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 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).

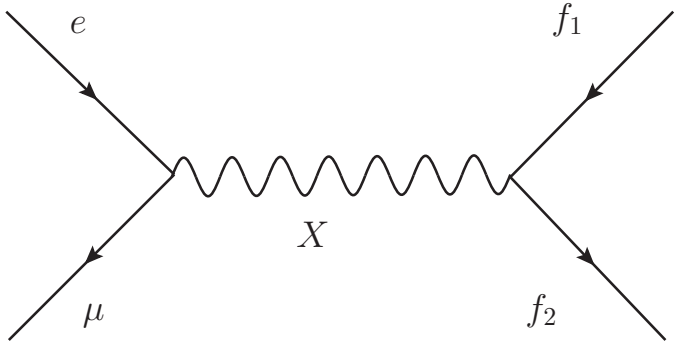
Relevant Observables

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 ($\mu \to 3e$, $\tau \to \mu\mu e$...)
  - Radiative lepton decays ($\mu \to e\gamma$, $\tau \to e\gamma$, $\tau \to \mu\gamma$)
  - Muonium-antimuonium conversion

Analysis Strategy

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



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

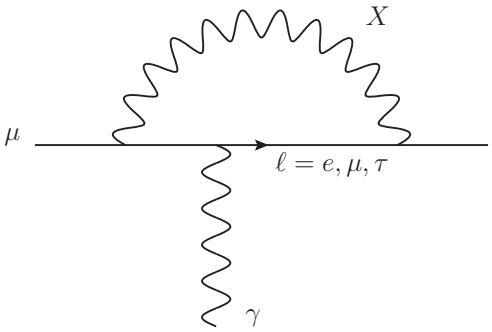
- Attempt to be model-independent; will not specify flavor gauge group.
- Will allow flavor-nondiagonal couplings of flavor gauge bosons to leptons (*i.e.*, gauge bosons can carry flavor).
- DM, SM share common flavor interaction; expect similar Λ for DM and flavor observables.

Flavor Interactions with μ and τ

- Currently 3.6σ deviation from SM expectation in μ $g-2$.
- Constraints on interactions only involving μ & τ 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:
    $\mu \to 3e$: NP scale ~ 270 TeV.
    $\tau \to 3\mu$: NP scale ~ 15 TeV.
    Operator like $\bar{\mu}\gamma_\mu\tau\bar{\mu}\gamma^\mu\tau$ completely unconstrained.
- For this talk, will concentrate on interactions with μ and τ, flavor-conserving observables.

Constraints: $g-2$

- Can get limits on some interactions from μ $g-2$ at 1-loop:



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

- For $a_\mu = (g-2)/2$, $a_\mu^{exp} - a_\mu^{SM} = 287 \pm 80 \times 10^{-11}$. 3.6σ!
- Requiring 2σ agreement with experiment gives scale

Operator	Λ/TeV
$\bar{\mu}\gamma_\mu\mu\bar{\mu}\gamma^\mu\mu$	0.15-0.27
$\bar{\mu}\gamma_\mu\mu\bar{\tau}\gamma^\mu\tau$	1.0-1.9

- Note: Limits on purely muonic interactions rather weak.

Constraints: Relic Density

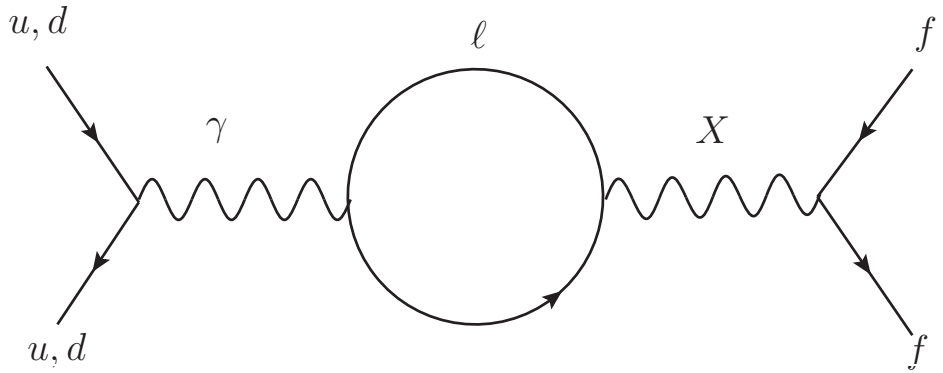
- For a thermal relic, need velocity-averaged DM→SM annihilation cross-section $< \sigma v > \sim 3 \times 10^{-26}$ cm^3/s.
- For vector interaction *e.g.* $\frac{1}{\Lambda^2} \bar{f} \gamma_\mu f \bar{\mu} \gamma^\mu \mu$, we get

$$< \sigma v > \sim \frac{m_f^2}{\pi \Lambda^4} \rightarrow \Lambda \sim 4 \text{ TeV} \left(\frac{m_f}{\text{TeV}} \right)^{1/2}.$$

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



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

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

- Could have gauge group with cancellation between leptons; $\ln \Lambda^2/m_\ell^2 \to \ln m_\mu^2/m_\tau^2$. Changes results by factor $\mathcal{O}(1)$.

$g-2$ + Relic Density + Direct Detection

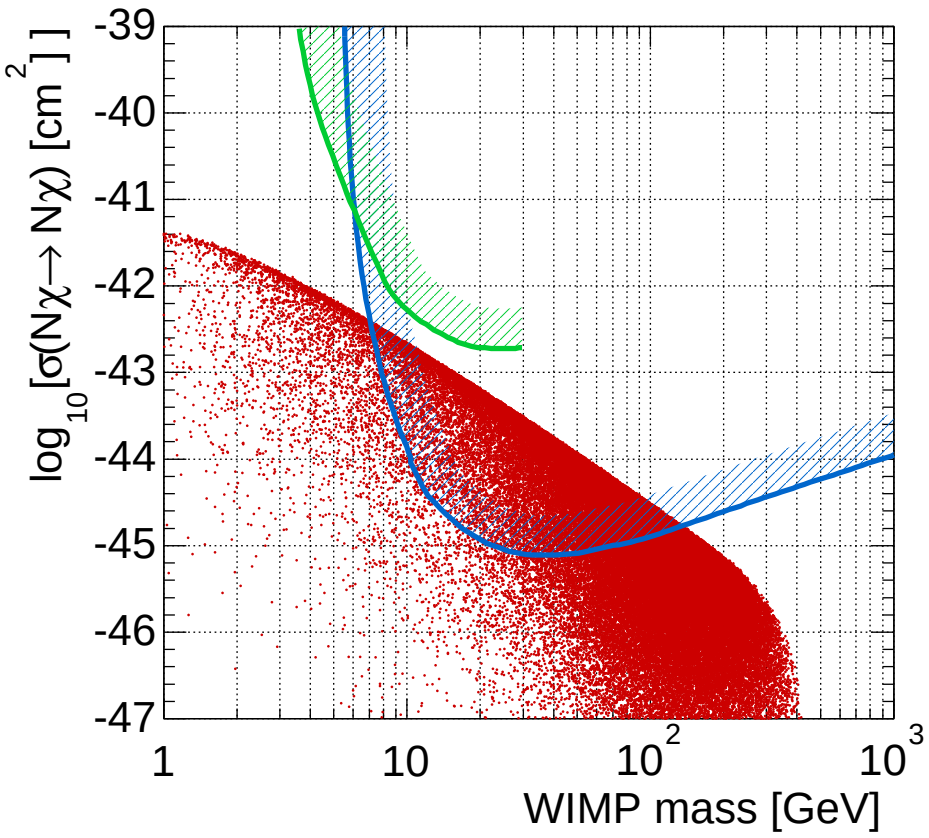
Compatibility with $g-2$, direct detection, and relic density:

- 100 GeV $< M_X <$ 5 TeV.
- Kept X-DM coupling $= 1$.
- Varied X couplings to $\bar{\mu}\mu$, $\bar{\tau}\mu$, $\bar{\tau}\tau$ between ± 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.

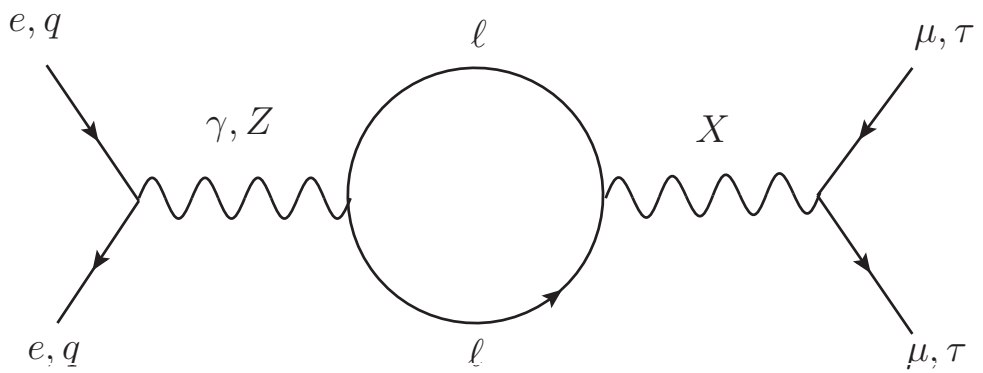


Constraints: Indirect Detection

- 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. $\rightarrow$ 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 τ's few $\times 10^{-27}$ cm$^3/s$. (1309.0525, 1308.4135...)
  - Limits from AMS to x-sect to μ'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 3×10^{-26} cm$^3/s$.

Constraints: Colliders

- By hypothesis, new flavor interaction only involves DM, μ, τ. 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.

Conclusions

- 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, μ, τ charged under flavor symmetry, limits from flavor observables rather weak.
  - DM interacts only with τ: only limits from dark matter observables.
  - DM interacts only with μ: low NP scale needed for $g-2$; would require light DM.
  - DM interacts with μ and τ: 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!