Direct detection of light dark matter

Joachim Kopp

IDM 2012, Chicago
Outline

1. Why light WIMPs?

2. Experimental techniques for direct detection of light dark matter

3. Theoretical interpretation of direct detection data
   - Material-dependent scattering cross sections
   - Dependence on the WIMP velocity distribution
   - Light WIMPs and annual modulation
   - Neutrinos as WIMP impostors

4. Conclusions
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Hints for light dark matter

On the Earth...

- Several intriguing **direct detection signals**
- But **severe tension** with null results
Hints for light dark matter

On the Earth ...

Plot based on JK Schwetz Zupan 1110.2721

$\sigma_{\text{SI}}$ vs $m$ [GeV]

- DAMA ($\chi \pm 10\%$)
- $v_0 = 220$ km/s
- $v_{\text{esc}} = 550$ km/s
- CRESST
- CoGeNT (no surface BG)
- CoGeNT (small surface BG)
- CoGeNT (large surface BG)
- Limits: 90%
- Countours: 90\%, 3\$

$\chi$ mass $m$ [GeV]

...and in the skies

- An tentative $\gamma$ ray excess from the Galactic Center
  Hooper Goodenough 0912.2998, 1010.2752, 1201.1303
  - Morphology $\neq$ point source
- Radio filaments
  Linden Hooper Yusef-Zadeh 1106.5493
- Isotropic radio background
  Hooper Belikov Jeltema Linden Profumo Slatyer 1203.3547

Several intriguing direct detection signals
But severe tension with null results
Theoretical motivation for light DM

- Conventional DM paradigm: DM has electroweak scale mass, weak scale couplings $\rightarrow$ Thermal production $\rightarrow$ The WIMP Miracle
- But note: Thermal production also possible for lighter DM

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Theoretical motivation for light DM

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- But note: Thermal production also possible for lighter DM

- An interesting alternative: Asymmetric dark matter
  - Based on the observation that \( \Omega_{DM} \approx 5 \times \Omega_{\text{baryon}} \)
  - Suggests related production mechanisms
  - Baryon abundance determined by matter–antimatter asymmetry
  - If DM carries baryon number and \( m_{DM} \sim 10m_p \), the observed \( \Omega_{DM} \) could be explained.
  - Many model-building and phenomenology papers related to this idea:

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Semiconductor detectors

- Binding energy of electrons in semiconductor detectors is very small (3 eV in Ge)
  - Already a very feeble nuclear recoil leads to excitation
- Practical limitation: Electronic noise
- Possible solution: Reduce capacitance of the device
  - Make them smaller — for instance CCDs (DAMIC)
  - Change the electrode geometry → Point-contact detectors (CoGeNT)

DAMIC collaboration 1105.5191
Barbeau Collar Tench nucl-ex/0701012
Ionization (S2) signals in liquid Xenon

- Ionization energy in LXe: $\mathcal{O}(12 \text{ eV})$
Ionization (S2) signals in liquid Xenon

- Ionization energy in LXe: $\mathcal{O}(12\text{ eV})$
- Actual experimental energy threshold depends on kinematics:
  - Threshold energy for WIMP–nucleus scattering depends on $L_{\text{eff}}$
    - Difficult to measure (requires experiments with low-$E$ neutrons)
    - Difficult to calculate (interactions of primary recoil nucleus with other Xe atoms requires complicated many-body dynamics)


Primary recoil ion hits Xe atom at rest

Outer electrons rearrange themselves under the influence of both nuclei.

Some of them may end up in excited or unbound states
Ionization (S2) signals in liquid Xenon

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- WIMP–electron scattering very inefficient for $\mathcal{O}(100 \text{ GeV})$ dark matter

  JK Niro Schwetz Zupan 0907.3159
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- WIMP–electron scattering very inefficient for $O(100\ GeV)$ dark matter

JK Niro Schwetz Zupan 0907.3159

- ... but an ideal process for MeV–GeV DM

Essig Mardon Volansky 1108.5383, Essig Manalaysay Mardon Sorensen Volansky 1206.2644

![Excluded by XENON10 data](image)
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4 Conclusions
Material-dependent scattering cross sections

How can the tension in the global data set — when interpreted in terms of dark matter scattering — be resolved?

![Plot based on JK Schwetz Zupan 1110.2721](image_url)

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Direct detection of light dark matter
Material-dependent scattering cross sections

How can the tension in the global data set — when interpreted in terms of dark matter scattering — be resolved?

Isospin-violating DM

Different couplings to protons and neutrons

→ “switch off” xenon

![Plot: JK Schwetz Zupan 1110.2721]
Material-dependent scattering cross sections

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Material-dependent scattering cross sections

How can the tension in the global data set — when interpreted in terms of dark matter scattering — be resolved?

Isospin-violating DM  
Feng Kumar Marfatia  
Sanford 1102.4331

Different couplings to protons and neutrons  
→ “switch off” xenon

Inelastic DM  
Tucker-Smith Weiner hep-ph/0101138

Inelastic scattering  
→ prefers heavy targets (CRESST!)

Plot: JK Schwetz Zupan 1110.2721
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Dependence on the WIMP velocity distribution

Conventional assumption:

\[ f(v) \propto \left( \exp \left[ -\frac{v^2}{v_0^2} \right] - \exp \left[ -\frac{v_{esc}^2}{v_0^2} \right] \right) \Theta(v_{esc} - v) \]

However, *N*-body simulations predict deviations from this simple form

Also: Streams and debris flow  Lisanti Spergel 1105.4166, Kuhlen Lisanti Spergel 1202.0007
Dependence on the WIMP velocity distribution

$\sigma_{\text{SI}}$ in cm$^2$

$M_{\text{DM}}$ in GeV

Standard

$f_p/f_n = 1$

$v_0 = 270$ km/s

$v_{\text{esc}} = 500$ km/s

$q_{\text{Na}} = 0.3$

$\chi^2 = 242., 50.4$

Farina Pappadopulo Strumia Volansky 1107.0715
Dependence on the WIMP velocity distribution

Farina Pappadopulo Strumia Volansky 1107.0715
Dependence on the WIMP velocity distribution

\begin{itemize}
  \item \textit{standard} \hspace{1cm} \frac{f_p}{f_n} = 1
  \item \textit{v}_0 = 220 \text{ km/s}
  \item \textit{v}_\text{esc} = 500 \text{ km/s}
  \item q_{\text{Na}} = 0.3
  \item \chi^2 = 249., 72.0
\end{itemize}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{dark_matter_plot.png}
\caption{Dependence on the WIMP velocity distribution}
\end{figure}
Dependence on the WIMP velocity distribution

$k = 3$
$f_p/f_n = 1$
$v_0 = 220 \text{ km/s}$
$v_{\text{esc}} = 500 \text{ km/s}$
$q_{\text{Na}} = 0.3$
$\chi^2 = 250., 72.3$

Farina Pappadopulo Strumia Volansky 1107.0715
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Light WIMPs and annual modulation

For light WIMPs, detectors are probing the tail of the velocity distribution → Larger fractional annual modulation expected

Arisaka et al. 1107.1295
Light WIMPs and annual modulation

For light WIMPs, detectors are probing the tail of the velocity distribution → Larger fractional annual modulation expected

What would reduced annual modulation in the new CoGeNT data mean for the DM interpretation?

Data points: CoGeNT, 1106.0650 (after subtraction of known cosmogenic peaks)
Red curve: Prediction (signal + BG @ best fit) for spin-independent scattering

Extra surface BG = \(0 \text{ keV}^{-1}\text{day}^{-1} \times \exp (-E/0.3\text{keV})\)
(signal fraction in 0.5–1 keV bin = 73%)
**Light WIMPs and annual modulation**

For **light WIMPs**, detectors are probing the **tail of the velocity distribution**

→ **Larger fractional annual modulation expected**

What would **reduced annual modulation** in the **new CoGeNT data** mean for the DM interpretation?

![Plot](image_url)

**Data points:** CoGeNT, 1106.0650 (after subtraction of known cosmogenic peaks)

**Red curve:** Prediction (signal + BG @ best fit) for spin-independent scattering

**Extra surface BG =** $12 \text{ keV}^{-1}\text{day}^{-1} \times \exp\left( - E / 0.3\text{keV}\right)$

(signal fraction in 0.5–1 keV bin = 46%)
Light WIMPs and annual modulation

For light WIMPs, detectors are probing the tail of the velocity distribution → Larger fractional annual modulation expected

What would reduced annual modulation in the new CoGeNT data mean for the DM interpretation?

Data points: CoGeNT, 1106.0650 (after subtraction of known cosmogenic peaks)  
Red curve: Prediction (signal + BG @ best fit) for spin-independent scattering

Extra surface BG = 24 keV$^{-1}$day$^{-1}$ × exp (− $E/0.3$keV)  
(signal fraction in 0.5–1 keV bin = 30%)
Light WIMPs and annual modulation

For light WIMPs, detectors are probing the tail of the velocity distribution → Larger fractional annual modulation expected

What would reduced annual modulation in the new CoGeNT data mean for the DM interpretation?

Plot based on Fox JK Lisanti Weiner 1107.0717 and JK Schwetz Zupan 1110.2721

Data points: CoGeNT, 1106.0650 (after subtraction of known cosmogenic peaks)
Red curve: Prediction (signal + BG @ best fit) for spin-independent scattering

When surface backgrounds are accounted for, reduced modulation in CoGeNT would make the data more consistent with a WIMP hypothesis
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Neutrinos as WIMP impostors

Solar neutrinos are a well-known background to future direct DM searches: see e.g. Gütlein et al. arXiv:1003.5530

\[
\frac{d\sigma_{\text{SM}}(\nu N \rightarrow \nu N)}{dE_r} = \frac{G_F^2 m_N F^2(E_r)}{2 \pi E^2_{\nu}} \left[ A^2 E^2_{\nu} + 2AZ(2E^2_{\nu}(s^2_w - 1) - E_r m_N s^2_w) + 4Z^2(E^2_{\nu} + s^4_w(2E^2_{\nu} + E^2_r - E_r(2E_{\nu} + m_N)) + s^2_w(E_r m_N - 2E^2_{\nu})) \right],
\]

Plots from Harnik JK Machado 1202.6073
Neutrinos as WIMP impostors

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\frac{d\sigma_{\text{SM}}(\nu N \rightarrow \nu N)}{dE_r} = \frac{G_F^2 m_N F^2(E_r)}{2\pi E_\nu^2} \left[ A^2 E_\nu^2 + 2AZ(2E_\nu^2(s_w^2 - 1) - E_r m_N s_w^2) + 4Z^2(E_\nu^2 + s_w^4(2E_\nu^2 + E_r^2 - E_r(2E_\nu + m_N)) + s_w^2(E_r m_N - 2E_\nu^2)) \right],
\]

SM signal will only become sizeable in multi-ton detectors

But: New physics can enhance the rate

⇒ New \( \nu \) physics can be confused with a dark matter signal

⇒ DM detectors can search for new physics in the \( \nu \) sector
Enhanced neutrino scattering from BSM physics

Harnik JK Machado 1202.6073

Enhanced scattering at low $E_r$ for light $A'$

Negligible compared to SM scattering at energies probed in dedicated neutrino experiments

Various mechanisms for daily and annual modulation  Pospelov 1103.3261, Harnik JK Machado 1202.6073

A: $\nu$ magnetic moment

B, C, D: kinetically mixed $A' +$ sterile $\nu_S$:

$$
\mathcal{L} \ni -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} \epsilon F'_{\mu\nu} F^{\mu\nu} + \bar{\nu}_S i \phi \nu_S + g' \bar{\nu}_S \gamma^\mu \nu_S A'_\mu - (\nu_L)^c m_{\nu_L} \nu_L - (\nu_S)^c m_{\nu_S} \nu_S - (\nu_L)^c m_{\text{mix}} \nu_S
$$

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Enhanced neutrino scattering from BSM physics

Enhanced scattering at low $E_r$ for light $A'$

Negligible compared to SM scattering at energies probed in dedicated neutrino experiments

Various mechanisms for daily and annual modulation

- A: $\nu$ magnetic moment
- B, C, D: kinetically mixed $A'$ + sterile $\nu_S$

- B: $U(1)_{B-L}$ boson
- C: kinetically mixed $U(1)' +$ sterile $\nu$
- D: $U(1)_B +$ sterile $\nu$ charged under $U(1)_B$

Pospelov 1103.3261, Harnik JK Machado 1202.6073

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Summary and conclusions

- Several intriguing experimental hints for $\lesssim 10 \text{ GeV}$ DM
- Theoretical motivation in asymmetric DM scenarios, but can be accommodated in many popular DM models
- Direct detection of light dark matter requires new experimental techniques
- Currently, data from different experiments contradict each other
  - CoGeNT, DAMA, CRESST see unexplained signals
  - Strong exclusion from Xenon-100, CDMS, ... (under standard assumptions)
  - Note: Reduced modulation removes tension within the CoGeNT data
- Ways out:
  - Material-dependent scattering cross sections? (isospin-violating DM, inelastic DM)
  - New physics in the neutrino sector can fake WIMP signals
Thank you!
Bonus slides
Example: A model with a 4th neutrino

Introduce a 4th neutrino $\nu_s$ and a light $U(1)'$ gauge boson $A'$ (hidden photon)

- $\nu_s$ charged under $U(1)' \rightarrow$ direct coupling to $A'$
- SM particles couple to $A'$ only through kinetic mixing

$$\mathcal{L} \ni -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} \epsilon F'_{\mu\nu} F^{\mu\nu} + \bar{\nu}_s i \gamma_5 \nu_s + g' \bar{\nu}_s \gamma^\mu \nu_s A'_\mu$$

$$- (\bar{\nu}_L)^c m_{\nu_L} \nu_L - (\bar{\nu}_s)^c m_{\nu_s} \nu_s - (\bar{\nu}_L)^c m_{\text{mix}} \nu_s$$

A small fraction of solar neutrinos can oscillate into $\nu_s$

$\nu_s$ scattering cross section in the detector given by

$$\frac{d\sigma_{A'}(\nu_s e \rightarrow \nu_s e)}{dE_r} = \frac{\epsilon^2 e^2 g' m_e}{4\pi p_{\nu}^2 (M_{A'}^2 + 2E_r m_e)^2} \left[2E_\nu^2 + E_r^2 - 2E_r E_\nu - E_r m_e - m_\nu^2 \right]$$
Temporal modulation of neutrino signals

Signals of new light force mediators and/or sterile neutrinos can show seasonal modulation:

- The Earth–Sun distance: Solar neutrino flux **peaks in winter.**
Temporal modulation of neutrino signals

Signals of **new light force mediators** and/or **sterile neutrinos** can show seasonal modulation:

- The **Earth–Sun distance**: Solar neutrino flux **peaks in winter**.
- **Active–sterile neutrino oscillations**: For oscillation lengths $\lesssim 1$ AU, sterile neutrino appearance depends on the time of year.

---

**Modulation fraction**

$\frac{R_{\text{jun}} - R_{\text{Dec}}}{R_{\text{jun}} + R_{\text{Dec}}}$

- $-1...-0.2$
- $-0.2...-0.1$
- $-0.1...-0.05$
- $-0.05...-0.02$
- $-0.02...0$
- $0...0.02$
- $0.02...0.05$
- $0.05...0.1$
- $0.1...0.2$
- $0.2...1$

Harnik JK Machado, arXiv:1202.6073
Temporal modulation of neutrino signals

Signals of new light force mediators and/or sterile neutrinos can show seasonal modulation:

- **The Earth–Sun distance**: Solar neutrino flux peaks in winter.
- **Active–sterile neutrino oscillations**: For oscillation lengths $\lesssim 1$ AU, sterile neutrino appearance depends on the time of year.
- **Sterile neutrino absorption**: For strong $\nu_s-A'$ couplings and not-too-weak $A'$–SM couplings, sterile neutrino cannot traverse the Earth. → lower flux at night. And nights are longer in winter.
Temporal modulation of neutrino signals

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- **Sterile neutrino absorption**: For strong $\nu_s-A'$ couplings and not-too-weak $A'$–SM couplings, sterile neutrino cannot traverse the Earth. → lower flux at night. And nights are longer in winter.
- **Earth matter effects**: An MSW-type resonance can lead to modified flux of certain neutrino flavors at night. And nights are longer in winter.
Hidden photons

\[ \mathcal{L} \supset -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} \epsilon F'_{\mu\nu} F^{\mu\nu} + \bar{\nu}_s i \gamma^\mu \nu_s + g' \bar{\nu}_s \gamma^\mu \nu_s A'_\mu \]

Constraints from Jaeckel Ringwald 1002.0329, Redondo 0801.1527, Bjorken Essig Schuster Toro 0906.0580, Dent Ferrer Krauss 1201.2683, Harnik JK Machado 1202.6073