Leptonically Flavored Dark Matter

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Based on work with Andrew Kobach & Amarjit Soni, 1405.soon. Results preliminary.
What is Leptonically Flavored DM?

- Hypothesize that dark matter has flavor quantum numbers, both DM & SM charged under common flavor gauge symmetry.
- Take symmetry to be spontaneously broken, so flavor gauge bosons heavy ($\sim 100 \text{ GeV-TeV}$).
- Considering only leptonic flavor for this work.

Why is this scenario interesting?

- Flavor & dark matter both require BSM explanations. Related?
- Should consider any reasonable DM-SM interaction. Flavor interactions with DM relatively unexplored.
- Tension between scales needed to explain direct detection & relic density: should consider DM interactions with SM particles other than 1st-generation quarks.
- Indirect detection experiments (Pamela, AMS...) give intriguing signals which can be interpreted as leptonic DM annihilation (but cross-sections high).
The effects of a unified flavor interaction can show up in many places:

- **Dark matter observables:**
  - Relic density
  - Direct detection
  - Indirect detection

- **Flavor-conserving processes:**
  - Constraints on four-lepton operators from LEP
  - Muon $g - 2$
  - Leptonic resonances at colliders

- **Flavor-violating processes:**
  - Three-body lepton decays ($\mu \rightarrow 3e$, $\tau \rightarrow \mu\mu e...$)
  - Radiative lepton decays ($\mu \rightarrow e\gamma$, $\tau \rightarrow e\gamma$, $\tau \rightarrow \mu\gamma$)
  - Muonium-antimuonium conversion
Analysis Strategy

- Take DM fermionic; consider vector interactions.
- Notation: Will call DM $f$, generic flavor gauge boson $X_{\mu}$.
- For low-energy observables, will often abbreviate interactions in terms of effective operators, e.g,

$$\rightarrow \frac{1}{\Lambda^2} \bar{\mu} \gamma_{\mu} e \bar{f}_2 \gamma^\mu f_1 \quad (\Lambda = \text{NP scale})$$

- Attempt to be model-independent; will not specify flavor gauge group.
- Will allow flavor-nondiagonal couplings of flavor gauge bosons to leptons (i.e., gauge bosons can carry flavor).
- DM, SM share common flavor interaction; expect similar $\Lambda$ for DM and flavor observables.
Flavor Interactions with $\mu$ and $\tau$

- Currently $3.6\sigma$ deviation from SM expectation in $\mu \, g - 2$.
- Constraints on interactions only involving $\mu$ & $\tau$ far less constrained than interactions involving electrons:
  - Flavor-conserving:
    LEP limits on flavor-conserving effective operators including $\bar{e}e$ give NP scales $\Lambda \gtrsim 4 - 5.6$ TeV.
    $\bar{\tau}\gamma_{\mu}\tau\bar{\mu}\gamma^{\mu}\mu$ and $\bar{\mu}\gamma_{\mu}\mu\bar{\mu}\gamma^{\mu}\mu$ constrained primarily by $g - 2$.
    $\bar{\tau}\gamma_{\mu}\tau\bar{\tau}\gamma^{\mu}\tau$ completely unconstrained.
  - Flavor-violating:
    $\mu \rightarrow 3e$: NP scale $\sim 270$ TeV.
    $\tau \rightarrow 3\mu$: NP scale $\sim 15$ TeV.
    Operator like $\bar{\mu}\gamma_{\mu}\tau\bar{\mu}\gamma^{\mu}\tau$ completely unconstrained.
- For this talk, will concentrate on interactions with $\mu$ and $\tau$, flavor-conserving observables.
Can get limits on some interactions from $\mu \ g - 2$ at 1-loop:

For $a_\mu = (g - 2)/2$, $a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 287 \pm 80 \times 10^{-11}$. 3.6$\sigma$!

Requiring $2\sigma$ agreement with experiment gives scale

\[
\Delta a_\mu = \frac{m_\mu^2}{4\pi^2 \Lambda^2} \left( \frac{m_\ell}{m_\mu} - \frac{2}{3} \right)
\]

<table>
<thead>
<tr>
<th>Operator</th>
<th>$\Lambda$/TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\mu} \gamma_\mu \mu \bar{\mu} \gamma^\mu \mu$</td>
<td>0.15-0.27</td>
</tr>
<tr>
<td>$\bar{\mu} \gamma_\mu \mu \bar{T} \gamma^\mu \tau$</td>
<td>1.0-1.9</td>
</tr>
</tbody>
</table>

Note: Limits on purely muonic interactions rather weak.
Constraints: Relic Density

- For a thermal relic, need velocity-averaged DM→SM annihilation cross-section $<\sigma v> \sim 3 \times 10^{-26}$ cm$^3$/s.
- For vector interaction e.g. $\frac{1}{\Lambda^2} \bar{f} \gamma_\mu f \bar{\mu} \gamma^\mu \mu$, we get
  
  $$<\sigma v> \sim \frac{m_f^2}{\pi \Lambda^4} \rightarrow \Lambda \sim 4 \text{ TeV} \left(\frac{m_f}{\text{TeV}}\right)^{1/2}.$$  

  Note: Vector interaction; included neutrinos.
- If many annihilation channels → larger $\Lambda$. If $f$ only small fraction of DM, → smaller $\Lambda$.
- $\Lambda \sim \mathcal{O}(100 \text{ GeV-TeV})$. Smaller $\Lambda$ gives smaller $m_f$. 

Constraints: Direct Detection

- Direct detection exp’ts mainly sensitive to interactions w/nucleons.
- Here, DM can only interact with leptons at tree level, but can interact with nucleons at 1 loop:

\[ \sigma_{SI} = \frac{\mu^2}{\pi \Lambda^4} \left[ \frac{1}{(4\pi)^2} \frac{4}{3} \ln \left( \frac{\Lambda^2}{m^2_\ell} \right) \right]^2 ee_{nucleon} \]

- Since loop attaches to photon, only couples to protons in nucleus.
- Take loop to be of order running from NP scale \( \Lambda \) to \( m_\ell \), get DM-nucleon cross-section (\( \mu = \) DM-nucleon reduced mass):

- Could have gauge group with cancellation between leptons; \( \ln \Lambda^2/m^2_\ell \rightarrow \ln m^2_\mu/m^2_\tau \). Changes results by factor \( \mathcal{O}(1) \).
Compatibility with $g - 2$, direct detection, and relic density:

- $100 \text{ GeV} < M_X < 5 \text{ TeV}$.
- Kept $X$-DM coupling $= 1$.
- Varied $X$ couplings to $\bar{\mu}\mu$, $\bar{\tau}\mu$, $\bar{\tau}\tau$ between $\pm 2$.
- Special cases:
  - Only $\bar{\mu}\mu X$ coupling, very light DM, $m_f \sim$ few GeV.
  - Only $\bar{\tau}\tau X$: no $g - 2$ constraint, all $m_f$ OK.
  - $X$ only couples off-diagonally, $X\bar{\mu}\tau$: no dir. det. constraint.

![Graph showing $\sigma(N_X \rightarrow N\chi)$ vs. WIMP mass]
Constraints: Indirect Detection

- Large cross-sections for DM annihilation to leptons needed to explain excesses in Pamela, AMS, etc.
- Here, assumed DM annihilation cross-section which gives observed relic density. → This analysis not relevant for explaining those experiments.
- Low-mass DM has mild tension with indirect detection:
  - CMB puts constraints on DM annihilating at relic density x-sect for $m_f \lesssim$ several GeV. (Madhavacheril et al, 1310.3815)
  - Limits from Fermi on x-sect to $\tau$’s few $\times 10^{-27}$ cm$^3$/s. (1309.0525, 1308.4135...)
  - Limits from AMS to x-sect to $\mu$’s $\mathcal{O}(10^{-27} - 10^{-26}$ cm$^3$/s). (1309.2570, 1306.3983, 1308.4135...)
  - Gives mild tension with relic density x-sect of $3 \times 10^{-26}$ cm$^3$/s.
By hypothesis, new flavor interaction only involves DM, $\mu$, $\tau$. Can only affect LEP, LHC through loop processes:

At 1 loop:
- Contributions to LEP 4-lepton effective op’s.
- X-Z mixing.
- LHC leptonic resonance searches.

Still in progress.
Flavor and DM both require BSM physics—maybe it’s the same BSM physics!

Sensitive to a wide range of observables (DM observables, flavor-violating processes, flavor-conserving processes)
  - If only DM, $\mu$, $\tau$ charged under flavor symmetry, limits from flavor observables rather weak.
  - DM interacts only with $\tau$: only limits from dark matter observables.
  - DM interacts only with $\mu$: low NP scale needed for $g - 2$; would require light DM.
  - DM interacts with $\mu$ and $\tau$: could explain $g - 2$ deviation.

Future work/extensions:
  - Observables with $e$’s.
  - Can also look at DM-induced leptonic flavor violation.
  - Could try to build explicit models or add DM to existing flavor models.

Remarkably rich subject!