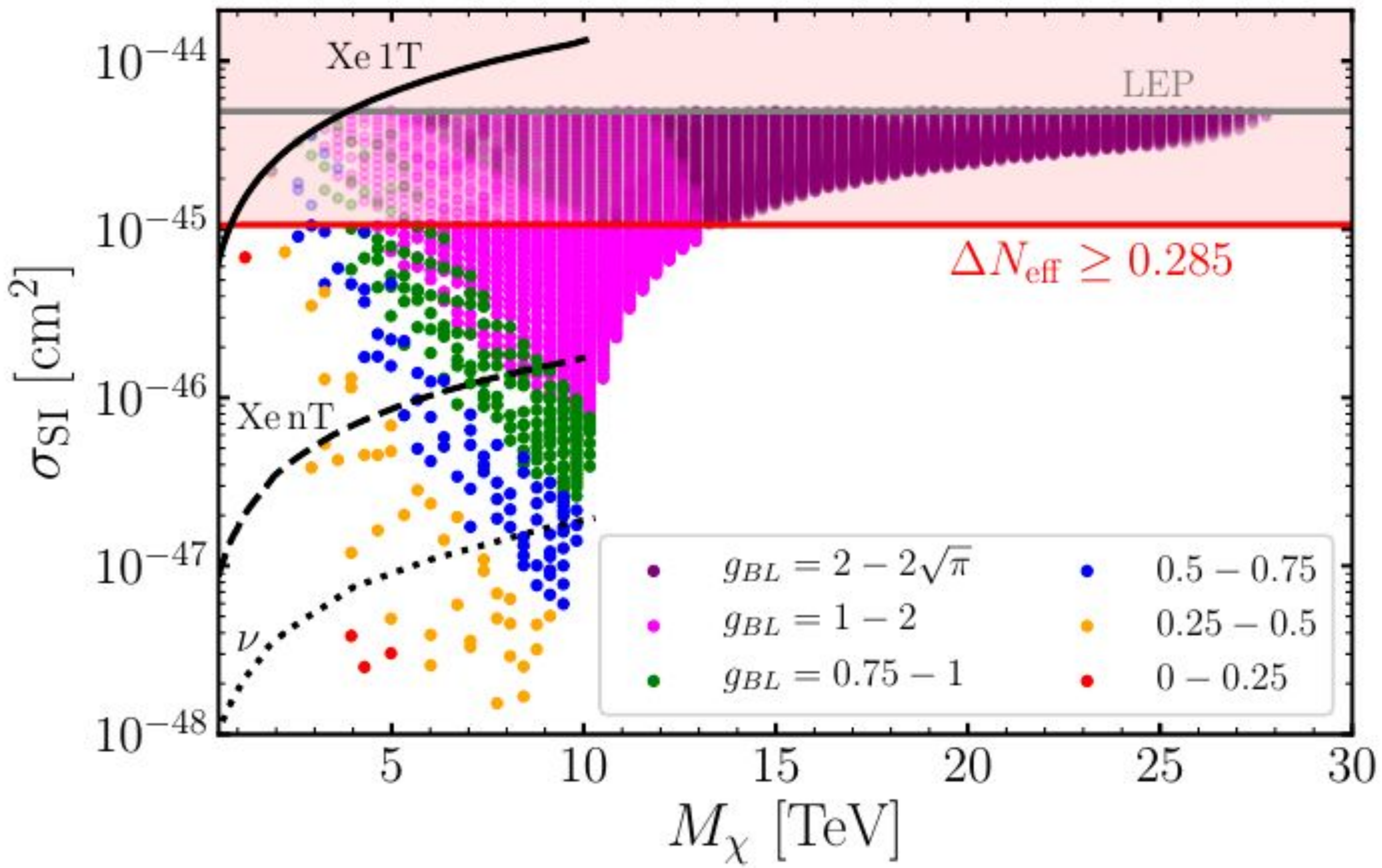
$\Delta N_{eff} < 0.285$ gives the strongest bound

Dark Matter - direct detection

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



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



Conclusions

- In $U(1)_L$ and dark matter is predicted from gauge anomaly cancellation
- Not overproducing dark matter implies an upper bound on all new states < 40 TeV
- In $U(1)_L$, neutrinos are Dirac. Next generation CMB will fully test these theories (with DM) using ΔN_{eff} . Same holds for unbroken local $B - L$
- New sources of CP violation lead to a large electron EDM and can be tested at experiments such as ACME

Thank you!


рахмат
danke
謝謝
ngiyabonga
teşekkür ederim
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Баярлалаа
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kia ora
barka
welalin
tack
mahalo
tapadh leat
спасибо
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nandri
dhanyavad
thank you
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তোমাকে ধন্যবাদ
감사합니다
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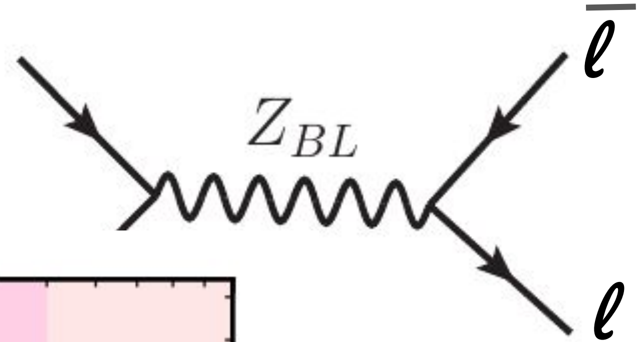
Back-up

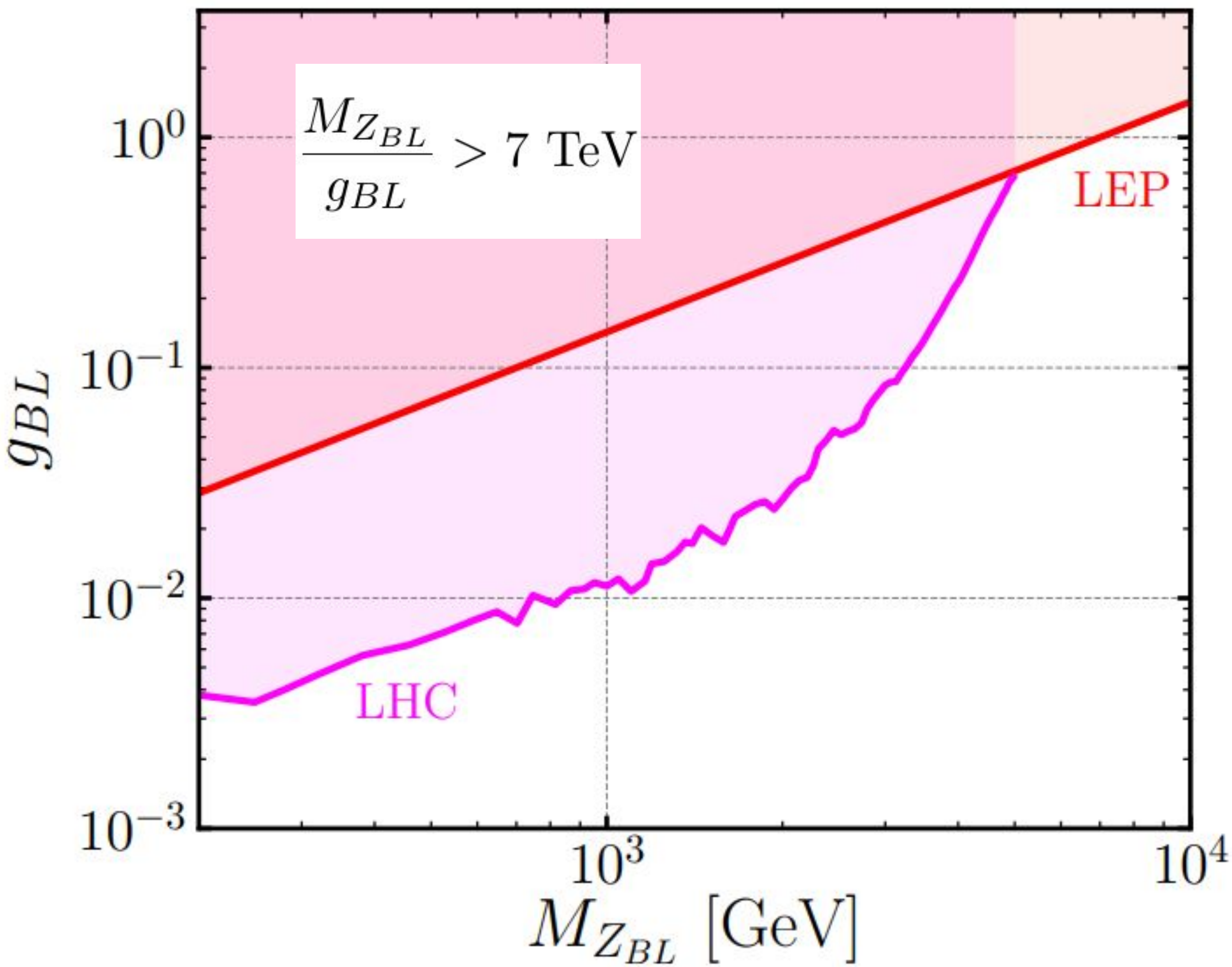
Model II

Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
$\Psi_L = \begin{pmatrix} \Psi_L^0 \\ \Psi_L^- \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	B_1
$\Psi_R = \begin{pmatrix} \Psi_R^0 \\ \Psi_R^- \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	B_2
η_R	$\mathbf{1}$	$\mathbf{1}$	-1	B_1
η_L	$\mathbf{1}$	$\mathbf{1}$	-1	B_2
χ_R	$\mathbf{1}$	$\mathbf{1}$	0	B_1
χ_L	$\mathbf{1}$	$\mathbf{1}$	0	B_2

[Duerr, Fileviez Perez, Wise 1304.0576]

B - L as a local symmetry





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

N_{eff}

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

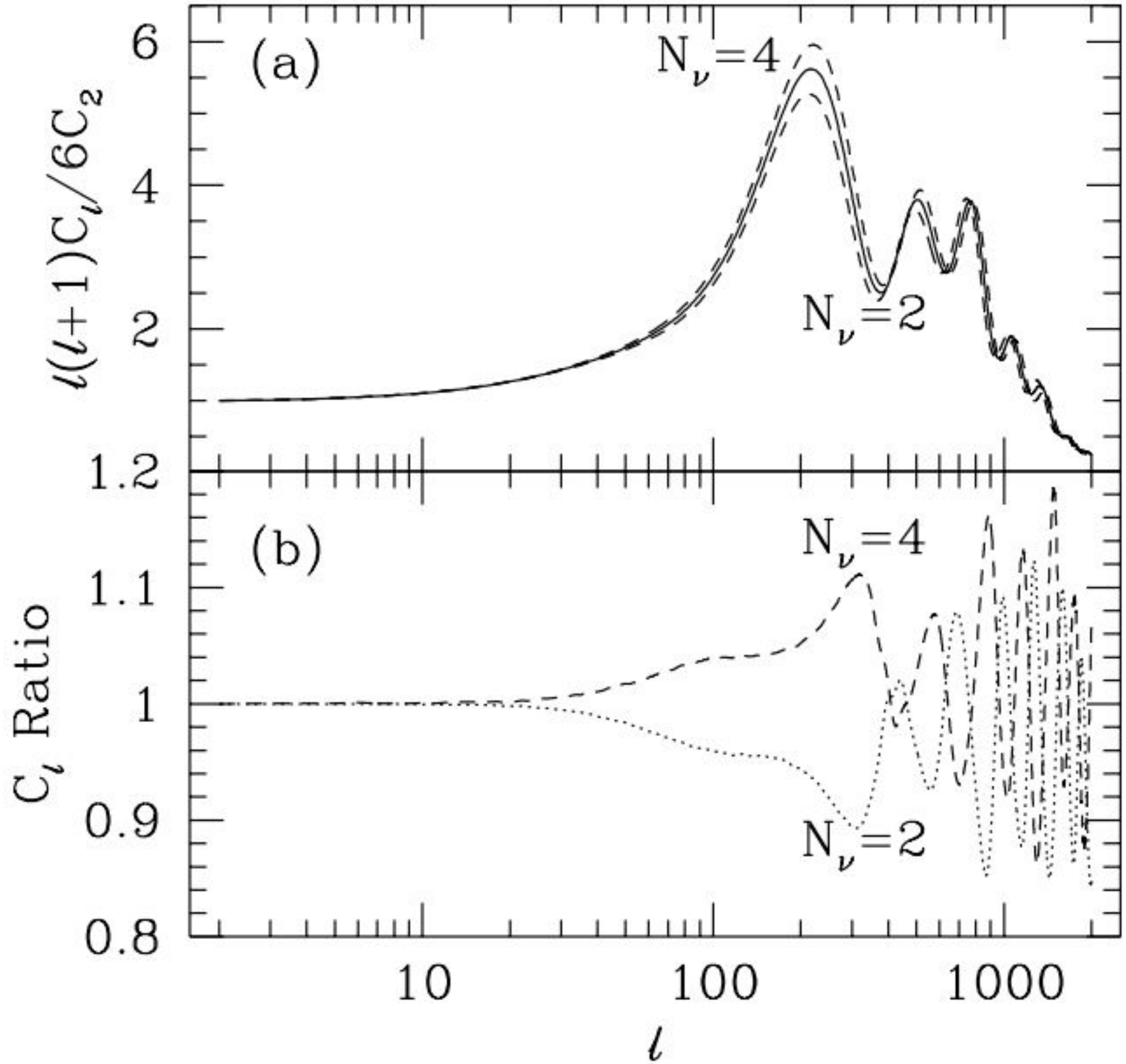
[Planck 2018] $\text{at } 95\% \, \text{CL}$

Projection for CMB Stage-IV:

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

[CMB-S4 Science Book 2016]

N_{eff}



[Hu et al 1995]

Stueckelberg scenario

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}(mZ_{\mu}^{BL} + \partial_\mu\sigma)(mZ_{BL}^{\mu} + \partial^\mu\sigma)$$

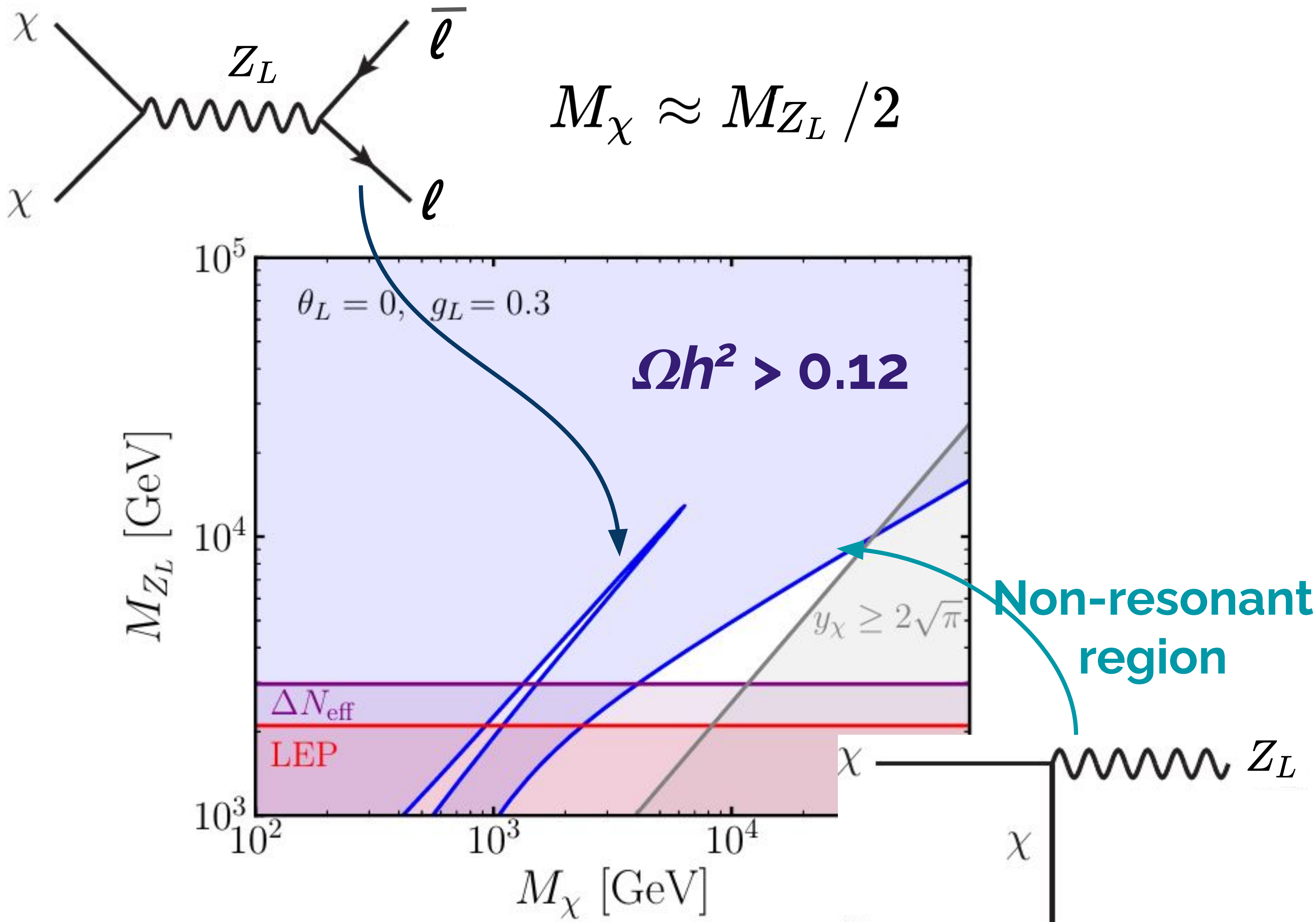
The above Lagrangian is invariant under gauge transformations:

$$\delta Z_{BL}^{\mu} = \partial^\mu \lambda(x) \qquad \text{and} \qquad \delta\sigma = -M_{Z_{BL}}\lambda(x)$$

Massive gauge boson and σ field decouples from the theory

$$\begin{aligned}\mathcal{L} = &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{m^2}{2}Z_{\mu}^{BL}Z_{BL}^{\mu} - \frac{1}{2\xi}(\partial_\mu Z_{BL}^{\mu})^2 \\ &- \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \xi\frac{m^2}{2}\sigma^2\end{aligned}$$

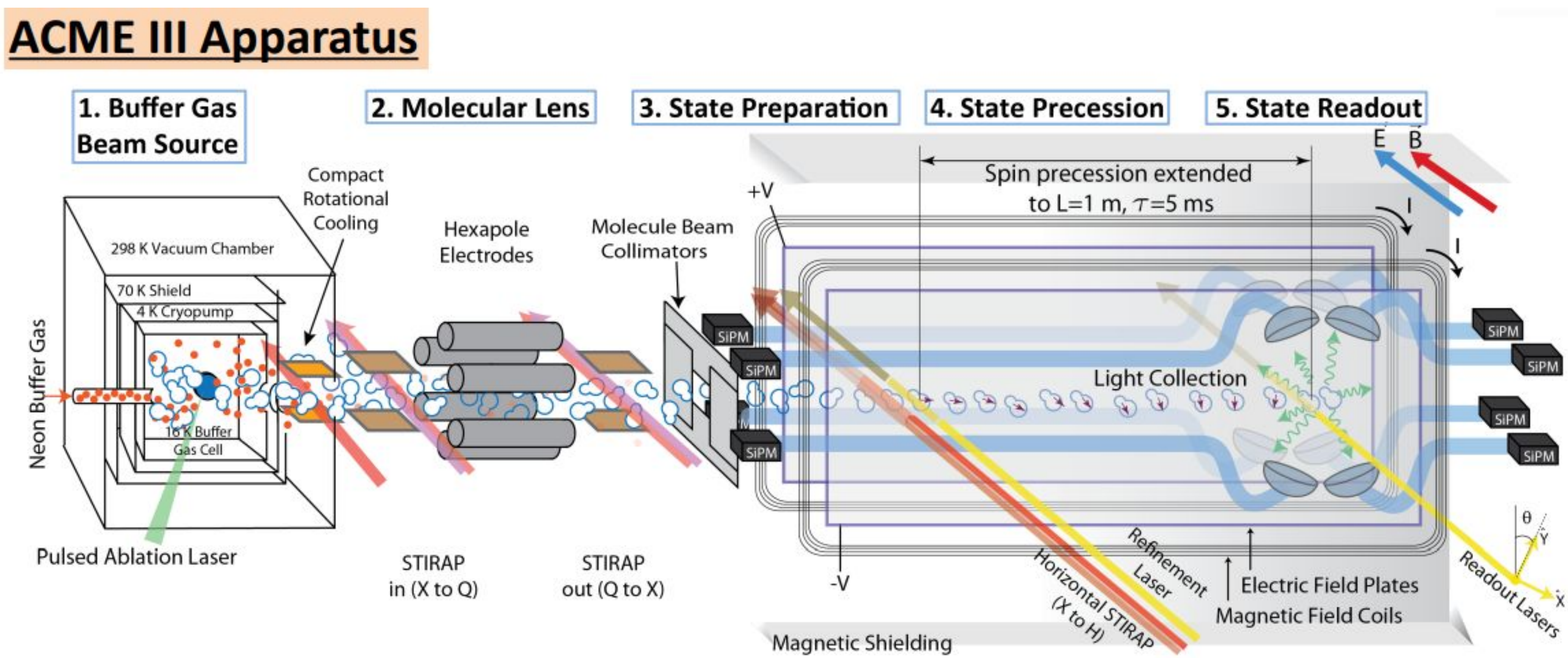
For Abelian theories renormalizable and unitary.



Alexis Plascencia

ACME experiment

- Measures the electron EDM
- Beam of thorium monoxide molecule
- ThO has a strong internal electric field



[ACME collaboration]