Signals of Dark Matter

Roni Harnik, Fermilab

with Joachim Kopp and Pedro Manchado
1202.6073

See related works-
Pospelov 1103.3261
Pospelov and Pradler 1203.0545

yesterday’s talk
Direct Detection

* In past decades direct detection collaborations have made a heroic (and successful!) effort in background reduction.

* Try as you might, these experiments are still completely exposed to the sun....

...in neutrinos!!!
The irreducible background from solar and atmospheric neutrinos will be the eventual end-game of direct detection.
Direct Detection

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![Graph showing WIMP-Nucleon Cross Section vs. WIMP Mass]

**Question:** Can this background be "raised" to be a signal?
What does this look like in a direct detection experiment?

\[
\frac{dR}{dE_r} = N_T \int_{E_{\nu}^\text{min}}^{\infty} \frac{d\Phi}{dE_\nu} \frac{d\sigma}{dE_r} dE_\nu
\]

with \(E_{\nu}^\text{min} = \frac{1}{2} \left( E_r + \sqrt{E_r^2 + 2E_r m_T} \right)\)

(relativistic version of \(\frac{dR}{dE_r} = \frac{M_N N_T \rho_X \sigma_n}{2m_X \mu_{ne}^2} F^2 \left( f_p Z + f_n (A - Z) \right)^2 \int_{v_{min}}^{v} \frac{f(v)}{v} \))
For nuclear recoil: see Joseph Pradler's talk

* The scattering is coherent, \( \propto A^2 \).

* The flux is low above threshold.

\[
E_r^{\text{max}} = \frac{2E_{\nu}^2}{m_T + 2E_{\nu}}
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$$E_{r}^{\text{max}} = \frac{2E_{\nu}^2}{m_T + 2E_{\nu}}$$
Spectrum

* Electron recoil:
  - pp neutrinos are above threshold. High flux.
    \[ E_r^{\text{max}} = \frac{2E_\nu^2}{m_T + 2E_\nu} \]
  - But, lower cross section, (phase space and coherence).

scattering on effectively free electrons.
All experiments in one plot!
New Physics?

* Can new physics in the neutrino sector “raise” this background and give interesting signals?

Since Joseph cover nuclear, I’ll focus on e-recoil.
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Outline

* New light gauge bosons (A')
* Electron recoil
  o SM neutrinos or light steriles
  o Heavy steriles
* Potential sources of modulation-
  o Solar distance
  o Matter effects
  o Channeling
* Constraints on A's
* Conclusion.
New Physics Models

* Many models with new light gauge boson:
  - A light B-L gauge boson
  - Kinetically mixed U(1) (a.k.a dark photon).

* New **sterile** neutrinos can also come in handy. Can be emitted by the sun via mixing or oscillation.

* Another “new” gauge boson that can couple to neutrinos is the photon.
  A magnetic dipole moment:  \( \mu_\nu \bar{\nu} \sigma^{\mu\nu} \nu F_{\mu\nu} \)
B-L is constrained. There are holes:
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Parameter Space

* Dark photons are a bit more open.

**Kinetic mixing $\epsilon$**

Dark Photon Mass $M_{A}'$(GeV)

$g_v^2 \sin^2 2\theta = 10^{-12}$

$g_v^2 \sin^2 2\theta = 10^{-4}$

Old Stars, energy loss via sterile neutrinos (only if they are light)

Kinetically Mixed Gauge Boson
Dark photons are a bit more open.
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Parameter Space

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* Kinetic mixing \( \epsilon \)

\[ g^2 \sin^2 2\theta = 10^{-12} \]

\[ g^2 \sin^2 2\theta = 10^{-4} \]

CMB

Atomic Physics

LSW

\( \mathcal{N}^{\text{eff}} \)

\( (g - 2)_\mu \)

\( (g - 2)_\mu \)

Borexino

\( \\text{Old Stars, energy loss via sterile neutrinos (only if they are light)} \)

\( \\text{SN1987A} \)

\( \\text{Sun} \)

\( \\text{Captured in Sun} \)

\( \\text{Fixed target} \)

\( \\text{chameleons} \)

\( \\text{closed yesterday? (An et al.)} \)
A Light Gauge Boson

* The exchange of A’ contributes to neutrino-nucleus and neutrino-electron scattering:

\[ \frac{d\sigma}{dE_r} = \frac{g_{\nu}^2 g_T^2 m_T}{4\pi p_\nu^2 (M_{A'}^2 + 2E_r m_T)^2} \left[ 2E_\nu^2 + E_r^2 - 2E_r E_\nu - E_r m_T - m_\nu^2 \right] \]

propagator: \( q^2 - M^2 \)
A Light Gauge Boson

* What does a direct detection experiment see?

back to the master formula:

\[
\frac{dR}{dE_T} = N_T \int_{E_{\nu}^{\text{min}}}^{\infty} \frac{d\Phi}{dE_\nu} \frac{d\sigma}{dE_T} dE_\nu
\]

with

\[
E_{\nu}^{\text{min}} = \frac{1}{2} \left( E_T + \sqrt{E_T^2 + 2E_T m_T} \right)
\]
CoGeNT or DAMA?

* If we want to do CoGeNT or DAMA there is clear tension with XENON100 (and also Borexino).
Heavy Sterile

* Is there a way around XENON?

Can we get a sharp threshold?

* The solar flux has lines....

A kinematic threshold near the $^7$Be line. Its tuned...

* I would like to thank IDM and its variants for the moral license to do this.
Heavy Sterile

Interesting spectra can arise:

![Graph showing expected event spectra in a dark matter detector from enhanced scattering of heavy sterile neutrinos on electrons. We have assumed the mass to be negligible and we have chosen the cross section such that the CoGeNT excess can be explained. Black lines show the count rate in the Standard Model, and red curves show the observed event rates in XENON.]

5. ENHANCED NEUTRINO–NUCLEUS SCATTERING FROM NEW PHYSICS

While neutrino–electron scattering in a dark matter detector, as discussed in the previous section, is a very interesting discovery channel for new physics in the neutrino sector, it is not the process that most of these detectors are designed to look for. Let us therefore now turn our attention to neutrino–nucleus scattering, focusing in particular on scenarios in which the scattering rate at low energies is enhanced, thus possibly mimicking a dark matter signal.

As for neutrino–electron scattering, the simplest way of achieving such enhancement is by introducing a neutrino magnetic moment. The expected neutrino–nucleus scattering rate for solar neutrinos with a magnetic moment at the current upper limit is shown in figure q, curve A for two different target materials: Germanium (used in CoGeNT and CDMSe) and CaWO₄ (used in CRESSTek). As we can see, the effect is very small and certainly not detectable by dark matter experiments in the foreseeable future.

The situation is different for neutrino–nucleus scattering through the exchange of a new light gauge boson ("dark photon") \( A \) (see for instance the models from sections pko–pkq). In this case, the couplings can still be sufficient to allow for substantial enhancement of the scattering rate. Moreover, when scattering on a heavy nucleon, a low energy neutrino cannot resolve the nuclear structures and hence the scattering happens coherently on all nucleons. This leads to an increase in the cross section proportional to \( A^2 \) where \( A \) is the nuclear mass number.

On the other hand, since nuclei are much heavier than electrons, an electron nuclear recoil energy (above the detection threshold in a dark matter detector) requires neutrino energies of \( O(10^{-11}) \) MeV, as opposed to the \( O(10^{-9}) \) keV required for the detectable electron recoil. This means that, while all solar neutrino flux components can contribute to \(-\nu_e\) scattering, only the...
Modulation

2-4 keV

DAMA/LIBRA ≈ 250 kg (0.87 ton×yr)
Modulation and the Sun

* Annual modulation is an important part of past and (hopefully) future anomalies.

* What modulation signals can the Sun produce?

* Many possibilities for modulation:
  - daily.
  - annually.
  - even semi-annually.
Elliptical Orbit & Just-So

* We are on an elliptical orbit. Wikipedia:
  - Closest to the Sun on **Jan 3rd** (wrong phase for DAMA).
  - The amplitude is 1.6% (flux is double that).

* Introduce oscillation on AU scale (with sterile):

\[ P_{1\to 2} \sim \sin^2 2\theta \sin^2 \frac{\Delta m_{12}^2 L}{2E_{\nu}} \]
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\]

![Graph showing oscillation probability over AU scale](image)
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**Just-So**

* A variety of modulation amplitudes are possible

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**Figure:** Relative annual modulation fraction $g/R_{\text{Jun}} - g/R_{\text{Dec}}$ of the rate of immediate sterile neutrino–electron scattering as a function of the recoil energy $E_r$ and the mass squared difference between active and sterile neutrinos. For simplicity, we use a two-flavor vacuum oscillation framework. One can clearly distinguish four different regimes, in which the rate is dominated by pp neutrinos, $^7$Be neutrinos, pep neutrinos, CNO neutrinos, and $^8$B neutrinos, respectively. In each of these regimes, the modulation fraction is determined mostly by the oscillation length at the peak energy of the corresponding neutrino flux, as long as the recoil energy is large enough for this peak energy to be kinematically accessible.

Note that for mass squared values larger than the ones shown in figure $u$, the impact of oscillations will fade away once the oscillation length at the relevant neutrino energies becomes larger than the diameter of the neutrino production region in the Sun. For pp neutrinos, which are produced at radii $r < r_p$ in the Sun and whose flux peaks at around $s_{\text{pp}}$ keV, this happens for $m^2 < 9 eV^2$, whereas for $^8B$ neutrinos, which are produced at $r < r_q$ and whose flux peaks at around $v_{^8B}$ MeV, the effects become relevant only for $m^2 < 7 eV^2$.

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**6.3. Diurnal and annual modulation from Earth matter effects**

Another mechanism by which solar neutrino signals can modulate with time is Mikheyev–Smirnov–Wolfenstein (mMSW) type matter effects in the Earth. It is well known (see for instance reference $x$ and references therein) that even in the standard three-flavor oscillation framework, matter-enhanced $\mu$, $\tau$, and $\tau$ oscillations of solar neutrinos inside the Earth can lead to a slightly enhanced $e$ flux during the night, when solar neutrinos have to traverse the Earth before reaching a detector. This leads to diurnal modulation of the $e$ detection rate, and since nights are longer in winter than in summer, it also leads to annual modulation. In the standard framework, the day–night asymmetry is predicted to be very small, on the few per cent level, but we will argue here that it can be sizeable in the new physics sector.

Consider, for instance, a scenario based on the model from section $s$, but with two sterile neutrinos weakly mixed with the active ones. We assume that one of the

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### Modulation fraction

$$(R_{\text{Jun}} - R_{\text{Dec}})/(R_{\text{Jun}} + R_{\text{Dec}})$$

- **Blue**: $-1...-0.2$
- **Light blue**: $-0.2...-0.1$
- **Darker blue**: $-0.1...-0.05$
- **Lighter blue**: $-0.05...-0.02$
- **Gray**: $-0.02...0$
- **Yellow**: $0...0.02$
- **Light yellow**: $0.02...0.05$
- **Orange**: $0.05...0.1$
- **Dark orange**: $0.1...0.2$
- **Red**: $0.2...1$
A variety of modulation amplitudes are possible.
Matter Effects

* The new gauge boson can lead to new “MSW-like” matter effects:

\[ V_{\text{matter}} = \frac{g_\nu}{M_A^2} (g_e n_e + g_p n_p + g_n n_n) \]

* Active-sterile oscillations in matter can be very different from those in vacuum.

* **Day-night asymmetry** due to an oscillation b/w among sterile species in matter. This asymmetry can be large.

* The matter oscillation length, \( L_{\text{osc}} = \frac{4\pi E}{\Delta m^2} \), can be anywhere between a kilometer and the earth radius.
Zenith Angles

* At noon, the sun is high in the sky in summer. Low in winter.

* At midnight, the Sun is lower below the horizon in winter. Higher in summer.
Zenith Angle

* The average baseline in rock for solar neutrinos going to Gran Sasso **modulates:**

A strong daily modulation is induced here too.

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Channeling

- The dark matter signal is isotropic to zeroth order.
- A signal coming from the sun is maximally anisotropic.
- Imagine channeling occurs in some target crystals:

- A highly angle dependent effect → modulation!
Channeling

* This can lead to a **daily** modulation, as well as a **annual** or **semi-annual** modulation.

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**Figure 7:** Illustration of the relative orientation of a detector with respect to the solar neutrino flux throughout the years. In blue we show the cones which the detector’s normal axis traces out during a day, and in red we show the Earth’s trajectory around the Sun. As explained in the text, a detector whose detection efficiency depends on the direction of the incoming particles can observe both diurnal and semiannual modulation in the solar neutrino signals. There would be no contribution to annual modulation, though, because the orientation of the Earth’s axis relative to the dark matter velocity does not change during the years.

The situation is different for signals induced by particles coming from the Sun, such as neutrinos. In this case, direction-dependent detection efficiencies will lead to both diurnal modulation and semiannual modulations. This can be understood from Figure 7, in which the blue cones illustrate the trajectory of the detector’s normal axis during a day, and the red ellipse depicts the Earth’s orbit around the Sun. We see that the angles under which the detector sees solar neutrinos in opposite seasons differ by \( \pi \times 8 \). Since the target materials typically used in dark matter detectors like Ge, Si, NaI, Tl, CsI, Tl, and CaWO\(_4\) form parity symmetric crystals, their response is invariant with respect to reversal of the incoming particle direction, and the signal will be the same in opposite seasons but may be different between. This explains why solar neutrino signals in solid dark matter detectors can show semiannual modulations.

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5. **CONCLUSIONS**

In this paper, we have discussed the rich phenomenology of standard and nonstandard solar neutrino signals in dark matter direct detectors. In particular, we have considered models featuring a “dark photon” \( A \) like light, weakly coupled new gauge boson, and have shown that \( A \)-mediated neutrino–electron and neutrino–nucleus scattering can be much stronger than Standard Model weak interactions at the low recoil energies to which dark matter detectors are sensitive while being consistent with constraints from higher energy experiments such as Borexino.

If we moreover assume that a small fraction of solar neutrinos has oscillated into new “sterile” flavors, whose couplings to the dark photon are much less constrained than those of Standard Model particles, the scattering rates can be large enough to explain at least some of the recently reported signals.

We have also discussed possible sources of temporal variations in the neutrino count rate, in particular the annual variation of the Earth–Sun distance (possibly in conjunction with oscillation...
Concluding

* **Dark matter** and **neutrino** experiments share some features: low backgrounds, large exposure, low thresholds.

* They can probe similar physics.

* New physics connecting the SM to neutrinos can lead to **interesting direct detection signals**:
  - New light gauge bosons.
  - Neutrino dipole moments.

* Many possibilities for rich **modulation** signals.
Deleted Scenes
Nuclear Recoil
Nuclear Recoil

* The situation is very different w/ nuclear recoil.
* SNO has measured Boron 8 neutrinos through deuterium dissociation.
* SNO is probing a momentum transfer that is only a factor of a few higher than DAMA or CoGent.
* A light mediator does not buy you much.

But...
Nuclear Recoil

* Deuterium dissociation is an inelastic process.
* The standard model rate at SNO is dominated by the axial-vector component of the Z interaction.
* The vector component is suppressed by....

\[
\frac{\sigma_{\nu_b - \text{Nucl}(\text{elastic})}}{\sigma_{\nu_b - \text{Nucl}(\text{inelastic})}} \sim \frac{A^2}{E_{\nu}^4 R_N^4} \sim 10^8
\]

understanding this is in progress.
Nuclear Recoil

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Pospelov:

\[
\langle d | \exp(i q r^{(n)}) + \exp(i q r^{(p)}) | np \rangle = 2 \langle d | n p \rangle + i q \cdot \langle d | r^{(n)} + r^{(p)} | n p \rangle - \frac{q_k q_l}{2} \langle d | r^{(n)}_k r^{(n)}_l + r^{(p)}_k r^{(p)}_l | n p \rangle = -\frac{q_k q_l}{4} \langle d | r_k r_l | n p \rangle
\]
Nuclear recoil

* Interesting spectra are achievable:

![Nuclear recoil - Ge](image)
![Nuclear recoil - CRESST](image)

SNO constraints may still be too much... (in progress)
Absorption

* If the sterile scattering cross section is high, its m.f.p may be smaller than earth radius.

* Neutrinos are captured during the night, but reach the detector during the day.

* Steriles can still be produced via oscillation outside the sun.

* The sterile flux may still be adjusted to fit the signal strength in direct detection.