Hidden Light Dark Matter in Neutrino Detectors

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Motivation

- Dark matter makes up $\sim 20\%$ of our universe.
- Not much known of nature of DM (number of species, masses, interactions, coupling to SM,...).
- Recent possible DM observations point to “nontraditional” interactions (large annihilation cross-sections, leptophilic couplings).
- Should consider all experimentally observable DM-SM interactions.
- Desirable to do model-independent study of possible DM-SM interactions.
Motivation

- Recent interest in “hidden” models: low-mass particles connected to SM only via high-energy interactions. Could still discover new low-mass particles!

  \[ \rightarrow \text{Light DM?} \]

- Should consider DM masses below weak scale. (Eventually, \( \lesssim 100 \text{ MeV.} \))
Relevant Features of Dark Matter

We know a few things about DM (relevant for this talk):

- DM must have long lifetime ($\tau \sim$ age of the universe).
- DM is dark: Must rarely annihilate or decay to easily observable SM particles ($\gamma$'s, $e^+e^-$).
- In our neighborhood, density of DM is $\sim 3 \text{ GeV/cm}^3$.
- DM is nonrelativistic ($v \sim 230 \text{ km/sec}$).
Usual DM direct search:

- $O(10 \text{ GeV} - 10 \text{ TeV})$ DM bounces 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 similar momenta in final state products via other scenarios.

Possible to use existing detectors to find/rule out other interactions?
Instead, could consider inelastic scattering $f N \rightarrow FN'$ ($f = \text{DM}, N, N' = \text{nuclei, nucleons, } F = \text{BSM, } \nu, e...$).

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 $F = e$. 

→ NEUTRINO DETECTORS!
Consider processes with $\bar{f} u \rightarrow de^+$, $fd \rightarrow ue^-$.

Solar & reactor experiments probe $O(1 - 100 \text{ MeV})$ range in $E_\nu$ for various nuclei.

Will specifically look at Super-K:

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

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

$\rightarrow f$ looks like neutrinos but monoenergetic signal. $\rightarrow$ must translate limits on $\bar{\nu}_e$ to limits on $\bar{f}$.

Will only consider $\bar{f} p \rightarrow ne^+$ here.
Flux in Neutrino Experiments

DM Flux in $\nu$ experiments (if $f$ comprises all DM):

$$\Phi_{DM} \lesssim \frac{0.3 \text{ GeV/cm}^3}{m_f} \times 230 \text{ km/s}$$

$m_f = 100 \text{ MeV}: \Phi \lesssim 7 \times 10^7/(\text{cm}^2\text{s})$

$\implies m_f = 10 \text{ MeV}: \Phi \lesssim 7 \times 10^8/(\text{cm}^2\text{s})$

$m_f = 1 \text{ MeV}: \Phi \lesssim 7 \times 10^9/(\text{cm}^2\text{s})$

Compare to flux limit from Super-K relic SN $\bar{\nu}_e$ search:

$$\Phi_{\bar{\nu}_e} < 1.2/\text{cm}^2\text{s} \text{ for } 19.3 \text{ MeV} < E_\nu \lesssim 80 \text{ MeV}.$$
Assumptions and Simplifications

Want model-independence: effective operator analysis.
Here, we consider DM which
  - is fermionic \textit{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 $\bar{f}u \rightarrow de^+$ \textit{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 $\Lambda^2$):

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

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

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

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

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

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

Mag. mom. op: $f \to \nu\gamma$ at tree level ($\nu = $ Higgs vev):

$$\frac{C_W}{\Lambda^2} \mathcal{O}_W : \Gamma(f \to \nu\gamma) = \frac{|C_W|^2}{\Lambda^4} \frac{\alpha v^2}{2} m_f^3$$

Insist that $f$ have lifetime $\sim$ age of universe, $\sim 4 \times 10^{17} \text{ s.}$

$\to \Gamma \lesssim (4 \times 10^{17} \text{s})^{-1} = 1.6 \times 10^{-42} \text{ GeV.}$

Observability in $\nu$ experiments requires $m_f \gtrsim 1 \text{ MeV}:$

$$\frac{|C_W|^2}{\Lambda^4} \lesssim \frac{1}{(6 \times 10^5 \text{ TeV})^4} \left( \frac{1 \text{ MeV}}{m_f} \right)^3$$

Stronger limits for larger $m_f$!
Limits from DM Lifetime and $\gamma$’s

$O_W = g L \tau^a \tilde{\phi} \sigma^{\mu\nu} f W^a_{\mu\nu}$ cont’d:

But, wait, that’s not all!

Yuksel & Kistler (arXiv:0711.2906 [astro-ph]):
$\gamma$-ray data from INTEGRAL, COMPTEL & EGRET give

$$\Gamma(\chi \to \chi' \gamma) \lesssim (10^{26} \text{s})^{-1}$$

$$\frac{|C_W|^2}{\Lambda^4} \lesssim \frac{1}{(8 \times 10^7 \text{ TeV})^4} \left( \frac{1 \text{ MeV}}{m_f} \right)^3$$

Will use this limit to place limits on other op’s.
Limits from DM Lifetime and $\gamma$’s

\[ \mathcal{O}_{\tilde{V}} = \bar{\ell}_R \gamma_\mu f \phi^\dagger D_\mu \tilde{\phi} \rightarrow \text{EWSB} \rightarrow \frac{-ig|C_{\tilde{V}}|v^2}{2\sqrt{2}\Lambda^2} \bar{\ell}_R \gamma^\mu f W_\mu \text{ vertex} \]

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

\[ \Gamma(f \rightarrow e^+ e^- \nu) = \frac{|C_{\tilde{V}}|^2}{\Lambda^4} \frac{1}{1536\pi^3} \frac{1}{m_f^5} \]

Picciotto & Pospelov (hep-ph/0402178) constrain decays to $e^+ e^-$ via INTEGRAL 511 keV line:

\[ \tau_{\tilde{V}} \simeq 5 \times 10^{17} \text{yr} \frac{10 \text{MeV}}{m_f} \]
Limits from DM Lifetime and $\gamma$’s

\( \mathcal{O}_\tilde{V} = \bar{\ell}_R \gamma_\mu f \phi^\dagger D_\mu \tilde{\phi} \) cont’d:

\[
\rightarrow \quad \frac{|C_\tilde{V}|^2}{\Lambda^4} \lesssim \frac{1}{(9.5 \times 10^5 \text{ TeV})^4} \quad (m_f = 20 \text{ MeV})
\]

\[
\lesssim \frac{1}{(2.4 \times 10^6 \text{ TeV})^4} \quad (m_f = 50 \text{ MeV})
\]

\[
\lesssim \frac{1}{(3.8 \times 10^6 \text{ TeV})^4} \quad (m_f = 80 \text{ MeV}).
\]

Other 4 op’s constrained by mixing into \( \mathcal{O}_W \) and \( \mathcal{O}_\tilde{V} \).
Limits from DM Lifetime and $\gamma$’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

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

- 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 $\pi^+$.*

- Diagram suppressed by $f$, $e$ mass via $\pi$ coupling.

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

- 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.
Other constraints on $O_{VR}$

- Mixing into $O_W$ only at two loops; strongly suppressed.

- $\nu - f$ mixing:
  - $O_{VR}$ gives neutrino mass term $\bar{L}\tilde{\phi}f$ at 2 loops.
  - Allows $\nu \rightarrow f \rightarrow \nu \nu \bar{\nu}$ and $f \rightarrow \nu e^+ e^-$. 
  - Mixing angle proportional to $e$, $u$, and $d$ Yukawas, $O(10^{-16}) \rightarrow \tau \sim 10^{26}$ s.

- $\pi^+ \rightarrow e^+ f$:
  - Searches for heavy $\nu$’s in $\pi$ decay give limits on $|C_{VR}|/\Lambda^2$ of order $1/(10$ TeV$)^2$ for $m_f < 130$ MeV.
Limits from DM Lifetime and $\gamma$'s

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

Can mix into $\mathcal{O}_W$ via 2-loop diag, give $f \rightarrow \nu \gamma$. Only 1 Yukawa suppression.

Order-of-magnitude estimate for mixing into $\mathcal{O}_W$:

$$\frac{C_W(v)}{\Lambda^2} \sim \frac{C_{Su,Sd}(\Lambda)}{\Lambda^2} \frac{1}{(4\pi)^4} g^2 \frac{m_{u,d}}{v} \ln \left( \frac{\Lambda^2}{v^2} \right)$$
Limits from DM Lifetime and γ’s

$O_{Sd}$ and $O_{Su}$ cont’d:
Suppression is not enough to make $f$ long-lived.
Order-of-magnitude limit:

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

$O_T = \epsilon_{ij} \bar{L}^i \sigma^{\mu\nu} f \bar{Q}^j \sigma_{\mu\nu} d_R$:
Mixes into $O_W$ at one-loop order, with one Yukawa suppression $\rightarrow$ even tighter limit.
Most interesting op: $\mathcal{O}_{VR}$

- Of 6 op’s, 5 strongly constrained by DM lifetime & decays.
- $\mathcal{O}_{VR}$ least constrained operator—will concentrate on this operator in neutrino experiments.
- Led to mass range $m_f \lesssim m_\pi$—light DM!
- Operator looks like right-handed $\nu$ interaction. Will not assume usual related physics ($W'$, $Z'$, etc).
Review: MeV Dark Matter

- Original motivation: 511 keV line observed from galactic center by INTEGRAL, flux evades explanation.

- Thought that 511 keV line could get contribution from positrons produced in DM-DM annihilations to $e^+ e^-$. 

- Beacom & Yuksel and Sizun et al showed injection energy of positrons had to be less than few MeV.

→ Will assume $f$ has small (or no) contribution to 511 keV line.
MeV Dark Matter

- Must consider relic density.
- Lee-Weinberg bound: Heavy $\nu$ interacting with weak-scale cross-section must have mass $> O(\text{GeV})$ in order to not overclose universe.
- Raising $\Lambda \rightarrow$ cross-section smaller $\rightarrow$ interaction freezes out earlier $\rightarrow$ Lee-Weinberg bound even stronger.
- $O_{VR}$ cannot be $f$’s only interaction.
- $f$ must have some stronger-than-weak interaction to give correct relic density.
MeV Dark Matter

- Correct relic density requires velocity-averaged annihilation cross-section at freezeout
  \[ \langle \sigma_{\text{ann}} | v_r | \rangle \sim O(10^{-25}) \text{cm}^3/\text{s}. \]

- If annihilates as \( f \bar{f} \rightarrow e^+ e^- \), same \( \langle \sigma_{\text{ann}} | v_r | \rangle \) would overproduce 511-keV line.

- Solution: \( f \bar{f} \rightarrow e^+ e^- \), but \( \langle \sigma_{\text{ann}} | v_r | \rangle \) velocity-dependent, \( \langle \sigma_{\text{ann}} | v_r | \rangle \sim v_r^2 \) (p-wave).
  \( (v_r \sim 10^{-3} \text{ today.}) \)

- Light U-boson with axial-vector coupling to \( f \) (i.e. as if \( f \) Majorana) and vector coupling to electrons does the trick.

(Boehm et al, Fayet.....)
MeV Dark Matter

- We’ll just introduce an operator:

\[
\frac{C_{Ve}}{\Lambda_a^2} O_{Ve} = \frac{C_{Ve}}{\Lambda_a^2} \bar{f} \gamma^\mu \gamma_5 f \bar{\ell} R \gamma_\mu \ell R
\]

- Assume \( \Lambda_a^2 \) high enough that eff. op. formalism valid.

- Gives \( \langle \sigma_{ann} | v_r | \rangle \sim v_r^2 \).

Correct freeze-out cross-section if

\[
\frac{C_{Ve}}{\Lambda_a^2} \sim \frac{1}{(\text{few GeV})^2}
\]
Or, we could couple $f$ to neutrinos! Add op:

$$\frac{C_{V\tau,\mu}}{\Lambda_a^2} \mathcal{O}_{V\tau,\mu} = \frac{C_{V\tau,\mu}}{\Lambda_a^2} \bar{f} \gamma^\mu f \bar{L}_{\tau,\mu} \gamma^\mu L_{\tau,\mu}$$

Lepton fields of $\mu$ or $\tau$ flavor, no $f \bar{f} \rightarrow e^+ e^-$. $f$ nonrelativistic during freezeout and at late times: Only $f \bar{f} \rightarrow \nu \bar{\nu}$ channel open (unless $m_f > m_\mu$).

Velocity-independent cross-section OK.

Again, need scale of order few GeV.

Limits on $\langle \sigma_{\text{ann}} | v | \rangle$ are $O(10^{-25})$ cm$^3$/s.

(Palomares-Ruiz and Pascoli, PRD 77 (2008))

A little room left!
Supernova cooling:
If $f$ interacts too strongly with $\nu$’s, can cause $\nu$’s to be too trapped inside supernova, causing it to cool too slowly. Only a problem if $m_f \lesssim 10$ MeV.
(Fayet et al., Phys Rev. Lett 96 (2006))

Big-Bang Nucleosynthesis:
$f$ coupled to neutrinos: OK if $m_f > 10$ MeV.
$f$ coupled to electrons: Only p-wave cross-section OK.
(Serpico and Raffelt, PRD 70 (2004))
If $f$ comprises all DM, $\Phi_{DM} \sim 10^8/\text{cm}^2\text{s}$.

Take $\bar{\nu}_e$ flux limit from Super-K:

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

(8 orders of magnitude smaller!)

Ratio of cross-sections:

$$\frac{\sigma_O(m_f = E_\nu)}{\sigma_{SM}(E_\nu)} = \left(\frac{c}{v_f}\right) \frac{|C_{VR}|^2 v^4}{(8)\Lambda^4}$$

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

Results:

\[ m_f = 20 \text{ MeV} : \quad \frac{|C_{VR}|^2}{\Lambda^4} \lesssim \frac{1}{(120 \text{ TeV})^4} \]

\[ m_f = 50 \text{ MeV} : \quad \frac{|C_{VR}|^2}{\Lambda^4} \lesssim \frac{1}{(90 \text{ TeV})^4} \]

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

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

But, very strong limits!
Open Questions

Questions not addressed, *(but interesting!)*:

- Other mass ranges in $\nu$ exp’ts?
- Neutral current $f_1 \rightarrow f_2$, $f \rightarrow \nu$ at $\nu$ detectors and DM direct search experiments?
- Scalar DM?
- Lower bounds on scale of NP far beyond what accessible at LHC–what if $f$ contained in hidden sector, but not DM?
- Models?
Conclusions

- We don’t know much about DM—should consider “nontraditional” interactions!
- Model-independent analysis of DM interaction $\bar{f}p \rightarrow ne^+\nu$ in $\nu$ exp’ts.
- Inelasticity of interaction allows us to probe different mass range ($\sim 100$ MeV).
- Find one operator (comparatively!) unconstrained 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!
Other Flavors?

Changing quark flavors?

- Need $u, d$ quarks for $\bar{f}p \rightarrow n\ell^+$.  
- Right-handed quark fields must be from 1st generation; Left-handed doublets can be from any.
- $O_{Su}$: Limit no longer valid.
- $O_{Sd}, O_T$: diagrams CKM-suppressed, can arrange unconstrained linear combinations of op’s.
- Would be unexpected that flavor-nondiagonal cases be at much lower NP scale.
- $O_{VR}$: All right-handed fields; other flavors not applicable here.
Other Flavors?

Changing lepton flavor?

- $m_f > m_\ell$ to be useful for charged-current interaction in neutrino expts.

- $O_W, O_{Sd}, O_{Su},$ and $O_T$: Constraints independent of lepton flavor, except interested in larger $m_f$; constraints only get stronger.

- $O_{\tilde{V}}$: 
  $m_f \gtrsim m_\ell$ gives tree-level decay $f \rightarrow \ell^- e^+ \nu_e$.

- $O_{V R}$: 
  Possibly interesting mass range ($\mu$ case): $105 \text{ MeV} \lesssim m_f \lesssim 245 \text{ MeV}$. Left for further study.