Cosmology With a Very Light $L_\mu - L_\tau$ Gauge Boson

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Dark Side of the Universe
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Based on [1901.02010] with M. Escudero, D. Hooper & G. Krnjaic
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The \((g - 2)_\mu\) anomaly

\[ \vec{\mu}_\mu = g_\mu \frac{\sqrt{4\pi\alpha}}{2m_\mu} \vec{S}_\mu \]

\[ a_\mu \equiv \frac{g_\mu - 2}{2} \]

- Long standing \(\sim 3.5\sigma\) discrepancy

\[ \Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 268(63)(43) \times 10^{-11} \]

[PDG]

- SM prediction very robust

[Blum et al. 1311.2198]

- Many BSM interpretations SUSY, extra Higgses and symmetries

[Lindner et al. 1610.06587]

- Fermilab should reduce error by a factor \(\sim 4\) : early 2019?

- Experiment at J-PARC should reach same sensitivity
The Hubble tension

\[ H_0 = 73.45 \pm 1.66 \text{ km s}^{-1} \text{ Mpc}^{-1} \]

3.5 \sigma tension!

\[ H_0 = 67.27 \pm 0.60 \text{ km s}^{-1} \text{ Mpc}^{-1} \]

Planck 2018 1807.06209

- Tension unlikely generated by CMB systematics
  [Verde et al. 1601.01701]

- Local measurement have been checked against systematics
  [Follin & Knox 1707.01175]

- Discrepancy also present with BAO
  [Addison 1707.06547]
The Hubble tension

- Latest determination of $H_0$ based on HST: $H_0 = 74.03 \pm 1.42 \text{ km s}^{-1} \text{ Mpc}^{-1}$

- Possible solutions?
  - Early dark energy
    [Poulin et al. 1811.04083]
  - Decaying dark matter
    [Bringmann et al. 1803.03644]
  - Goldstones as dark radiation
    [Weinberg 1305.1971]
  - Non-zero curvature
    [Riess et al. 1903.07603]

- Future Gaia data will increase precision on local determination of $H_0$

- Stage-IV CMB experiment expected to deliver $\sigma N_{\text{eff}} \sim 0.03$
The Hubble tension: $\Delta N_{\text{eff}} > 0$?

- Modifying $N_{\text{eff}}$ before recombination changes the sound horizon, that can be compensated by a larger $H_0$ for keeping the same acoustic angular scale.

- Planck+BAO+RIESS18
  \[
  N_{\text{eff}} = 3.27 \pm 0.15 \\
  H_0 = (69.32 \pm 0.97) \text{ km s}^{-1} \text{Mpc}^{-1}
  \]
  [Planck 1807.06209]

- $\Delta N_{\text{eff}} < 0.53$ from Planck → sterile ν interpretation?

- $2.3 < N_{\text{eff}} < 3.5$ from BBN  [Cyburt et al. 1505.01076]

$\Delta N_{\text{eff}} = 0.2 - 0.5$ alleviates the $H_0$ tension
The main idea

Consider the generation of $\Delta N_{\text{eff}} > 0$ from interactions and decay of a light neutrophilic $Z'$ gauge field

\[
N_{\text{eff}} \equiv \frac{8}{7} \left( \frac{11}{4} \right)^{4/3} \left( \frac{\rho_{\text{rad}} - \rho_{\gamma}}{\rho_{\gamma}} \right)
\]

$T_{\nu} > T_{\nu}^{\text{SM}} \quad \Rightarrow \quad \Delta N_{\text{eff}} > 0$

$\Delta a_{\mu}$

$\Delta N_{\text{eff}} > 0$, $N_{\nu} = 3$, $N_{\text{DR}} = 0$, $\Delta a_{\mu}$
A light $L_\mu - L_\tau$ gauge boson

- Assuming a local U(1) gauged $L_\mu - L_\tau$ number

$$\mathcal{L}_{\text{int}} = g_{\mu-\tau} Z'_\alpha (\bar{\mu} \gamma^\alpha \mu + \bar{\nu}_\mu \gamma^\alpha P_L \nu_\mu - \bar{\tau} \gamma^\alpha \tau - \bar{\nu}_\tau \gamma^\alpha P_L \nu_\tau)$$

- Simple **anomaly-free** BSM extension: 2 parameters

$$10^{-15} < g_{\mu-\tau} < 10^{-1}$$  
$$1 \text{ eV} < m_{Z'} < 2m_\mu$$

- Kinetic mixing

$$\epsilon = -\frac{e g_{\mu-\tau}}{12\pi^2} \log \frac{m_\tau^2}{m_\mu^2} = -\frac{g_{\mu-\tau}}{70}$$

- Neutrinoophilic

$$\Gamma_{Z'\rightarrow \bar{\nu}_i \nu_i} = \frac{g_{\mu-\tau}^2 m_{Z'}}{24\pi}$$

- Coupling to electrons

$$\text{Br}_{Z'\rightarrow e^+ e^-} \approx 2 \times 10^{-5}$$
A light $L_\mu - L_\tau$ gauge boson

3 regimes:
- Thermal $Z'$ at $\nu$ decoupling
- Thermal $Z'$ after $\nu$ decoupling
- Non-thermal $Z'$
The thermal regime

- $Z'$ in thermal equilibrium with $\nu$ due to large coupling
  $$T_{Z'} = T_\nu$$

- $\nu$-oscillations are active at $T \sim 3$ MeV:
  $$T_\nu \equiv T_{\nu_\mu} = T_{\nu_\tau} = T_{\nu_e}$$

$$\frac{dT_\nu}{dt} = - \left( 4H\rho_\nu + 3H (\rho_{Z'} + p_{Z'}) - \frac{\delta \rho_\nu}{\delta t} - \frac{\delta \rho_{Z'}}{\delta t} \right) \left( \frac{\partial \rho_\nu}{\partial T_\nu} + \frac{\partial \rho_{Z'}}{\partial T_\nu} \right)^{-1}$$

$$\frac{dT_\gamma}{dt} = - \left( 4H\rho_\gamma + 3H (\rho_e + p_e) + \frac{\delta \rho_\nu}{\delta t} + \frac{\delta \rho_{Z'}}{\delta t} \right) \left( \frac{\partial \rho_\gamma}{\partial T_\gamma} + \frac{\partial \rho_e}{\partial T_\gamma} \right)^{-1}$$

- Need to solve
  [Escudero 1812.05605]

- Need to compute thermal averaged rates

$e^+ e^- \leftrightarrow \bar{\nu}_\nu$

$Z' \leftrightarrow e^+ e^-$
The thermal regime

\[ g_{\mu-\tau} = 4 \times 10^{-4} \approx g_{\mu-\tau}|_{g-2} \]

SM, \( N_{\text{eff}} = 3.04 \)
- \( m_{Z'} = 20 \text{ MeV}, \ N_{\text{eff}} = 3.17 \)
- \( m_{Z'} = 15 \text{ MeV}, \ N_{\text{eff}} = 3.3 \)
- \( m_{Z'} = 10 \text{ MeV}, \ N_{\text{eff}} = 3.69 \)
- \( m_{Z'} = 5 \text{ MeV}, \ N_{\text{eff}} = 5.84 \)

\[ \epsilon = -g_{\mu-\tau}/70 \]

Delayed \( \nu \) Decoupling
The thermal regime

\[ N_{\text{eff}}, \text{with } \nu \text{-oscillations, } \epsilon = g_{\mu-\tau}/70 \]

- **Compatible** with simultaneous \( H_0 \) and \((g - 2)_\mu\)!

\[ m_{Z'} \simeq 10 - 20 \text{ MeV} \quad g_{\mu-\tau} \simeq (4 - 8) \times 10^{-4} \]
Weakly coupled regime

- **For small couplings**, no early thermal $Z'$-SM equilibrium, only one relevant process

- **Non-thermal**! Need the full phase space distribution

\[
\begin{align*}
\frac{\partial f_{Z'}}{\partial t} - H_{p_{Z'}} \frac{\partial f_{Z'}}{\partial p_{Z'}} &= -\frac{m_{Z'} \Gamma_{Z'}}{E_{Z'} p_{Z'}} \int_{(m_{Z'}^2/4p_{\nu})-p_{\nu}}^\infty \frac{dE_{\nu} F_{\text{dec}}(E_{Z'}, E_{\nu}, E_{Z'} - E_{\nu})}{E_{Z'}} F_{\text{dec}}(E_{Z'}, E_{\nu}, E_{Z'} - E_{\nu}) dE_{\nu} \\
\frac{\partial f_{\nu}}{\partial t} - H_{p_{\nu}} \frac{\partial f_{\nu}}{\partial p_{\nu}} &= \frac{m_{Z'} \Gamma_{Z'}}{E_{\nu} p_{\nu}} \int_0^\infty \frac{dp_{Z'} p_{Z'}}{E_{Z'}} F_{\text{dec}}(E_{Z'}, E_{\nu}, E_{Z'} - E_{\nu}) dp_{Z'}
\end{align*}
\]

with \( F_{\text{dec}}(E_{Z'}, E_{\nu_1}, E_{\nu_2}) = f_{Z'}(E_{Z'}) [1 - f_{\nu}(E_{\nu_1})] [1 - f_{\nu}(E_{\nu_2})] - f_{\nu}(E_{\nu_1}) f_{\nu}(E_{\nu_2}) [1 + f_{Z'}(E_{Z'})] \).

- **Stiff** set of equations, solved for 100 bins in comoving momentum for the $Z'$ and $\nu$ distributions

- Check continuity equation \( \frac{d\rho}{dt} = -3H (\rho + p) \)
• **Non-thermal** distribution: our approach is justified!
Weakly coupled regime

\[\Delta N_{\text{eff}} = 0.21\]

- \(m_{Z'} = 1\ \text{keV}\)
- \(g_{\mu-\tau} = 10^{-10}\)
- \(m_{Z'} = 2.2\ \text{keV}\)
- \(g_{\mu-\tau} = 1.3 \times 10^{-11}\)

\(\rho / T_\gamma^4\) vs. \(T_\gamma\) (MeV)

- Thermalized
- Non-thermalized
The results

$L_\mu - L_\tau$ Gauge Boson, No Kinetic Mixing

- $\Delta N_{\text{eff}} = 0.21$ over a large plateau of parameter space
- Due to secluded $\nu$-$Z'$ system after $\nu$-decoupling and out-of-equilibrium decay
The results

$L_{\mu} - L_{\tau}$ Gauge Boson, Natural Kinetic Mixing ($\epsilon = g_{\mu-\tau}/70$)

- **Stellar cooling** important when **kinetic mixing** considered
- For $m_{Z'} < 100$ keV: $\Delta N_{\text{eff}} = 0.21$ at CMB but $\Delta N_{\text{eff}} = 0$ at BBN!
Take-home message

- The $H_0$ and $(g - 2)_\mu$ tensions: physics beyond $\Lambda$CDM?

- $H_0$ and $(g - 2)_\mu$ tensions can be simultaneously addressed for
  
  $m_{Z'} \simeq 10 - 20$ MeV \hspace{1cm} g_{\mu-\tau} \simeq (4 - 8) \times 10^{-4}$

- $\Delta N_{\text{eff}} = 0.21$ a generic prediction of a light $L_\mu$-$L_\tau$ gauge boson

- Local measurements of $H_0$ expected to deliver a precision of $\sim 1\%$ within the next few years

- The $\Delta N_{\text{eff}} \sim 0.2 - 0.5$ hypothesis could be tested at stage-IV CMB experiments, expected to deliver $\sigma N_{\text{eff}} \sim 0.03$

- Very reach interplay between particle physics and cosmology
Back-up Slides
The \((g - 2)_e\) anomaly

[Adam Falkowski’s blog Resonaances]
A light $L_\mu - L_\tau$ gauge boson

- $Z'$ in kinetic equilibrium with $e^\pm, \gamma, \nu$?

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<th>Decays and Inverse decays</th>
<th>Scatterings and Annihilations</th>
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<td><strong>Electro</strong></td>
<td></td>
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<tr>
<td>$Z'$</td>
<td>$\sim g_{\mu-\tau}$</td>
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<tr>
<td>$e^+ \rightarrow e^- + e^+$</td>
<td>$\sim g_{\mu-\tau}/70$</td>
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<td>$e^- \rightarrow \mu^+ + \nu$</td>
<td>$\sim g_{\mu-\tau}^2/70$</td>
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<tr>
<td><strong>Neutrino</strong></td>
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<tr>
<td>$\bar{\nu}_{\mu,\tau}$</td>
<td>$\sim g_{\mu-\tau}$</td>
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\( \nu - \text{decoupling and } N_{\text{eff}} \)

- \( \nu \)-decoupling \( T_d \) when \( n_\nu \langle \sigma v \rangle \sim H \) with \( n_\nu \langle \sigma v \rangle \simeq G_F^2 T^5 \)

\[ T_d \sim 1 \text{ MeV} \]

- \( N_{\text{eff}} = \frac{8}{7} \left( \frac{11}{4} \right)^{4/3} \left( \frac{\rho_{\text{rad}} - \rho_\gamma}{\rho_\gamma} \right) \)

- \( N_{\text{eff}} = 3 \left( \frac{11}{4} \right)^{4/3} \left( \frac{T_\nu}{T_\gamma} \right)^4 \)

- \( N_{\text{eff}}^{\text{SM}} = 3.045 \) \([\text{Salas & Pastor 1606.06986}]\)

- Why \( N_{\text{eff}} \neq 3 \)?
  - \( T_d \neq 1 \text{ MeV} \)
  - Non-instantaneous decoupling
  - \( \nu \)-oscillations
  - QED finite temperature corrections

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Cosmology With a Very Light \( L_\mu - L_T \) Gauge Boson

07-16-2019 --/--
Phase space distribution

\[ \Delta N_{\text{eff}} = 0.21, \ g_{\mu \tau} = 10^{-10}, \ m_{Z'} = 1\,\text{keV} \]

\[ \Delta N_{\text{eff}} = 0.21, \ g_{\mu \tau} = 1.3 \times 10^{-11}, \ m_{Z'} = 2.2\,\text{keV} \]

\[ \Delta N_{\text{eff}} = 0.16, \ g_{\mu \tau} = 1.7 \times 10^{-12}, \ m_{Z'} = 2.2\,\text{keV} \]

\[ \Delta N_{\text{eff}} = 0.08, \ g_{\mu \tau} = 6 \times 10^{-13}, \ m_{Z'} = 2.2\,\text{keV} \]
Constraints

Laboratory constraints

- Neutrino Tridents: Relevant for large couplings and large masses
- Kaon decays: Relevant if no kinetic mixing
- B-factories: Relevant for the g-2 anomaly region
- Beam dumps: Absent due to $\text{Br}_{Z' \to e^+e^-} \simeq 2 \times 10^{-5}$
- Solar neutrino scatterings: Relevant for the g-2 anomaly region

Astrophysical constraints

- SN1987A: Very important in a considerable portion of parameter space
- Stellar Cooling: Very important in a considerable portion of parameter space

Cosmological constraints

- Energy injection at the CMB: Absent due to $\text{Br}_{Z' \to e^+e^-} \simeq 2 \times 10^{-5}$
- Energy injection during BBN: Absent due to $\text{Br}_{Z' \to e^+e^-} \simeq 2 \times 10^{-5}$
The $(g - 2)_\mu$ anomaly

History of $(g - 2)_e$

\[ \bar{\mu}_e = g_e \frac{\sqrt{4\pi\alpha}}{2m_e} \tilde{S}_e \]

- 1948 Schwinger \( (g - 2)_e / 2 \simeq \alpha / (2\pi) \)

\[ (g - 2)^{\text{exp}}_e / 2 = 1 159 652 180.73(28) \times 10^{-12} \]

[Hanneke et al. 0801.1134]

- 2008

\[ (g - 2)^{\text{SM}}_e / 2 = 1 159 652 181.61(23) \times 10^{-12} \]

[Aoyama et al. 1712.06060]

- 2018 : \( \sim 2\sigma \) discrepancy in \( (g - 2)_e \)?

[Parker et al. 1812.04130]
I. Motivation: $H_0$ and $(g - 2)_\mu$
   1. The $(g - 2)_\mu$ discrepancy
   2. The $H_0$ tension
   3. $\nu$-decoupling and $N_{\text{eff}}$

II. A very light $L_\mu$-$L_\tau$ gauge boson
   1. The model
   2. Main processes and regimes

III. Results and conclusion