Light Fermionic Dark Matter and its Possible Detection in Neutrino Experiments

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Motivation

- Dark matter makes up $\sim 20\%$ of our universe.
- Recent interest in “hidden” models: low-mass particles connected to SM only via high-energy interactions. New particles don’t have to be heavy to be undiscovered!
- DM could be light, but coupled to SM particles at high scale.
- Should consider all observable DM-SM interactions.
- Desirable to do model-independent study of possible interactions of low-mass DM with SM.

Results Preliminary!
Dark Matter Direct Searches

Usual DM direct search:

- $O(10 \text{ GeV} - 10 \text{ TeV})$ DM scatters elastically off $O(10 - 100 \text{ GeV})$ nucleus.
- DM nonrelativistic, $v \sim 10^{-3}c$.
- Example:
  100 GeV DM particle scattering off 100 GeV nucleus: nucleus receives momentum kick $p \sim 100 \text{ MeV}$

However, could get same signature via other (inelastic) interactions.

Can we use existing detectors to find/rule out a broader range of interactions?
Instead, could consider inelastic scattering
\[ fN \rightarrow FN' \ (f = \text{DM}, \ N, N' = \text{nuclei, nucleons}, \ F = \text{DM, } \nu, e...) \].

Take \( m_F << m_f \).

If \( m_f \sim 100 \text{ MeV} \), final state similar to that of usual DM detection case.

Can use existing detectors to consider 1 – 100 MeV mass range, but with inelastic scattering?

Can consider case where \( F \) is invisible (not done here) or visible. We take case \( F = e \).

\[ \rightarrow \text{NEUTRINO DETECTORS!} \]
Neutrino Experiments

- Consider processes with $\bar{f}_u \to d e^+$. 
- Solar & reactor experiments probe $O(1 - 100 \text{ MeV})$ range in $E_\nu$ for various nuclei.
- Will specifically look at Super-K:
  - Usual interaction: $\bar{\nu}_e p \to n e^+ E_e \simeq E_\nu$.
  - Replace $\nu$ with nonrelativistic $f$: $\bar{f} p \to n e^+ E_e \simeq m_f$.
  - $f$ looks like monoenergetic neutrinos.
  - must translate limits on $\bar{\nu}_e$ to limits on $\bar{f}$.
- Will only consider $\bar{f} p \to n e^+$ for this talk.
Assumptions and Simplifications

Here, we consider DM which

- is fermionic and
- is a singlet under SM gauge group

So, we look for operators which

- are dimension-6 (or less)
- are $SU(3) \times SU(2) \times U(1)$-invariant
- can give the process $\overline{f} u \rightarrow d e^+$ and
- aren’t suppressed by $\nu$ mass.

Will find $f$ is of the mass relevant to $\nu$ experiments.
Operator Basis

This leaves 6 operators (all 6-D, suppressed by $\Lambda^2$):

\[
\mathcal{O}_W = g \bar{L} \tau^a \tilde{\phi} \sigma^{\mu\nu} f W^a_{\mu\nu}
\]

\[
\mathcal{O}_{\tilde{V}} = \bar{\ell}_R \gamma_\mu f \phi^\dagger D_\mu \tilde{\phi}
\]

\[
\mathcal{O}_T = \epsilon_{ij} \bar{L}^i \sigma^{\mu\nu} f \bar{Q}^j \sigma_{\mu\nu} d_R
\]

\[
\mathcal{O}_{Sd} = \epsilon_{ij} \bar{L}^i f \bar{Q}^j d_R
\]

\[
\mathcal{O}_{Su} = \bar{L} f \bar{u}_R Q
\]

\[
\mathcal{O}_{VR} = \bar{\ell}_R \gamma_\mu f \bar{u}_R \gamma^\mu d_R
\]

$L, Q$: $SU(2)$ doublets.

$\ell_R, u_R, d_R$: right-handed $SU(2)$ singlets.

$\phi =$ SM Higgs, $\tilde{\phi} = i \tau^2 \phi^*$.

In all cases, $f$ right-handed.
Limits from DM Lifetime and $\gamma$’s

DM must have long lifetime. Rarely decays to $\gamma$’s ($\tau \gtrsim 10^{19} \text{yr}$), $e^+e^-$ ($\tau \gtrsim 10^{17} \text{yr}$).

$O_W = g \bar{L} \tau^a \phi \sigma^{\mu\nu} f W^{a}_{\mu\nu}$: gives $f \rightarrow \nu \gamma$ at tree level.

$$\rightarrow \frac{|C_W|^2}{\Lambda^4} \lesssim \frac{1}{(7.5 \times 10^7 \text{TeV})^4} \quad (m_f = 1 \text{ MeV})$$

$O_{\tilde{V}} = \bar{\ell}_R \gamma_\mu f \phi^\dagger D_\mu \tilde{\phi}$ → EWSB → $-ig |C_{\tilde{V}}| v^2 \bar{\ell}_R \gamma^\mu f W_\mu \text{ vertex}$

$\rightarrow$ If $m_f \gtrsim 2m_e$, $f \rightarrow e^+e^-\nu$ at tree level.

$$\rightarrow \frac{|C_{\tilde{V}}|^2}{\Lambda^4} \lesssim \frac{1}{(10^6 \text{ TeV})^4} \quad (m_f = 20 - 80 \text{ MeV})$$

These results used to get limits on coeff’s of other $O$s.
Limits from DM Lifetime and $\gamma$'s

$\mathcal{O}_{VR} = \bar{\ell}_R \gamma_\mu \bar{f} \bar{u}_R \gamma^\mu d_R$:

$m_f \gtrsim m_\pi$; tree-level $f \to \pi^+ e^-$; must have $m_f \lesssim m_\pi$.

$\mathcal{O}_{VR}$ mixes into $\mathcal{O}_{\tilde{\nu}}$, gives $f \to e^+ e^- \nu_e$ at 1-loop.

All fermions in $\mathcal{O}_{VR}$ right-handed; Diag suppressed by $u$, $d$ Yukawas, log divergent.

$\mathcal{O}_{VR}$ gives a contribution to $C_{\tilde{\nu}}/\Lambda^2_{of}$

$$\frac{C_{\nu R}}{\Lambda^2} \left( \frac{12}{(4\pi)^2} \right) \frac{m_u m_d}{v^2} \ln \left( \frac{\Lambda^2}{m_f^2} \right)$$
Limits from DM Lifetime and $\gamma$’s

$\mathcal{O}_{VR}$ cont’d:
Suppression strong enough to make $\mathcal{O}_{VR}$ viable DM interaction.

\[ \rightarrow \frac{|C_{VR}|^2}{\Lambda^4} \lesssim \frac{1}{(20 \text{ TeV})^4} \quad (m_f = 20 \text{ MeV}) \]
\[ \lesssim \frac{1}{(50 \text{ TeV})^4} \quad (m_f = 50 \text{ MeV}) \]
\[ \lesssim \frac{1}{(80 \text{ TeV})^4} \quad (m_f = 80 \text{ MeV}) \]

Strong constraints, but weak enough to be interesting for $\nu$ experiments!
Limits from DM Lifetime and $\gamma$’s

$O_{Sd}(= \epsilon_{ij} \bar{L}^i f \bar{Q}^j d_R)$ and $O_{Su}(= \bar{L} f \bar{u}_R Q)$:

Mix into $O_W$ via 2-loop diag, give $f \rightarrow \nu \gamma$.

Only 1 Yukawa suppression: inadequate to make $f$ long-lived.

Order-of-magnitude limit:

$\frac{C_{Su, Sd}}{\Lambda^2} < O \left( \frac{1}{(10^3 \text{ TeV})^2} \right)$

$O_T = \epsilon_{ij} \bar{L}^i \sigma^{\mu\nu} f \bar{Q}^j \sigma_{\mu\nu} d_R$:

Mixes into $O_W$ at one-loop order, with one Yukawa suppression $\rightarrow$ even tighter limit.

Will only consider $O_{VR}$ for rest of talk.
Neutrino Detector Cross-Section

If $f$ comprises all DM,
\[ \Phi_{DM} \sim \frac{.3 \text{ GeV/cm}^3}{m_f} \times 230 \text{ km/s} \sim 10^8 - 10^{10}/\text{cm}^2\text{s}. \]

Take $\bar{\nu}_e$ flux limit from Super-K relic supernova $\bar{\nu}_e$ search:
\[ \Phi_{\bar{\nu}_e} \lesssim 1.2/\text{cm}^2\text{s} \text{ for } 20 \text{ MeV} \lesssim E_\nu \lesssim 80 \text{ MeV} \]
(8-10 orders of magnitude smaller!)

Ratio of cross-sections:
\[ \frac{\sigma_\mathcal{O}(m_f = E_\nu)}{\sigma_{SM}(E_\nu)} = \left( \frac{c}{v_f} \right) \frac{|C_{VR}|^2 v^4}{(4)\Lambda^4} \]

$f$ nonrelativistic $\rightarrow v_f \simeq 10^{-3} c$: extra enhancement.
Results from Super-K

Preliminary Results:

\[ m_f = 20 \text{ MeV} : \quad \frac{|C_{VR}|^2}{\Lambda^4} \lesssim \frac{1}{(140 \text{ TeV})^4} \]

\[ m_f = 50 \text{ MeV} : \quad \frac{|C_{VR}|^2}{\Lambda^4} \lesssim \frac{1}{(110 \text{ TeV})^4} \]

\[ m_f = 80 \text{ MeV} : \quad \frac{|C_{VR}|^2}{\Lambda^4} \lesssim \frac{1}{(100 \text{ TeV})^4} \]

Limits weaker if \( f \) only fraction of DM.

But, very strong limits!
Conclusions

- We don’t know much about DM—should consider other interactions!
- Model-independent analysis of DM interaction \( \bar{f}p \rightarrow ne^+ \) in ν exp’ts.
- Inelasticity of interaction allows us to probe different mass range (\( \sim 100 \) MeV).
- Find one operator (comparatively!) unconstrained by DM lifetime for light DM case.
- Reach of ν exp’ts to find light DM huge (\( \sim 100 \) TeV!)
- Should see if can be applied elsewhere!
- DM & ν exp’ts might be telling us more than we think!