Hidden Light Dark Matter in Neutrino Detectors

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Outline

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- Relevant Characteristics of Dark Matter
- Neutrino Experiments
- Operator Basis
- Limits On Operators from DM Lifetime and Decays
- MeV DM review
- Results from Super-K relic SN $\bar{\nu}_e$ search
- Open Questions
- Conclusions

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!

  $\longrightarrow$ Light DM?

- Should consider DM masses below weak scale. (Eventually, $\lesssim 100$ 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 (γ's, e^+e^-).
- In our neighborhood, density of DM is $\sim .3$ GeV$/$cm^3.
- DM is nonrelativistic ($v \sim 230$ km/sec).

Dark Matter Direct Searches

Usual DM direct search:

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

Possible to use existing detectors to find/rule out other interactions?

Dark Matter Direct Searches

- Instead, could consider inelastic scattering $fN \to FN'$ ($f =$ DM, $N, N' =$ nuclei, nucleons, $F =$ 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 $F = e$.

$\longrightarrow$ NEUTRINO DETECTORS!

Neutrino Experiments

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

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

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

  Will only consider $\bar{f}p \to ne^+$ here.

Flux in Neutrino Experiments

DM Flux in ν experiments (if f comprises all DM):

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

$$\begin{aligned} m_f &= 100\ \text{MeV:} & \Phi &\lesssim 7 \times 10^7/(\text{cm}^2\text{s}) \\ \Longrightarrow \qquad m_f &= 10\ \text{MeV:} & \Phi &\lesssim 7 \times 10^8/(\text{cm}^2\text{s}) \\ m_f &= 1\ \text{MeV:} & \Phi &\lesssim 7 \times 10^9/(\text{cm}^2\text{s}) \end{aligned}$$

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

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

$\sigma \sim 1/\Lambda^4 \rightarrow$ Should be able to probe New Physics scale > 2 orders of magnitude beyond weak scale!

Assumptions and Simplifications

Want model-independence: effective operator analysis.

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 $\bar{f}u \to de^+$ *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.
$\tilde{\phi} = i\tau^2\phi^*$.
In all cases, f right-handed.

Limits from DM Lifetime and γ's

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

Mag. mom. op: $f \to \nu\gamma$ at tree level ($v =$ 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, $\sim 4 \times 10^{17}$ s.

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

Observability in ν experiments requires $m_f \gtrsim 1$ 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 γ's

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

But, wait, that's not all!

Yuksel & Kistler (arXiv:0711.2906 [astro-ph]):
γ-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 γ's

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

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

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

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 γ's

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

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

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

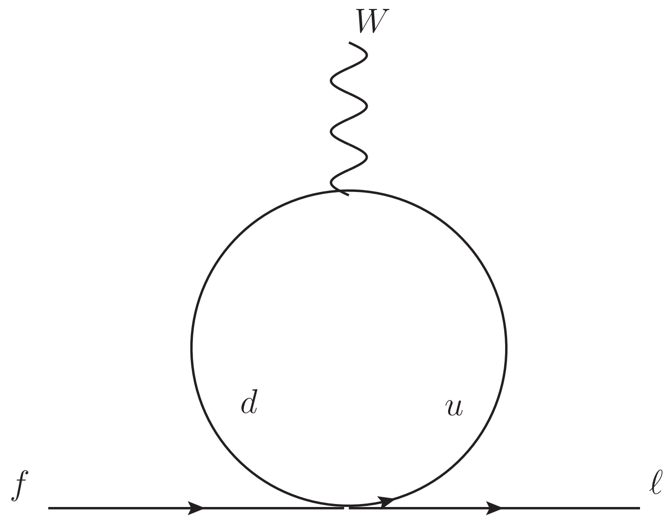
$$\lesssim \frac{1}{(3.8 \times 10^6 \text{ TeV})^4} \; (m_f = 80 \text{ MeV}).$$

Other 4 op's constrained by mixing into $\mathcal{O}_W$ and $\mathcal{O}_{\tilde{V}}$.

Limits from DM Lifetime and 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.

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

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.

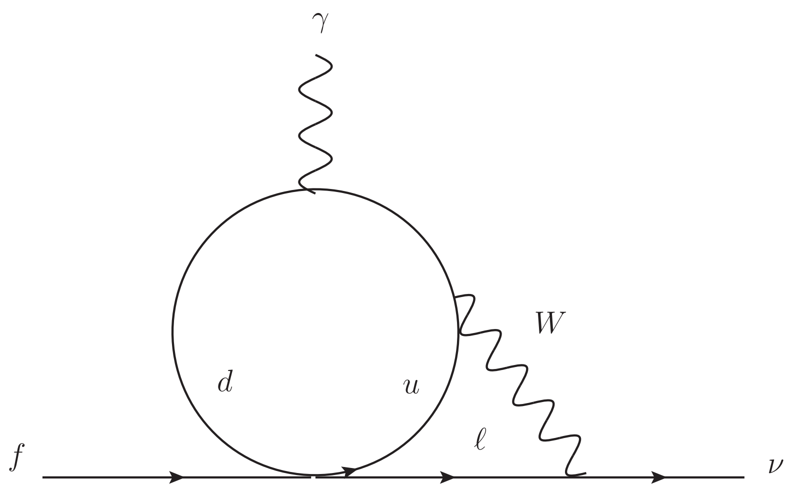
Other constraints on $\mathcal{O}_{VR}$

- Mixing into $\mathcal{O}_W$ only at two loops; strongly suppressed.
- $\nu - f$ mixing:
  $\mathcal{O}_{VR}$ gives neutrino mass term $\bar{L}\tilde{\phi}f$ at 2 loops.
  Allows $\rightarrow f \rightarrow \nu\nu\bar{\nu}$ 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 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 $\mathcal{O}_{Su}(=\bar{L} f \bar{u}_R Q)$:

Can mix into $\mathcal{O}_W$ via 2-loop diag, give $f \to \nu\gamma$. 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

$\mathcal{O}_{Sd}$ and $\mathcal{O}_{Su}$ cont'd:
Suppression is not enough 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 $\rightarrow$ 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 ν 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.

  $\rightarrow$ Will assume f has small (or no) contribution to 511 keV line.

MeV Dark Matter

- Must consider relic density.
- Lee-Weinberg bound: Heavy ν 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.
- $\mathcal{O}_{VR}$ 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 $\langle\sigma_{ann}|v_r|\rangle \sim O(10^{-25})\text{cm}^3/\text{s}$.
- If annihilates as $f\bar{f} \to e^+e^-$, same $\langle\sigma_{ann}|v_r|\rangle$ would overproduce 511-keV line.
- Solution: $f\bar{f} \to e^+e^-$, but $\langle\sigma_{ann}|v_r|\rangle$ velocity-dependent, $\langle\sigma_{ann}|v_r|\rangle \sim v_r^2$ (p-wave). ($v_r \sim 10^{-3}$ 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:

$$\frac{C_{Ve}}{\Lambda_a^2}\mathcal{O}_{Ve} = \frac{C_{Ve}}{\Lambda_a^2}\bar{f}\gamma^\mu\gamma_5 f\bar{\ell}_R\gamma_\mu\ell_R$$

- Assume Λ_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

$$\frac{C_{Ve}}{\Lambda_a^2} \sim \frac{1}{(\text{few GeV})^2}$$

MeV Dark Matter

- 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 μ or τ flavor, no $f\bar{f} \to e^+e^-$.
- f nonrelativistic during freezeout and at late times: Only $f\bar{f} \to \nu\bar{\nu}$ channel open (unless $m_f > m_\mu$).
- Velocity-independent cross-section OK.
- Again, need scale of order few GeV.
- Limits on $\langle\sigma_{ann}|v|\rangle$ are $O(10^{-25})$ cm^3/s.

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

A little room left!

MeV Dark Matter

Supernova cooling:
If f interacts too strongly with ν's, can cause ν'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))

Neutrino Detector Cross-Section

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:

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

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

Results from Super-K

Results:

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

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

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

Limits weaker if f only fraction of DM.

But, very strong limits!

Open Questions

Questions not addressed, (but interesting!):

- Other mass ranges in ν exp'ts?
- Neutral current $f_1 \to f_2$, $f \to \nu$ at ν 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 $\bar{f}p \to ne^+$in ν exp'ts.
- Inelasticity of interaction allows us to probe different mass range (~ 100 MeV).
- Find one operator (comparatively!) unconstrained 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!

Backup Slides

Other Flavors?

Changing quark flavors?

- Need u, d quarks for $\bar{f}p \to n\ell^+$.
- Right-handed quark fields must be from 1st generation; Left-handed doublets can be from any.
- $\mathcal{O}_{Su}$: Limit no longer valid.
- $\mathcal{O}_{Sd}$, $\mathcal{O}_T$: diagrams CKM-suppressed, can arrange unconstrained linear combinations of op's.
- Would be unexpected that flavor-nondiagonal cases be at much lower NP scale.
- $\mathcal{O}_{VR}$: 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.
- $\mathcal{O}_W$, $\mathcal{O}_{Sd}$, $\mathcal{O}_{Su}$, and $\mathcal{O}_T$:
  Constraints independent of lepton flavor, except interested in larger m_f; constraints only get stronger.
- $\mathcal{O}_{\tilde{V}}$:
  $m_f \gtrsim m_\ell$ gives tree-level decay $f \to \ell^- e^+ \nu_e$.
- $\mathcal{O}_{VR}$:
  Possibly interesting mass range (μ case):
  105 MeV $\lesssim m_f \lesssim 245$ MeV. Left for further study.