Particle physics and cosmology of an MeV-scale $L_\mu - L_\tau$ model [2107.14528]

Manuel Drees, Wenbin Zhao

Bethe Center for Theoretical Physics and Physikalisches Institut, Universität Bonn

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Outline

1. $U(1)_{L_\mu - L_\tau}$ model
2. Constraints: From Particle Physics to Cosmology
3. Further Application: 511 keV Excess
4. Future Tests
5. Summary

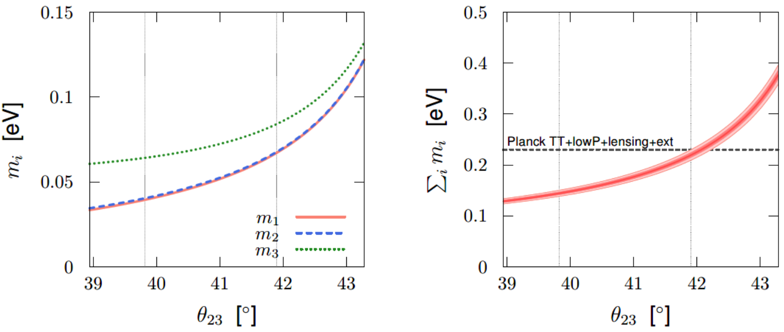
The Model

Gauging the accidental symmetry of the SM.

particles	$SU(2)_L$	$U(1)_Y$	$U(1)_{L_\mu - L_\tau}$
L_e, L_μ, L_τ	2	-1/2	(0,+1,-1)
e_R, μ_R, τ_R	1	-1/2	(0,+1,-1)
$^*N_e, N_\mu, N_\tau$	1	0	(0,+1,-1)
$^*\psi$	1	0	q_ψ

- Anomaly-Free: Unlike $B-L$, anomaly cancellation happens between the second and third generation, thus it is anomaly free even without right-handed neutrinos.
- $g_\mu - 2$: A new gauge boson X directly couple to muon, hence it contribute to $g_\mu - 2$ through one loop vertex.
- Dark Photon: New gauge boson couples to EM currents via loop corrections. Very little constraint from e^+e^- colliders.

Neutrino Sector



(a) Mass spectrum (b) $\sum_i m_i$

- Minimal: $3N$ and 1σ.(K. Asai et al.,1705.00419 & 1811.07571)
- Non-minimal: Relation breaks down, but can realize leptongenesis. (e.g. 3 scalars, D.Borah et al., 2106.14410.)

DM Model

Model Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} - g_X X_\lambda (\bar{\mu}\gamma^\lambda \mu - \bar{\tau}\gamma^\lambda \tau + \bar{\nu}_{\mu L}\gamma^\lambda \nu_{\mu L} - \bar{\nu}_{\tau L}\gamma^\lambda \nu_{\tau L})$$
$$- \frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \frac{1}{2} m_X^2 X_\mu X^\mu$$
$$+ \bar{\psi}(i\partial\!\!\!/ - m_\psi)\psi - q_\psi g_X X_\lambda \bar{\psi}\gamma^\lambda \psi \,.$$

Accommodates a rich phenomenology in Particle Physics experiments:

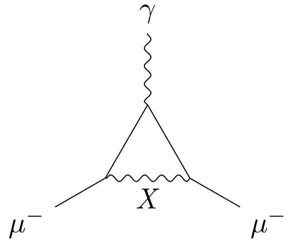
- Neutrino Trident Production: $\nu_\mu N \to \nu_\mu N \mu^+ \mu^-$.
- Muonic Dark Force: $e^+ e^- \to \mu^+ \mu^- X\,, \quad X \to \mu^+ \mu^-$.

Consider one loop corrections:

- Anomalous magnetic moment of muon: $g_\mu - 2$.
- Coherent Elastic Neutrino Nucleus Scattering: $\nu N \to \nu N$.
- White Dwarf Cooling: $e^+ e^- \to \nu\bar{\nu}$; Or $\nu e \to \nu e$ scattering.

One Loop Corrections

$g_\mu - 2$:

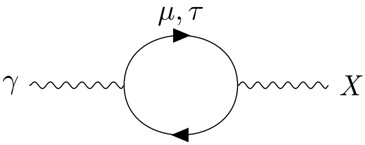


To explain the anomalous:

$$\Delta\alpha_\mu = (251 \pm 59) \times 10^{-11}$$

We need:
$m_X \backsim \mathcal{O}(\mathrm{GeV})\,, g_X \backsim 0.1$;
$m_X \backsim \mathcal{O}(\mathrm{MeV})\,, g_X \backsim 10^{-3(4)}$.

Mixing with photon:



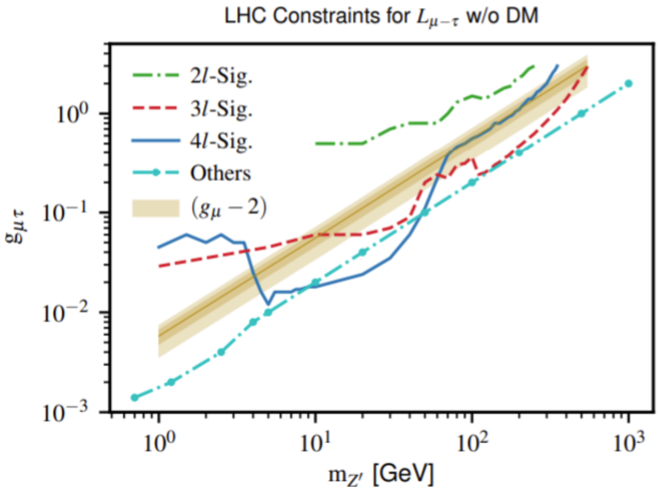
Additional Lagrangian term:

$$\mathcal{L}_{X,J_{\mathrm{em}}} = -\epsilon_A\, e X_\mu J^\mu_{\mathrm{em}}\,,$$

$$\epsilon_A = -\frac{e g_X}{12\pi^2} \ln\left(\frac{m_\tau^2}{m_\mu^2}\right) \approx -\frac{g_X}{70}\,.$$

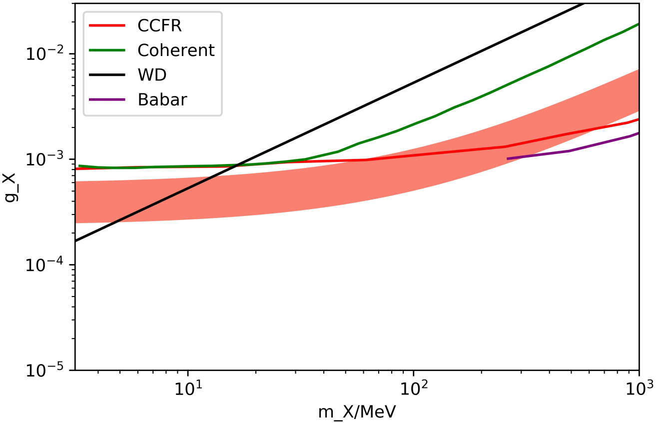
X can be regarded as a dark photon. Its mixing with Z boson is further suppressed by Z boson mass.

GeV DM: Hosts of constraints



M. Drees, M. Shi and Z. Zhang,1811.12446

MeV DM: Not well constrained yet!



A lot of parameter space in $\mathcal{O}(10)$MeV is still free!

Very small gauge coupling! $\langle \sigma v \rangle$ is expected to be samll.

Relic Density

For DM mass below 200 MeV, it mainly annihilates to neutrinos:

$$\sigma(\psi\bar{\psi} \to \nu_l \bar{\nu}_l)v \approx \frac{q_\psi^2 g_X^4}{8\pi m_X^2} \frac{1}{(\delta + v_{\rm rel}^2/4)^2 + \gamma_X^2} .$$

With

$$r = m_\psi / m_X ; \quad \delta = 4(m_\psi/m_X)^2 - 1 ; \quad \gamma_X = \Gamma_X / m_X ,$$

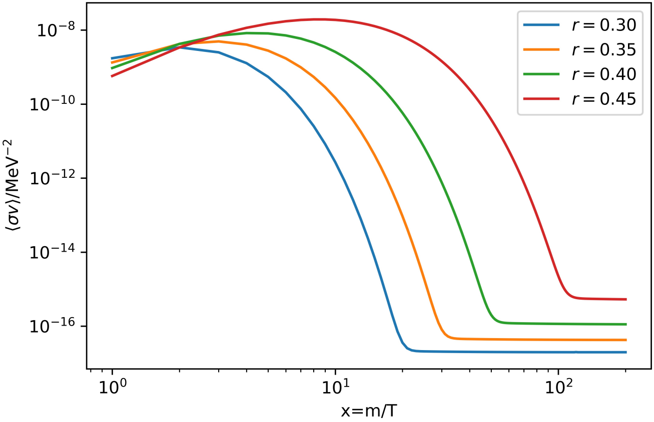
Need $\langle \sigma v \rangle$ in $\mathcal{O}(1\text{pb})$ to produce correct relic density:

- Introduce charge hierarchy. See K. Asai et al, 2011.03165.
- Resonant enhancement. Similar Work: P. Foldenauer, 1808.03647.

Need to treat the thermal average carefully to solve the Boltzmann equation.

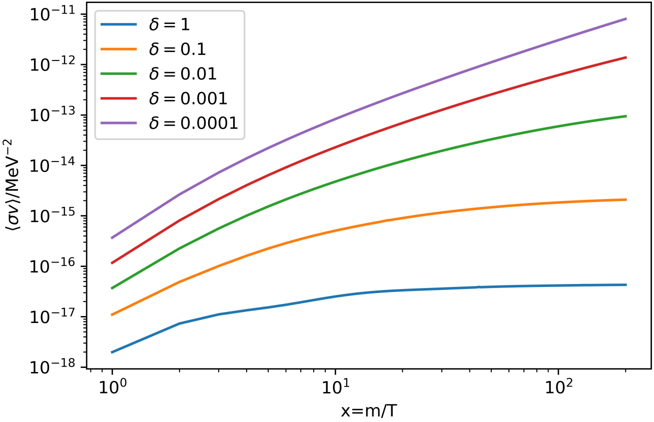
$$\frac{dn_\psi}{dt} + 3Hn_\psi = -\frac{\langle \sigma v \rangle}{2}(n_\psi^2 - n_{\psi,eq}^2) .$$

Relic Density: $\langle \sigma v \rangle$ Below the Pole



$r = \frac{m_\psi}{m_X}$, large r is close to the pole.
kinetic energy dominated $\rightarrow$ mass dominated

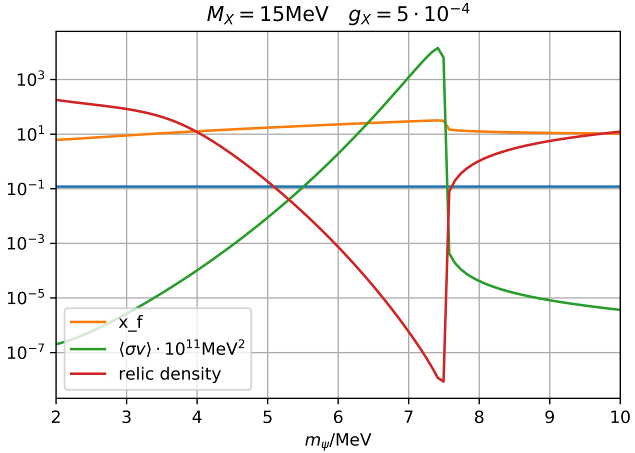
Relic Density: $\langle \sigma v \rangle$ Above the Pole



$\delta = 4(\frac{m_\psi}{m_X})^2 - 1$, small δ is close to the pole.

Focus on this case!

Relic density



Two possible solutions sit on both sides of the pole.

When $m_\psi < \frac{m_X}{2}$, need $\langle \sigma v \rangle_{x_f} \approx 40\,\text{pb}$.

BBN and Hubble tension

Both ψ and X couples to neutrinos and annihilate/decay to them. If decoupling happens after neutrino decoupling, neutrino temperature will be increased compared with the SM case.
The impact is usually parameterized by N_{eff}, defined by the total relativistic energy density well after electron–positron annihilation:

$$\rho_{\text{rad}} = \left[1 + N_{\text{eff}} \frac{7}{8} \left(\frac{4}{11}\right)^{\frac{4}{3}}\right] \rho_\gamma \, ,$$

Assuming the following condition, N_{eff} can be quantified by entropy conservation:

- No chemical potential.
- $m_\psi, m_X \gg T_r \rightarrow$ entropy was totally transferred.
- Instant neutrinos decouple at $T_{\nu,D}$.

What is the value of $T_{\nu,D}$?

In the Standard Model, the ν_μ, ν_τ decouple from photon plasma at $T = 2.3\,\text{MeV}$, while ν_e decouple a little later at $T = 1.5\,\text{MeV}$.
In the SM, the dominant processes are mediated by Z boson:

$$\nu_{\mu,\tau}\bar{\nu}_{\mu,\tau} \xrightarrow{Z} e^+e^-, \nu_e\bar{\nu}_e.$$

We have additional contribution mediated by X boson:

$$\nu_{\mu,\tau}\bar{\nu}_{\mu,\tau} \xrightarrow{X} e^+e^-.$$

A larger cross section means they would decouple later.
By comparing total thermally averaged cross section with the SM ones, we find $T_{\nu,D} \simeq 2.0\,\text{MeV}$.

BBN and Hubble tension

The contributions from dark matter annihilation and X boson decay are:

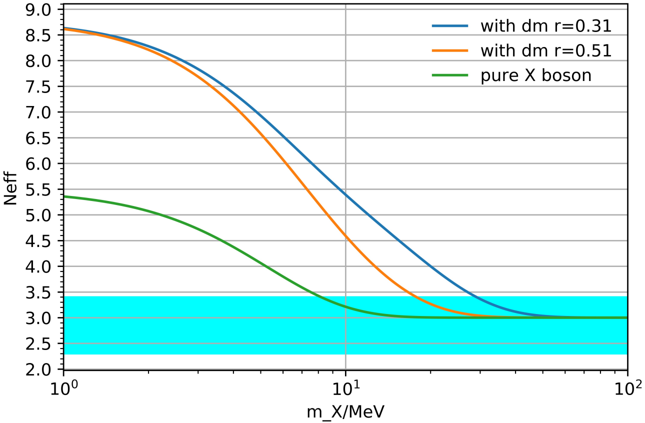
$$N_{\text{eff}} = N_\nu \left[1 + \frac{1}{N_\nu} \sum_i \frac{g_i}{2} F\left(\frac{m_i}{T_{\nu,D}}\right)\right]^{4/3} ;$$

Where

$$F(x) = \frac{30}{7\pi^4} \int_x^\infty dy \frac{(4y^2 - x^2)\sqrt{y^2 - x^2}}{e^y \pm 1} .$$

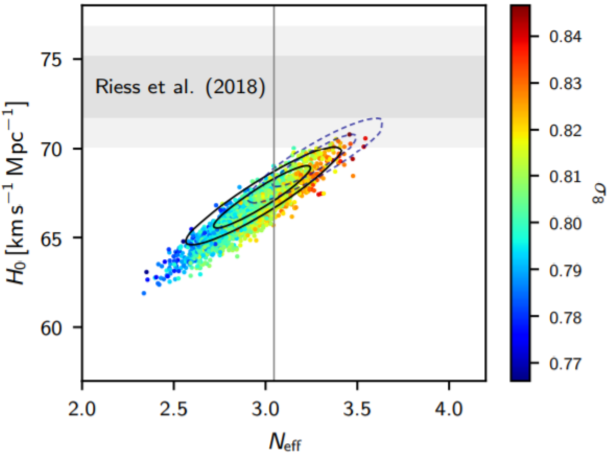
Note the maximum contribution is larger than simply adding massless particles.

BBN and Hubble tension



A lower bound on X boson mass with $m_\psi \approx 0.5\, m_X$, $m_X > 20$ MeV.

BBN and Hubble tension



Planck2018,1807.0620

$\delta N_{\mathrm{eff}} = 0.4$ is able to reduce the tension to 2σ. Sunny Vagnozzi,1907.07569

Cosmic Microwave Background

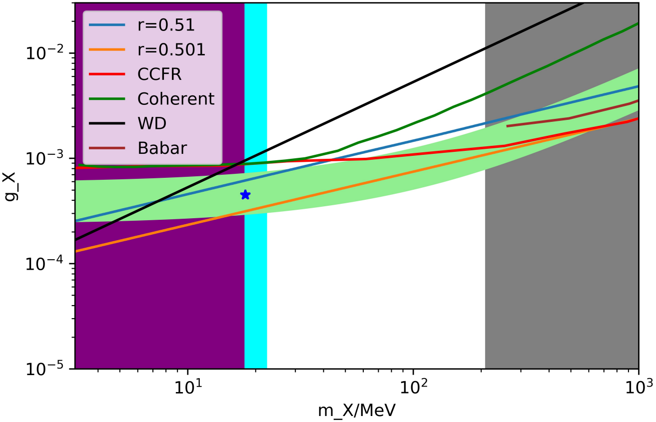
Light DM is also facing CMB constraints:

$$f_{\rm eff}(m_\psi)\frac{\langle \sigma v\rangle}{2} \leq 4.1\times 10^{-28}\left(\frac{m_\psi}{\rm GeV}\right){\rm cm}^3/{\rm s}\,,$$

This constraint applies to our model in two scenario:

- $m_\psi > m_\mu$: $\psi\bar{\psi}\to\mu\bar{\mu}$ becomes a main annihilation channel for dark matter, completely excluded.
- $m_\psi < m_\mu$: Only constrain $\psi\bar{\psi}\to e^+e^-$ process. The cross-section is $\left(\frac{e\epsilon_A}{g_X}\right)^2 \approx 2\times 10^{-5}$ smaller than that for $\psi\bar{\psi}\to\nu\bar{\nu}$.

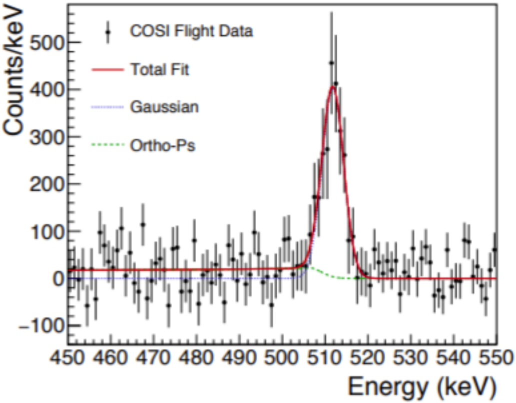
Overall Constraints



A small but charming region!

We use $g_X = 4.5 \cdot 10^{-4}$ and $m_X = 20$ MeV as a benchmark point.

511 keV Excess



COSI,1912.00110

Can be explained by DM annihilation to e^+e^-:

$$10^{-3}\text{fb} \leq \langle \sigma(\psi\bar{\psi} \to e^+e^-)v \rangle \cdot \left(\frac{m_\psi}{1\ \text{MeV}}\right)^{-2} /2 \leq 1\text{fb}$$

511 keV Excess

When calculating relic density:

$$\sigma(\psi\bar{\psi} \to \nu_l \bar{\nu}_l)v \approx \frac{q_\psi^2 g_X^4}{8\pi m_X^2} \frac{1}{(\delta + v_{\rm rel}^2/4)^2 + \gamma_X^2}$$

$$\langle \sigma(\psi\bar{\psi} \to e^+ e^-)v \rangle \approx 2 \times 10^{-5} \langle \sigma(\psi\bar{\psi} \to \nu\bar{\nu})v \rangle \,.$$

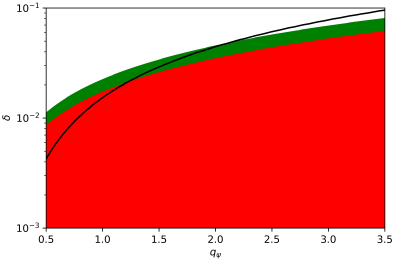
Today $v_{\rm rel}^2 \approx 10^{-6}$; when DM decouple $v_{\rm rel}^2 \approx 10^{-1}$:

$$\frac{\langle \sigma v \rangle_{t_0}}{\langle \sigma v \rangle_{x_f}} \approx \frac{\delta^{-1}}{10} \,.$$

To produce relic density correctly, q_ψ and δ has a one-to-one correspondence. Thus:

$$q_\psi \downarrow \to \delta \downarrow \to \langle \sigma v \rangle_{t_0} \uparrow$$

511 keV Excess

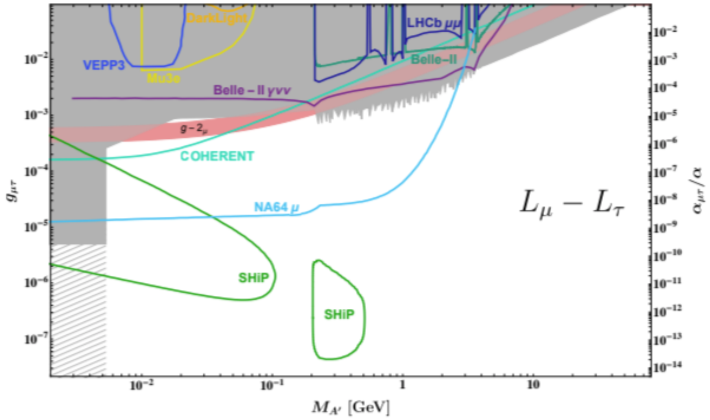


In the 2σ region of $g_\mu - 2$, q_ψ can vary from $0.9 \sim 4.9$.

More Comments:

- Can only contribute to $30\% - 40\%$ of the flux due to positron-electron in-flight annihilation.
- It will work better if DM density peaks near the galactic center.
- Given the constraints mentioned do NOT depend on q_ψ, it becomes a handle to tune the cross-section today.

Future Tests: Upcoming Experiments



M. Bauer, P. Foldenauer and J. Jaeckel,1803.05466.

Future Tests: In Low Energy Collider

It might also be testable through the process $e^+e^- \to X\gamma$ followed by invisible decays of the X boson. The differential cross section reads:

$$\frac{d\sigma}{d\cos\theta} = \frac{\alpha(e\epsilon_A)^2}{s(s-m_X^2)}\left[\frac{s^2+m_X^4}{\sin\theta^2} - \frac{(s-m_X^2)^2}{2}\right],$$

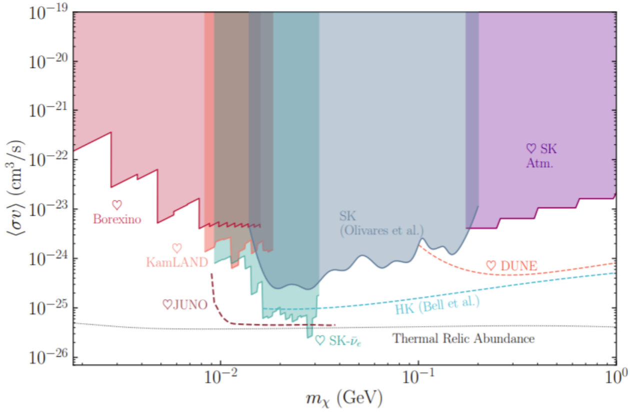
Requiring $|\cos\theta| < 0.985$ in order to make sure that the photon can be detected and taking $m_X^2 \ll s$ leads to a cross section of about

$$\sigma \simeq 20\text{ab}\left(\frac{g_X}{10^{-3}}\right)^2 \frac{(10\ \text{GeV})^2}{s}.$$

Hundreds of events in Belle-II.

Future Tests: Neutrino Experiments

It predicts $\langle\sigma(\psi\bar{\psi} \to \nu_l\bar{\nu}_l)v\rangle_{\text{now}} \approx 10^{-24} - 10^{-25}\ \text{cm}^3/\text{s}$ when solving the 511 keV excess, which can be tested through next generation of neutrino experiments.



C. A. Arguelles et al, 1912.09486

Summary

- $U(1)_{L_\mu - L_\tau}$ model can explain $g_\mu - 2$ in MeV region with a relatively small coupling g_X.
- Resonant structure can be used to give correct relic density in this region.
- If DM mass is around 10 MeV, it also impacts the neutrino sector as they decouple, hence increase N_{eff} and relax the Hubble tension.
- It also contributes to 511 keV excess through loop correction.
- The whole scenario can be tested in future experiments like NA64μ, JUNO and Belle-II.