



# Hidden Dark Matter at Neutrino Experiments

Jennifer Kile, Amarjit Soni  
(Brookhaven National Laboratory)

Mark Wise  
(Caltech)

May 12, 2009 Pheno 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:

- $O(10 \text{ GeV} - 10 \text{ TeV})$  DM recoils elastically off  $O(10 - 100 \text{ GeV})$  nucleus.
- DM nonrelativistic,  $v \sim 10^{-3}c$ .
- Example:  
100 GeV DM particle recoiling 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?

# Dark Matter Direct Searches

- Instead, could consider inelastic scattering  $fN \rightarrow FN'$  ( $f = \text{DM}, N, N' = \text{nuclei, nucleons}, F = \text{DM}, \nu, e \dots$ ).
- Take  $m_F \ll m_f$ .
- 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  $F = e$ .

→ NEUTRINO DETECTORS!

# Neutrino Experiments

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

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

Replace  $\nu$  with nonrelativistic  $f$ :  $\bar{f}p \rightarrow ne^+ \quad E_e \simeq m_f$ .

→  $f$  looks like monoenergetic neutrinos.

→ must translate limits on  $\bar{\nu}_e$  to limits on  $\bar{f}$ .

Will only consider  $\bar{f}p \rightarrow ne^+$  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  $\bar{f}u \rightarrow de^+$  *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  $\Lambda^2$ ):

$$\mathcal{O}_W = g \bar{L} \tau^a \tilde{\phi} \sigma^{\mu\nu} f W_{\mu\nu}^a$$

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

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

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

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

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

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

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

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

In all cases,  $f$  right-handed.

# Limits from DM Lifetime and $\gamma$ 's

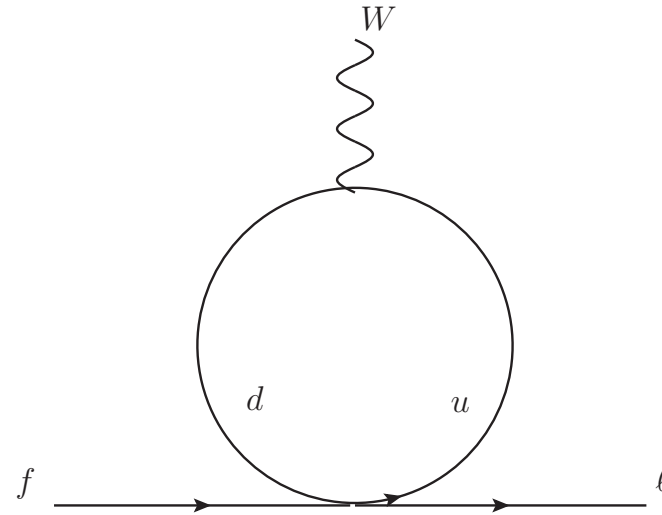
- DM lifetime must be long, rarely decay to  $\gamma$ 's ( $\tau \gtrsim 10^{19}$ yr) or  $e^+e^-$  ( $\tau \gtrsim 10^{17}$ yr):  
→ New Physics scale  $\Lambda > 10^3$  TeV for 5 op's.
- One op less constrained:  $\mathcal{O}_{VR} = \bar{\ell}_R \gamma_\mu f \bar{u}_R \gamma^\mu d_R$ :  
 $m_f \gtrsim m_\pi$ : tree-level  $f \rightarrow \pi^+ e^-$ ; must have  $m_f \lesssim m_\pi$ .
- At one loop,  $\mathcal{O}_{VR}$  mixes into  $\mathcal{O}_{\tilde{V}}$ .  $\mathcal{O}_{\tilde{V}}$  gives  $f \rightarrow e^+ e^- \nu_e$  at tree level.
- Note that all fermions in  $\mathcal{O}_{VR}$  are right-handed.



# Limits from DM Lifetime and $\gamma$ 's

$\mathcal{O}_{VR} \rightarrow \mathcal{O}_{\tilde{V}}$  mixing:

Diagram suppressed by Yukawa couplings for  $u, d$ .  
Diagram log divergent.



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

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

Enough suppression to make  $\mathcal{O}_{VR}$  viable DM interaction.

# Limits from DM Lifetime and $\gamma$ 's

$\mathcal{O}_{VR}$  cont'd:

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

Strong constraints, but weak enough to be interesting for  $\nu$  experiments!

# 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:

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

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

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

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  $\nu$  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  $\nu$  exp'ts to find light DM huge ( $\sim 100$  TeV!)
- Should see if can be applied elsewhere!

DM &  $\nu$  exp'ts might be telling us more than we think!