New Dark Matter Search Strategies at DUNE

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collaborators

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dark matter and monoenergetic neutrinos

- can search for dark matter using neutrino detectors
  - dark matter scatters off solar nuclei and collects in the core of the Sun
  - annihilates to Standard Model products
  - neutrinos get out and reach detector on earth

- focus is typically on a smooth distribution of high-energy events above background
- I’ll focus on a different possibility
  - models in which dark matter can produce monoenergetic sub-GeV neutrinos
  - detectors and strategies which can resolve a line signal
  - obtaining direction information about neutrino

- DUNE is an ideal setting for this type of search
standard lore

• expect to get a continuum signal
  – dark matter annihilates to intermediate particles
  – decays give a continuum neutrino spectrum

• look for high energy neutrinos
  – larger cross section with detector
  – smaller background from atmospheric neutrinos

• use directionality, but only for high energy neutrinos
  – try to identify neutrinos arriving from the direction of the Sun
  – looking for charged lepton produced by charged-current interaction
  – points away from source, but only for $E > \text{GeV}$
    • for lower energies, charged lepton is roughly isotropic
basic points

• **theory**
  – u, d, s final state quarks produce plenty of K^+
    • light hadrons *stop before they decay* (producing more K^+)
    • decay produces 236 MeV *monoenergetic neutrino*

• **experiment**
  – DUNE will do very well at total energy reconstruction for a charged-current interaction
    • sensitive to a *line signal*
  – DUNE can also get the direction of the neutrino from the *nucleon recoil*
    • new type of *directionality search*
    • great for *reducing systematic uncertainty*
neutrinos from the Sun
(see Carsten Rott’s talk....)

• basic idea
  – DM scatters off solar nuclei, loses energy through elastic scattering
  – falls below $v_{\text{esc}} \Rightarrow$ captured
    • orbits, eventually collects in core
    • rate depends on mass, $\sigma$
  – DM annihilates to SM matter
  – SM decay yields neutrinos $\Rightarrow$ seen at detector
  – DM in equilibrium $\Rightarrow \Gamma_C = 2 \Gamma_A$
  – so neutrino event rate probes DM capture rate ($\propto \sigma_{SI}, \sigma_{SD}$)
• usually ignore light q final state
  – why?

Dawn Williams

A. Zentner, arXiv:0907.3448
dark matter annihilation to light quarks

- u, d, s final states $\rightarrow$ hard!
  - u, d, s $\rightarrow$ light hadrons which stop in the Sun before decay
  - resulting $\nu$ spectrum is very soft
  - large background, small detector effective area

- but the stopping process produces a large number of $\pi^+, K^+$
  - trade a hard spectrum for a softer one, but with larger flux
    [Beacom, Rott, Siegal-Gaskins (1208.0827); Bernal, Martin-Albo, Palomares-Ruiz (1208.0834)]
spectrum

• care about $\pi^+$ and $K^+$
  – $\pi^0 \rightarrow \gamma\gamma$
  – $\pi^-$ Coulomb-captured by nuclei, and absorbed (not a lot of neutrinos)
• main relevant decay is $\pi^+, K^+ \rightarrow \nu_\mu \mu^+$
  – monoenergetic $\nu$ with $E = 29.8$ MeV ($\pi^+ - 100\%$) or $235.5$ MeV ($K^+ - 64\%$)
  – line signal
    • include oscillation effects

• just need the fraction of DM energy which goes into stopped $\pi^+, K^+$
  – determine with Pythia/GEANT
  – use Pythia to simulate showering and hadronization; output the spectrum of long-lived hadrons
  – GEANT deals with interaction in dense solar medium
K⁺

- I’ll focus on the 236 MeV neutrino arising from stopped K⁺ decay
- much larger cross section with detector target
  - more than offsets smaller number of kaons per annihilation

- now have all the pieces
  - given dark matter mass, scattering cross section, and annihilation channel, can get the flux of 236 MeV neutrinos from the Sun
  - with the energy resolution, can get the flux from atmospheric neutrino background
  - gives us the signal-to-background ratio
  - with the neutrino-nucleus scattering cross section (numerical) and exposure, can get signal significance
• Deep Underground Neutrino Experiment

• perfect for this type of search
  – large exposure
  – good total energy resolution
  – can identify outgoing particle tracks with good energy and angular resolution

• our benchmarks
  – angular resolution $\sim 5^\circ$
  – total energy res. – $\varepsilon \sim 10\%$

a theorist, for scale
sensitivity for non-directional search

• assume 34 kT yr exposure
  • electron channel
  • \( \sim 50 \) bgd. events
  • 90%CL exclusion, assuming observation consistent with bgd.
  • sig. signif. \( \propto (\text{exposure} / \epsilon)^{1/2} \)

• competitive with direct detection at \( \sim 4\text{-}5 \text{ GeV} \) (but PICO-60 wins above this)
• SK, HK \( \rightarrow \) win with exposure
  • WC detectors \( \rightarrow \) size advantage
• other neutrino searches not sensitive (focused on high-energy neutrinos)

In, Kumar, Rott, Yaylali - 1510.00170

90% CL annihilation to u or d spin-dep. scattering
directionality

• for 34 kT yr exposure, DUNE atm. $\nu$ background is significant
• would be great to get a directionality cut
  – preferentially select events where $\nu$ arrives from the direction of the Sun
• reduces systematic uncertainties in background by comparing on-axis to off-axis event rates
  – want $S / B > \delta B_{\text{sys.}} / B \rightarrow$ excess not just a systematic error
  – can measure $B$ by going off axis (reduces $\delta B_{\text{sys.}} / B$)
  – increases $S / B$ by picking events from the direction of the Sun
• can improve statistical significance
• most searches for neutrinos arising from dark matter annihilation utilize directionality...
• ... but usually when looking for a very energetic neutrino
  – CC-interaction produces a forward-peaked charged lepton
directionality for sub-GeV vs

- for sub-GeV $\nu$, the charged lepton produced is mostly isotropic
- but the hadronic recoil is not!
- at this energy, get a lot of events where a single proton is ejected
  - $\nu_\ell + ^{40}\text{Ar} \rightarrow \ell^- + p^+ + ^{39}\text{Ar}$
- ejected in the forward direction
  - cut on proton direction
- but analytic approximations to the cross sections and distributions are lacking
- rely on numerical techniques
- NuWro
generate $10^5$ events per flavor ($\nu_e$ or $\nu_\mu$)

select events with...
- one charged lepton track identified
- one ejected proton track identified (kills $\bar{\nu}$ bgd.)
- cuts at event generation level (no attempt to model detector)
  - just need particles generated above a threshold

lepton threshold $\rightarrow$ 30 MeV

proton threshold $\rightarrow$ 50 MeV (according to DUNE CDR...)
  - “tight”

we’ll also consider a more optimistic proton cut $\rightarrow$ 20 MeV
  - “loose”

determine efficiency for signal events ($\eta_S$) and bgd events ($\eta_B$) to satisfy event selection and angular cuts
sensitivity and systematics

- two efficiencies
  - event selection ($\eta_{\text{sel}}$)
    - common to S and B
  - directional ($\eta_{\text{dir}}$)
    - fraction of events in forward cone from the Sun
    - better for S than for B
- total efficiency $\eta_{S,B} = \eta_{\text{sel}} \times \eta_{\text{dir}(S,B)}$
- care about improvement to signal significance, and to S-to-B ratio
- we’ll choose cuts to maximize improvement for signal significance for fixed exposure
  - other choices possible...

<table>
<thead>
<tr>
<th>cut</th>
<th>proton threshold</th>
<th>selection efficiency ($\eta_{\text{sel}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tight:electron</td>
<td>$E_{\text{kin}} &gt; 50$ MeV</td>
<td>0.43</td>
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<tr>
<td>tight:muon</td>
<td>$E_{\text{kin}} &gt; 50$ MeV</td>
<td>0.28</td>
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<tr>
<td>loose:electron</td>
<td>$E_{\text{kin}} &gt; 20$ MeV</td>
<td>0.83</td>
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<tr>
<td>loose:muon</td>
<td>$E_{\text{kin}} &gt; 20$ MeV</td>
<td>0.75</td>
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</table>
cuts and efficiencies

\[
\frac{S}{B} \rightarrow \left( \frac{\eta_S}{\eta_B} \right) \times \frac{S}{B} \\
\frac{S}{\sqrt{B}} \rightarrow \left( \frac{\eta_S}{\eta_B} \sqrt{\eta_B} \right) \times \frac{S}{\sqrt{B}}
\]

- cuts: cone half-angle (\( \gg \) ang. res)
- tight: muon \( \rightarrow 45^\circ \)
- tight: electron \( \rightarrow 50^\circ \)
- loose: electron \( \rightarrow 55^\circ \)
- loose: muon \( \rightarrow 55^\circ \)
- \( S/B \) can improve by up to \( \times 5 \)
  - very good for on-/off-axis
- but signal significance only sees a modest improvement
  - big hit from small selection efficiencies
- win more on systematics than statistics

<table>
<thead>
<tr>
<th>cut</th>
<th>S/B enhancement</th>
<th>sensitivity enhancement</th>
</tr>
</thead>
<tbody>
<tr>
<td>tight:electron</td>
<td>4.8</td>
<td>1.2</td>
</tr>
<tr>
<td>tight: muon</td>
<td>4.5</td>
<td>1.0</td>
</tr>
<tr>
<td>loose:electron</td>
<td>3.4</td>
<td>1.4</td>
</tr>
<tr>
<td>loose:muon</td>
<td>3.5</td>
<td>1.4</td>
</tr>
</tbody>
</table>

\textbf{tight} \rightarrow \text{win on } S/B \text{ (up to } S/B \sim 0.4) \\
\textbf{loose} \rightarrow \text{win on sensitivity}
results

90%CL, q=u,d

David Yaylali

assume 340 kT yr ... need large exposure to offset selection efficiencies dozens of background events need a long run-time just to catch up to Super-K and PICO-60
what’s the point of doing this at DUNE?

- for signal significance, **WC detectors** will always win because of exposure
- except for a small mass range, **PICO** is already winning
- but there are **good reasons** to search at DUNE
- **directionality** gives a new handle on systematic uncertainties and bgd.
  - no such directionality possible with WC detectors
  - PICO sensitivity is **degrading** rapidly < 10 GeV
  - different **astrophysics uncertainties** than direct detection
- if a **signal** is seen in the future, can get a handle on **annihilation channel**
  - is it **asymmetric dark matter**?
  - a 236 MeV line signal at DUNE from the Sun would be **striking evidence** of dark matter annihilation producing **light quarks**
  - cross section could be $\ll 1$ pb, with Sun still in equilibrium
  - especially for low mass DM, **hard to see this any other way**
- important as a **complementary** search strategy
resolving uncertainties

- a lot of uncertainty in the **neutrino-nucleus scattering cross section**, etc.
  - really a **proof-of-principle**
- can “calibrate” by comparing rates **on-axis** vs. background **off-axis**
- but can also calibrate directly with a **stopped kaon experiment**
- a **stopped pion experiment** is also a stopped kaon experiment
- stopped pion proposals like **DAEδALUS** are under consideration for DUNE
- can also put an LArTPC at a stopped pion experiment
  - **CAPTAIN** at SNS (see Lisa Whitehead Koerner’s parallel talk....)
conclusion

- dark matter annihilation in the Sun can produce monoenergetic 236 MeV neutrinos
  - produce numerous stopped $K^+$
- LArTPC $\nu$-detectors can reconstruct energy and direction of products
  - can detect a neutrino line with good total energy resolution
  - can get directionality from ejected proton

- reduced backgrounds and systematic uncertainties
- sub-GeV $\nu$ directionality is a unique capability of DUNE
- stopped kaon experiment would help with calibration
- above all, need lots of exposure

Mahalo!
Back-up slides
why (not) $\chi\chi \rightarrow \bar{f}f$ ($f=u,d,s$)?

- can understand just from angular momentum
- for Majorana fermion, wavefunction is anti-symmetric
  - $L=0$, $S=0$ or $L=1$, $S=1$
- if outgoing fermions on z-axis
  - $L_z=0$ ( $Y_{lm}(\theta=0,\phi)\neq0$ only if $m=0$ )
  - $S_z = J_z$
- if $S_z=0$ need $f$, $\bar{f}$ with same helicity
  - not CP-conjugate
  - need Weyl spinor mixing
  - in MFV, mixing scales with mass
- if $S_z=\pm1$ need $f$, $\bar{f}$ with opp. helicity
  - no mixing needed

\[ J=0, L_z=0 \rightarrow S_z=0 \]
\[ J_z=1, L_z=0 \rightarrow S_z=1 \]
monoenergetic neutrinos

• this argument underlies the theoretical prejudice towards searches for the $\bar{b} b$, $\bar{\tau} \tau$ and $W^+ W^-$ channels
• but the chirality suppression arises from the assumption of Majorana fermion dark matter and minimal flavor violation
  – certainly true for the CMSSM, but need not be true in general
  – WIMPs need not be Majorana, and MFV can fail even in the general MSSM
• if dark matter is a Dirac fermion, then the initial state can be $L=0$, $S=1$, $J=1$, so s-wave annihilation, but no mixing needed
• if we drop minimal flavor violation, then mixing need not scale with quark mass
• either way, $\chi\chi \rightarrow \bar{q}q$ ($q = u, d, s$) branching fraction could be $\mathcal{O}(1)$
• worth studying these annihilation channels
signal limited – $K^+$

• **compare** to $\pi^+$ channel
• **larger cross section**
  – larger effective area ($> \times 100$)
  – need smaller exposure to get signal (or bgd.) events
• **fewer $K^+$ per annihilation**
  – backgrounds similar
    • smaller flux, larger bin
  – factor 5-10 smaller $S/B$
• **upshot**
  – **better sensitivity** with small exposure
  – leaves linear regime first
  – ultimate sensitivity comparable

\[
N_{\text{DUNE bgd.,236 MeV}} \approx (486)\varepsilon \left( \frac{M_{\text{Ar}}}{34 \text{ kT}} \right) \left( \frac{T}{\text{yr}} \right)
\]

\[
\frac{S}{B} \approx 0.83 \frac{\sigma_{\text{SD}}}{\varepsilon} \text{ pb}
\]

\[
E_{\text{opt}}^{\text{Ar}} \approx \frac{0.07}{\varepsilon}
\]
issues with the cross section at $\mathcal{O}(100)$ MeV (a novice’s view)

• basic idea $\rightarrow$ impulse approximation (IA)
  – neutrino interacts with a single struck nucleon
  – subsequent interactions between struck nucleon and rest of nucleus

• can model the nucleus state as...
  – Fermi gas
  – using a more detailed spectral function obtained from theory and electron scattering experiments

• spectral function is a better model...

• ...but analysis still based on IA

• IA becomes less valid an approximation for $E_\nu < 100$ MeV
  – Ankowski, Soczyk -- 0709.2139
  – no good tool for going beyond IA, though
  – best to just calibrate
$r$ decreases with $m_X$

about $\times 10$ more 30 MeV vs than 236 MeV vs per annihilation for $u$ and $d$ channels
the pieces we need....

- we have the neutrino fluxes from the Sun arising from DM....
- we have estimates of the $v_{e,\mu}$ background at $E \sim 236$ MeV (atm. $v$)
- charged current neutrino-nucleus scattering cross section ($v_\ell + n \rightarrow \ell + p$)
  - for $E \sim 236$ MeV, theory complicated
    - dominant contribution is quasi-elastic
    - not very well understood
    - rely on numerical packages
    - NuWro

Battistoni, Ferrari, Montaruli, Sala

$$\frac{d^2\Phi^e_B}{d\Omega dE} \approx 1.2 \text{ m}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{MeV}^{-1}$$

$$\frac{d^2\Phi^\mu_B}{d\Omega dE} \approx 2.3 \text{ m}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{MeV}^{-1}$$

($\bar{v}$ similar)

$$\sigma^e_{\text{CC}} (236 \text{ MeV}) \approx 4.2 \times 10^{-38} \text{ cm}^2$$

$$\sigma^\mu_{\text{CC}} (236 \text{ MeV}) \approx 2.7 \times 10^{-38} \text{ cm}^2$$

NuWro
90% CL numbers

non-directional search, electron channel

<table>
<thead>
<tr>
<th>experiment</th>
<th>status</th>
<th>exposure</th>
<th>$N_B$</th>
<th>$N_{obs}$</th>
<th>$f_S$</th>
<th>$N_S$</th>
<th>$N_B$</th>
<th>$N_{obs}$</th>
<th>$f_S$</th>
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<tbody>
<tr>
<td>KamLAND</td>
<td>current</td>
<td>4 kT yr</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>5.1</td>
<td>6</td>
<td>0.68</td>
<td>5.5</td>
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<tr>
<td>DUNE</td>
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<td>34 kT yr</td>
<td>0.2</td>
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<td>2.3</td>
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<td>762.5</td>
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<td>45.4</td>
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directional search, 340 kT yr exposure

<table>
<thead>
<tr>
<th>cuts</th>
<th>expected $N_B$</th>
<th>assumed $N_{obs}$</th>
<th>expected $N_S$ for exclusion</th>
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<tbody>
<tr>
<td>tight: electron</td>
<td>14.8</td>
<td>15</td>
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<tr>
<td>tight: muon</td>
<td>14.9</td>
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<td>6.4</td>
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<tr>
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