Light Hidden Fermionic Dark Matter in Neutrino Experiments

Jennifer Kile, Amarjit Soni
Brookhaven National Laboratory

July 31, 2009 DPF 2009

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:

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

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

Can we use existing detectors to find/rule out a broader range of interactions?

Dark Matter Direct Searches

- Instead, could consider inelastic scattering $fN \to FN'$ ($f =$ DM, $N, N' =$ nuclei, nucleons, $F =$ DM$, \nu, e$...).
- Take $m_F << m_f$.
- If $m_f \sim 100$ 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 $F = e$.

$\longrightarrow$ NEUTRINO DETECTORS!

Neutrino Experiments

- Consider processes with $\bar{f}u \to de^+$.
- Solar & reactor experiments probe $O(1 - 100$ MeV$)$ range in E_ν for various nuclei.
- Will specifically look at Super-K:

  Usual interaction: $\bar{\nu}_e p \to ne^+$ $E_e \simeq E_\nu$.

  Replace ν with nonrelativistic f: $\bar{f}p \to ne^+$ $E_e \simeq m_f$.
  $\to$ f looks like monoenergetic neutrinos.
  $\to$ must translate limits on $\bar{\nu}_e$ to limits on $\bar{f}$.

  Will only consider $\bar{f}p \to ne^+$ 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 $\bar{f} u \to d e^{+}$ *and*
- aren't suppressed by ν mass.

Will find f is of the mass relevant to ν experiments.

Operator Basis

This leaves 6 operators (all 6-D, suppressed by Λ^2):

$$
\begin{aligned}
\mathcal{O}_W &= g\bar{L}\tau^a\tilde{\phi}\sigma^{\mu\nu}fW^a_{\mu\nu} \\
\mathcal{O}_{\tilde{V}} &= \bar{\ell}_R\gamma_\mu f\phi^\dagger D_\mu\tilde{\phi} \\
\mathcal{O}_T &= \epsilon_{ij}\bar{L}^i\sigma^{\mu\nu}f\bar{Q}^j\sigma_{\mu\nu}d_R \\
\mathcal{O}_{Sd} &= \epsilon_{ij}\bar{L}^i f\bar{Q}^j d_R \\
\mathcal{O}_{Su} &= \bar{L}f\bar{u}_R Q \\
\mathcal{O}_{VR} &= \bar{\ell}_R\gamma_\mu f\bar{u}_R\gamma^\mu d_R
\end{aligned}
$$

L, Q: $SU(2)$ doublets.
ℓ_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 γ's

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

$\mathcal{O}_W = g\bar{L}\tau^a\tilde{\phi}\sigma^{\mu\nu} f W^a_{\mu\nu}$: gives $f \to \nu\gamma$ at tree level.

$$\to \frac{|C_W|^2}{\Lambda^4} \lesssim \frac{1}{(8\times 10^7\,\text{TeV})^4} \qquad (m_f = 1\ \text{MeV})$$

$\mathcal{O}_{\tilde{V}} = \bar{\ell}_R\gamma_\mu f\phi^\dagger D_\mu\tilde{\phi} \to$ EWSB $\to \frac{-ig|C_{\tilde{V}}|v^2}{2\sqrt{2}\Lambda^2}\bar{\ell}_R\gamma^\mu f W_\mu$ vertex
$\to$ If $m_f \gtrsim 2m_e$, $f \to e^+e^-\nu$ at tree level.

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

These results used to get limits on coeff's of other $\mathcal{O}$s.

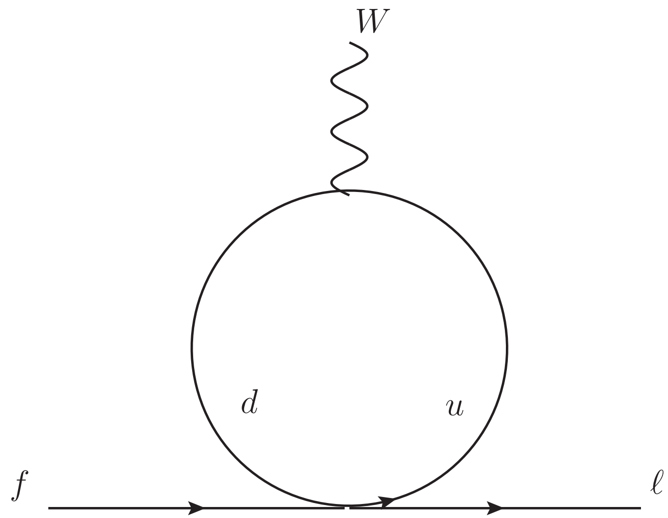
Limits from DM Lifetime and γ's

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

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

$\mathcal{O}_{VR}$ mixes into $\mathcal{O}_{\tilde{V}}$, 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 $C_{\tilde{V}}/\Lambda^2 of$

$$\frac{C_{VR}}{\Lambda^2} \frac{12}{(4\pi)^2} \frac{m_u m_d}{v^2} \ln\left(\frac{\Lambda^2}{m_f^2}\right)$$

Limits from DM Lifetime and γ's

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

$$
\begin{aligned}
\rightarrow \frac{|C_{VR}|^2}{\Lambda^4} \quad &\lesssim \quad \frac{1}{(20\ \text{TeV})^4}\ (m_f = 20\ \text{MeV}) \\
&\lesssim \quad \frac{1}{(50\ \text{TeV})^4}\ (m_f = 50\ \text{MeV}) \\
&\lesssim \quad \frac{1}{(80\ \text{TeV})^4}\ (m_f = 80\ \text{MeV})
\end{aligned}
$$

Strong constraints, but weak enough to be interesting for ν experiments!

Limits from DM Lifetime and γ's

- 1-loop calc of O_{VR} mixing into $O_{\tilde{V}}$ does not correctly represent contributions from low ($\lesssim$ few $\times\, 100$ MeV) quark momenta.
- Instead, consider diagram where f decays via π^+.*
- Diagram suppressed by f, e mass via π coupling.

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{ud}|^2 f_\pi^4 m_e^2}{1024\pi^3 m_f \Lambda^4} \frac{q^2(m_f^2 - q^2)^2}{(m_\pi^2 - q^2)^2}$$

- Gives limits on NP scale of few-50 TeV for 20 MeV $< m_f < 80$ MeV.
- Similar to 1-loop results; take 1-loop limits.

*Thanks to Mark Wise for this calculation.

Limits from DM Lifetime and γ's

- $\nu - f$ mixing:
  $\mathcal{O}_{VR}$ gives neutrino mass term $\bar{L}\tilde{\phi}f$ at 2 loops.
  Allows $\to f \to \nu\nu\bar{\nu}$ and $f \to \nu e^+e^-$.
  Mixing angle proportional to e, u, and d Yukawas,
  $O(10^{-16}) \to \tau \sim 10^{26}$ s.
- $\pi^+ \to e^+ f$:
  Searches for heavy ν's in π decay give limits on
  $|C_{VR}|/\Lambda^2$ of order $1/(10\text{ TeV})^2$ for $m_f < 130$ MeV.

Limits from DM Lifetime and γ's

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

Mix into $\mathcal{O}_W$ via 2-loop diag, give $f \to \nu\gamma$.
Only 1 Yukawa suppression: inadequate to make f long-lived.

Order-of-magnitude limit: $\frac{C_{Su,Sd}}{\Lambda^2} < O\left(\frac{1}{(10^3\ \text{TeV})^2}\right)$

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

Mixes into $\mathcal{O}_W$ at one-loop order, with one Yukawa suppression $\to$ even tighter limit.

Will only consider O_{VR} for rest of talk.

Constraints on MeV-Scale DM

- NP scale high: $\mathcal{O}_{VR}$ freezes out much too early to give correct relic density. ($\langle \sigma_{ann} |v_r| \rangle \sim 10^{-25}cm^3/$s needed at freezeout.)
- Need additional interaction(s):

  $\bar{f} f \to e^+ e^-$: overproduces 511-keV line unless $\langle \sigma_{ann} |v_r| \rangle$ velocity-dependent, $\sim v_r^2$. Possible with light U-boson (Boehm et al, Fayet....).

  $\bar{f} f \to \nu \bar{\nu}$: v_r-independent $\sim$OK; limits on $\langle \sigma_{ann} |v_r| \rangle$ $\sim O(10^{-25}$cm$^3/$s$)$ (Palomares-Ruiz & Pascoli, 2008).
- Supernova cooling (Fayet et al., 2006) and BBN (Serpico and Raffelt, 2004) OK if $m_f \gtrsim 10$ MeV.

Neutrino Detector Cross-Section

If f comprises all DM,

$\Phi_{DM} \sim \frac{.3\ \text{GeV}/\text{cm}^3}{m_f} \times 230$ 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:

$$\Phi_{\bar{\nu}_e} \lesssim 1.2/\text{cm}^2\text{s for } 20 \text{ MeV} \lesssim E_\nu \lesssim 80 \text{ MeV}$$

(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:

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

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

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

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 $\bar{f}p \to ne^+$in ν exp'ts.
- Inelasticity of interaction allows us to probe different mass range (~ 100 MeV).
- Find one operator (comparatively!) unconstrained by DM lifetime for light DM case.
- Reach of ν exp'ts to find light DM huge (~ 100 TeV!)
- Should see if can be applied elsewhere!

DM & ν exp'ts might be telling us more than we think!