Direct dark matter searches: status and implications

Paolo Gondolo
University of Utah
Direct WIMP searches

• The forbidden fruit
• Confusion of the mind
• Treason and murder
• That which does not kill us makes us stronger
The forbidden fruit
One naturally obtains the right cosmic density of WIMPs

*Thermal production in hot primordial plasma.*

One can experimentally test the WIMP hypothesis

*The same physical processes that produce the right density of WIMPs make their detection possible.*

- 524 ± 94 pJ/m³ dark energy
- 202 ± 5 pJ/m³ cold dark matter
- 37.2 ± 0.5 pJ/m³ ordinary matter
- 1 to 5 pJ/m³ neutrinos
- 0.04175 ± 0.00004 pJ/m³ photons
- 0.0417 ± 0.00004 pJ/m³ photons
The power of the WIMP hypothesis
Galactic dark matter

Our galaxy is inside a halo of dark matter particles

1 kpc = $2.06 \times 10^{11}$ AU

Image by R. Powell using DSS data
The principle of direct detection

Dark matter particles that arrive on Earth scatter off nuclei in a detector

Goodman, Witten 1985
Direct dark matter searches

- XMASS (800 kg LXe, Kamioka, 2011-)
- SuperCDMS (25 kg Ge, Soudan, 2012-)
- LUX (350 kg LXe, Homestake, 2012-)
- DarkSide (50 kg LAr, Gran Sasso, 2012-)
- COUPP (60 kg CF₃I, SNOLab, 2012-)
- XENON-1T (1 ton LXe, Gran Sasso, 2014-)
- EURECA, DARWIN, ....
Background discrimination

Finding the dark matter particles is a fight against background

From Sanglard 2005
DM Direct Search Progress Over Time (2009)

Gaitskell 2009

Dark Matter, Sept 2007
Rick Gaitskell, Brown University, DOE

DM Direct Search Progress Over Time (2009)

Searches Past, Present & Future

Limit Scalar Cross-section cm² [60 GeV WIMP]

10^{-40} 10^{-41} 10^{-42} 10^{-43} 10^{-44} 10^{-45} 10^{-46}


σ=10^{-48} LZ 20t

Gaitskell 2009
Direct WIMP searches

First publication of an underground experimental search for WIMP cold dark matter (Ahlen et al 1987)

33 kg-days

Sensitivity ~100 Events / kg / day

1 cts/keVee/kg/day

0.8 kg Ge ionization detector at Homestake Mine, SD
Direct WIMP searches

**Platonic ideal:** a simple binary indicator that only registers dark-matter-induced nuclear recoils and nothing else

“Almost there with COUPP” (Gaitskell at IDM2014)

**COUPP-60**

- Filled with 37 kg of CF$_3$I on April 26, 2013
- First bubble May 1, 2013 (radon decay)
- Installation completed May 31, 2013

- ~3000 kg-days of exposure between 9 and 25 keV threshold
- >1500 neutron source events
- Ultimate goal of 3 year run (50000 kg-days exposure)
Direct WIMP searches

Background (electron recoil)

- Reduction in Backgrounds
  - Electron Recoil Events

LUX-ZEPLIN (Xe 5.6 Tonne Fid.)

pp solar dominates

Thanks to David Malling, Brown, for preparing slide.
Expected event rate is small

Expected WIMP spectrum

Mass = 20 GeV
\( \sigma_{N,SI} = 10^{-45} \, \text{cm}^2 \)
10 zeptobarn

\(~1 \text{ event/kg/year} \)
(nuclear recoils)
Expected event rate is small

Mass = 20 GeV
\( \sigma_{N,SI} = 10^{-45} \text{ cm}^2 \)

~1 event/kg/year (nuclear recoils)

\( \sim 100 \text{ events/kg/second} \) (electron recoils)
Expected event rate is small

**Expected WIMP spectrum**

**Measured banana spectrum**

“**NO BANANAS IN THE LAB**”

(Feliciano-Figueroa)

\( \approx 1 \) event/kg/year
(nuclear recoils)

\( \approx 100 \) events/kg/second
(electron recoils)
Confusion of the mind
Evidence for light dark matter particles?

Bernabei et al (DAMA) 1997-10

An annually modulated...

Aalseth et al (CoGeNT) 2011

......and unmodulated

Collar (CoGeNT) 2013

Agnese et al (CDMS) 2013

Unexplained

Anglehor et al (CRESST) 2011
Evidence for light dark matter particles?

No significant modulation

Same target material

Ahmed et al (CDMS) 1203.1309

Not so many events

Adapted from Aprile et al (XENON-100) 2012
Evidence for light dark matter particles?

3 events in CDMS-Si

A model of our known backgrounds, including both neutron calibration multiple scattering events, was used to improve the response to WIMPs by shifting the upper limit parallel to the mass axis by a factor of 2. Below 20 GeV/cm², which would weaken the upper limit slightly. The reconstructed energy may be 10% lower than the true reconstructed energy.

In our letter, the 90% CL exclusion limits presented in Fig. 3 were incorrect, due to a software bug. The corrected limit calculation is in good agreement with the work of [1] if we make the same astrophysical assumptions.

In our analysis, neutron calibration multiple scattering events shift the limits parallel to the mass axis by a factor of 2. Below 20 GeV/cm², which would weaken the upper limit slightly. The reconstructed energy may be 10% lower than the true energy.

The correction will increase the significance of the current result and will also add an upper limit at 20 GeV/cm². Furthermore, a weak signal could be interpreted as evidence for WIMP dark matter models. We compute an updated surface-event leakage estimate [23], multiple-scatter events below the electron recoils, and WIMP-search data were used as inputs to this model. The final model predicts an updated surface-event leakage estimate [23]. Multiple-scatter events below the electron recoil energy may be 10% lower than the true reconstructed energy.

We are completing the calibration of the nuclear recoil energy for each detector and experimental run for each of the 8 Si detectors used in this analysis. Furthermore, as in the Ge analysis, we developed a Bayesian estimate of the rate of misidentified surface events based on a p-value of 68%, while the background-only hypothesis has a p-value of 0.19%.

In order to constrain the available parameter space in a p-value of 68%, while the background-only hypothesis has a p-value of 0.19%, we do not believe this result rises to the level of a discovery. This study indicates that our background-only hypothesis with a p-value of 0.19%.

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DM-nucleus elastic scattering

\[
\text{(event rate)} = \text{(detector response)} \times \text{(particle physics)} \times \text{(astrophysics)}
\]
Detector response model

\[
\begin{align*}
\text{(event rate)} &= \left( \text{detector response} \right) \times \left( \text{particle physics} \right) \times \left( \text{astrophysics} \right) \\
\text{(detector response)} &= G(E, E_R)
\end{align*}
\]

**Is a nuclear recoil detectable?**

Counting efficiency, energy resolution, scintillation response, etc.

Probability of detecting an event with energy (or number of photoelectrons) \( E \), given an event occurred with recoil energy \( E_R \).
Detector response model

\[
\begin{pmatrix}
\text{event rate} \\
\end{pmatrix}
= \begin{pmatrix}
\text{detector response} \\
\end{pmatrix} \times \begin{pmatrix}
\text{particle physics} \\
\end{pmatrix} \times \begin{pmatrix}
\text{astrophysics} \\
\end{pmatrix}
\]

A common model for $G(E, E_R)$ is a Gaussian with mean value

\[
E = Q E_R
\]

and standard deviation equal to the energy resolution (but there are exceptions, e.g., the XENON experiments)
Detector response model

\[
\frac{\text{event rate}}{\text{detector response}} = \frac{\text{detector response}}{\text{particle physics}} \times (\text{astrophysics})
\]

Compilation of measurements of the quenching factor $Q$ in germanium

Lin et al (TEXONO) 2007
Detector response model

\[
\text{(event rate)} = \text{(detector response)} \times \text{(particle physics)} \times \text{(astrophysics)}
\]

Compilation of measurements of the light efficiency factor \(L_{\text{eff}}\) in liquid xenon

\[
Q = \left( \frac{S_{\text{nr}}}{S_{\text{ee}}} \right) L_{\text{eff}}
\]

New preliminary measurements by LUX down to 2 keVnr

Aprile et al (XENON100), 1104.2549
Particle physics model

\[
\text{event rate} = \text{detector response} \times \text{particle physics} \times \text{astrophysics}
\]

What force couples dark matter to nuclei?

Coupling to nucleon number density, nucleon spin density, ...

- **WIMP speed**
- **WIMP mass**
- **WIMP-nucleus cross section**: spin-independent, spin-dependent, electric, magnetic, ...
- **Nucleus recoil energy**

\[
\begin{align*}
\text{(particle physics)} &= \frac{v^2}{m} \frac{d\sigma}{dE_R} \\
\end{align*}
\]
Particle physics model

\[
\begin{align*}
\left( \frac{\text{event}}{\text{rate}} \right) &= \left( \text{detector \ response} \right) \times \left( \text{particle \ physics} \right) \times \left( \text{astrophysics} \right)
\end{align*}
\]

Spin-independent

\[
\frac{d\sigma_{SI}}{dE_R} = \frac{2m}{\pi v^2} \left| Z f_p + (A - Z) f_n \right|^2 \left| F(E_R) \right|^2
\]

Effective four-particle vertices

Nuclear density form factor
Particle physics model

\[
\begin{pmatrix}
\text{(event)} \\
\text{rate}
\end{pmatrix} = \begin{pmatrix}
\text{(detector)} \\
\text{response}
\end{pmatrix} \times \begin{pmatrix}
\text{(particle)} \\
\text{physics}
\end{pmatrix} \times \text{(astrophysics)}
\]

Spin-dependent

\[
\frac{d\sigma_{SD}}{dE_R} = \frac{16mG_F^2}{(2J + 1)v^2} \left[ a_p^2 S_{pp}(q) + a_p a_n S_{pn}(q) + a_n^2 S_{nn}(q) \right]
\]

Effective four-particle vertices

\[
\begin{align*}
\chi \\
p \\
\times
\end{align*}
\times
\begin{align*}
\chi \\
p \\
2\sqrt{2}G_F a_p \vec{\sigma}_p \cdot \vec{\sigma}_\chi
\end{align*}
\times
\begin{align*}
\chi \\
n \\
2\sqrt{2}G_F a_n \vec{\sigma}_n \cdot \vec{\sigma}_\chi
\end{align*}
\]

Nuclear spin structure functions
Astrophysics model

\[
\begin{pmatrix}
\text{(event rate)} \\
\end{pmatrix} = \begin{pmatrix}
\text{(detector response)} \\
\end{pmatrix} \times \begin{pmatrix}
\text{(particle physics)} \\
\end{pmatrix} \times \begin{pmatrix}
\text{(astrophysics)} \\
\end{pmatrix}
\]

How much dark matter comes to Earth?

Local halo density

\[
\text{(astrophysics)} = \eta(v_{\text{min}}, t) \equiv \rho_X \int_{v > v_{\text{min}}} \frac{f(v, t)}{v} \, d^3v
\]

Velocity distribution

Minimum WIMP speed to impart recoil energy \(E_R\)

\[
v_{\text{min}} = \frac{ME_R/\mu + \delta}{\sqrt{2ME_R}}
\]
Annual modulation

\[ \eta(v_{\text{min}}, t) = \eta_0(v_{\text{min}}) + \eta_1(v_{\text{min}}) \cos(\omega t + \varphi) \]

\[ \frac{dR}{dE} = S_0(E) + S_1(E) \cos(\omega t + \varphi) \]

Unmodulated signal

Modulation amplitude

Drukier, Freese, Spergel 1986
Astrophysics model: velocity distribution

Standard Halo Model

The spherical cow of direct WIMP searches

\[
f(v) = \begin{cases} 
  \frac{1}{N_{\text{esc}} \pi^{3/2} \bar{v}_0^3} e^{-|v + v_{\text{obs}}|/\bar{v}_0^2} & |v| < v_{\text{esc}} \\
  0 & \text{otherwise}
\end{cases}
\]
Current limits and ultimate reach for direct dark matter searches (2014)
Direct dark matter searches (2014)

Spin-dependent

Aprile et al (XENON100) 2013, Oberlack at IDM2014
Treason and murder
DAMA modulation

The measured modulation amplitudes (A), period (T) and phase (t₀) from the single-hit residual rate vs time

<table>
<thead>
<tr>
<th>DAMA/NaI+DAMA/LIBRA-phase1</th>
<th>A (cpd/kg/keV)</th>
<th>T = 2π/ω (yr)</th>
<th>t₀ (day)</th>
<th>C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2-4) keV</td>
<td>0.0190 ± 0.0020</td>
<td>0.996 ± 0.0002</td>
<td>134 ± 6</td>
<td>9.5σ</td>
</tr>
<tr>
<td>(2-5) keV</td>
<td>0.0140 ± 0.0015</td>
<td>0.996 ± 0.0002</td>
<td>140 ± 6</td>
<td>9.3σ</td>
</tr>
<tr>
<td>(2-6) keV</td>
<td>0.0112 ± 0.0012</td>
<td>0.998 ± 0.0002</td>
<td>144 ± 7</td>
<td>9.3σ</td>
</tr>
</tbody>
</table>

Comparison between single hit residual rate (red points) and multiple hit residual rate (green points): Clear modulation in the single hit events; No modulation in the residual rate of the multiple hit events 

A = (0.0005 ± 0.0004) cpd/kg/keV

This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9.2σ C.L.
DAMA modulation

Model Independent Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1  Total exposure: 487526 kg×day = 1.33 ton×yr

- No modulation above 6 keV
- No modulation in the whole energy spectrum
- No modulation in the 2-6 keV multiple-hit events

\[ R(t) = S_0 + S_m \cos(\omega(t - t_0)] \]

here \( T = \frac{2 \pi}{\omega} = 1 \text{ yr} \) and \( t_0 = 152.5 \text{ day} \)

\[ \Delta E = 0.5 \text{ keV bins} \]

No systematics or side processes able to quantitatively account for the measured modulation amplitude and to simultaneously satisfy the many peculiarities of the signature are available.
DAMA modulation

Model Independent Annual Modulation Result

“Public? What does it mean?”

Pierluigi Belli at IDM2014

amplitude and to simultaneously satisfy the many peculiarities of the signature are available.
CoGeNT made their data public

Annual modulation in 3.4 yr of CoGeNT

Annual modulation exclusively at low energy and for bulk events.

Best-fit phase consistent with DAMA/LIBRA

Unoptimized frequentist analysis yields $\sim2.2\sigma$ preference over null hypothesis

Modulation amplitude is 4-7 times larger than in the standard halo model
CoGeNT made their data public

CoGeNT decided to publish energy and time of their events

Independent groups reanalyzed the CoGeNT data

*Pulse-shape discrimination of surface/bulk events*

No significant modulation found

The CoGeNT region of interest results from a biased analysis, and has no statistical meaning.

*Davis, McCabe, Boehm 1405.0495*

The likelihood gets worse when including a WIMP component either as a standard halo or Sagittarius like stream

*Bellis, Collar, Field, Kelso at IDM2014*
The likelihood gets worse when including a WIMP component either as a standard halo or Sagittarius like stream

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Maximum Likelihood Signal Extraction Method Applied to 3.4 years of CoGeNT Data

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(CoGeNT Collaboration)

arXiv:1401.6234v1 24 Jan 2014

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arXiv:1401.6234v2 27 Jan 2014

Bellis Collar, Field, Kelso at IDM2014
News from CRESST

Results from the CRESST-II upgrade

Strauss at IDM2014

Results from 29kg-days of TUM-40

CRESST low-mass WIMP solution completely ruled out by new CRESST
That which does not kill us makes us stronger
All particle physics models

Write down and analyze all possible WIMP-nucleus currents
Recoil spectrum

The recoil spectrum (scattering rate per unit target mass)

\[
\frac{dR}{dE_R} = \frac{1}{m_T m_\chi} \int_{v > v_{\text{min}}} v^2 \frac{d\sigma}{dE_R} \frac{f(v)}{v} d^3v
\]
Recoil spectrum

The recoil spectrum (scattering rate per unit target mass)

\[
\frac{dR}{dE_R} = \frac{1}{m_T m_\chi} \rho_\chi \int_{v>v_{\text{min}}} v^2 \frac{d\sigma}{dE_R} \frac{f(v)}{v} d^3v
\]

Traditionally, \( v^2 \frac{d\sigma}{dE_R} = \text{const} \times \) (nuclear form factor), with the same coupling to protons and neutrons (spin-independent case)

\[
\frac{dR}{dE_R} = \frac{A^2 F^2(E_R)}{2 \mu_{\chi p}^2} \tilde{\eta}(v_{\text{min}})
\]

with \( \tilde{\eta}(v_{\text{min}}) = \frac{\sigma_{\chi p}}{m_\chi} \eta(v_{\text{min}}) = \sigma_{\chi p} \rho_\chi \frac{1}{m_\chi} \int_{v_{\text{min}}}^\infty \frac{f(v)}{v} d^3v \)
Recoil spectrum

The recoil spectrum (scattering rate per unit target mass)

\[
\frac{dR}{dE_R} = \frac{1}{m_T m_\chi} \int_{v>v_{\text{min}}} v^2 \frac{d\sigma}{dE_R} \frac{f(v)}{v} d^3v
\]

In trying to explain the data, modify the cross section

– set different couplings to neutrons and protons ("isospin-violating")

– put additional velocity or energy dependence in \( v^2 \frac{d\sigma}{dE_R} \)

or modify the velocity distribution.
Isospin-violating (nonisoscalar) dark matter

Spin-independent couplings to protons stronger than to neutrons may allow modulation signals compatible with other null searches.

Kurylov, Kamionkowski 2003; Giuliani 2005; Cotta et al 2009; Chang et al 2010; Kang et al 2010; Feng et al 2011; Del Nobile et al 2011; ..... 

The coupling $N f_n + Z f_p \approx 0$ for $f_n/f_p \approx -Z/N$.

Why $f_n/f_p = -0.7$ suppresses the coupling to Xe.
### Particle physics model

Energy and/or velocity dependent scattering cross sections

<table>
<thead>
<tr>
<th>nucleus</th>
<th>DM</th>
<th>$\nu^2 \frac{d\sigma}{dE_R}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>light mediator</td>
</tr>
<tr>
<td>“charge”</td>
<td>“charge”</td>
<td>$1/E_R^2$</td>
</tr>
<tr>
<td>“charge”</td>
<td>dipole</td>
<td>$1/E_R$</td>
</tr>
<tr>
<td>dipole</td>
<td>dipole</td>
<td>const + $E_R/\nu^2$</td>
</tr>
</tbody>
</table>

All terms may be multiplied by nuclear or DM form factors $F(E_R)$

See e.g. Barger, Keung, Marfatia 2010; Fornengo, Panci, Regis 2011; An et al 2011
the various new nuclear responses, with an emphasis on their relative strength at di
different positions. In section 4, we give an overview of the theory given our assumptions. In section 3, we discuss the relevant nuclear physics, and in section 2, we mention the possible nuclear response function in a partial wave limit for some commonly used elements, however, it is useful to have a heuristic description of what sort of nuclear responses these operators illicit when DM couples to the nucleus.

Particularly a completely model independent treatment of the experiments requires data on the net angular-momentum of a nucleon (either longitudinally or transversely with respect to the momentum transfer) components of the nucleon spin.

Experimentally, the relevant question is whether DM interacts with nucleons. In particular, we thoroughly analyze the possible nuclear response function in a partial wave formalism, with an emphasis on the relative strength at different positions. In addition, there are T-violating operators that can contribute to the coupling of DM to elements with unpaired nucleons, occupying an orbital shell with non-zero angular momentum.

Local quantum field theory, CP-violation is equivalent to T-violation, so let us first consider the case of particles of spin one or less (i.e. at most quadratic in either longitudinal or transverse components of nucleon spin). All particle physics models are parity violating. In addition, there are T-violating operators that can contribute to the coupling of DM to elements with unpaired nucleons, occupying an orbital shell with non-zero angular momentum.

Finally, a completely model independent treatment of the experiments requires data on the net angular-momentum of a nucleon (either longitudinally or transversely with respect to the momentum transfer) components of the nucleon spin. All particle physics models are parity violating. In addition, there are T-violating operators that can contribute to the coupling of DM to elements with unpaired nucleons, occupying an orbital shell with non-zero angular momentum.

All particle physics models

All short-distance operators classified

\begin{align*}
1, \quad & S_N \cdot S, \quad v^2, \quad \iota (S_N \times q) \cdot v, \quad iv \cdot (\bar{S}_N \times \bar{q}), \quad \bar{v} \cdot (\bar{S}_N \times \bar{q}), \quad \bar{S}_N \cdot \bar{q}, \quad \iota \bar{S}_N \cdot \bar{q}, \quad \iota S_N \cdot \bar{q}, \\
& \bar{v}^\perp \cdot \bar{S}_N, \quad \bar{v}^\perp \cdot \bar{S}_N, \quad \iota \bar{S}_N \cdot (\bar{S}_N \times \bar{q}). \quad (\iota \bar{S}_N \cdot \bar{q})(\bar{v}^\perp \cdot \bar{S}_N), \quad (\iota \bar{S}_N \cdot \bar{q})(\bar{v}^\perp \cdot \bar{S}_N).
\end{align*}

All nuclear form factors classified

<table>
<thead>
<tr>
<th>Response $\times \left[ \frac{4\pi}{2J+1} \right]^{-1}$</th>
<th>Leading Multipoles $M_{0M}$</th>
<th>Long-wavelength Limit $\bar{M}_{1M}$</th>
<th>Response Type $M_{JM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sum_{J=0,2,\ldots}^\infty</td>
<td>\langle J_i</td>
<td></td>
<td>M_{JM}</td>
</tr>
<tr>
<td>$\sum_{J=1,3,\ldots}^\infty</td>
<td>\langle J_i</td>
<td></td>
<td>\Sigma_{JM}</td>
</tr>
<tr>
<td>$\sum_{J=1,3,\ldots}^\infty</td>
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<td>\Sigma_{JM}</td>
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<td>\Phi_{JM}</td>
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<tr>
<td>$\sum_{J=0,2,\ldots}^\infty</td>
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<td></td>
<td>\Phi_{JM}</td>
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<tr>
<td>$\sum_{J=2,4,\ldots}^\infty</td>
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<tr>
<td>$\sum_{J=2,4,\ldots}^\infty</td>
<td>\langle J_i</td>
<td></td>
<td>\Phi_{JM}</td>
</tr>
</tbody>
</table>

nuclear oscillator model

Fitzpatrick et al 2012
All particle physics models

Combined analysis of short-distance operators

Catena, Gondolo 2014

Profile-likelihood global analysis

LUX

$m = 10$ TeV

\begin{align*}
\mathcal{O}_1 &= 1_X^1 N \\
\mathcal{O}_3 &= -i \tilde{S}_N \cdot \left( \frac{\bar{q}}{m_N} \times \bar{u}_{XN} \right) \\
\mathcal{O}_4 &= \tilde{S}_X \cdot \tilde{S}_N \\
\mathcal{O}_5 &= -i \tilde{S}_X \cdot \left( \frac{\bar{q}}{m_N} \times \bar{u}_{XN} \right) \\
\mathcal{O}_6 &= \left( \tilde{S}_X \cdot \frac{\bar{q}}{m_N} \right) \left( \tilde{S}_N \cdot \frac{\bar{q}}{m_N} \right) \\
\mathcal{O}_7 &= \tilde{S}_N \cdot \bar{u}_{XN} \\
\mathcal{O}_8 &= \tilde{S}_X \cdot \bar{u}_{XN} \\
\mathcal{O}_9 &= -i \tilde{S}_X \cdot \left( \tilde{S}_N \times \frac{\bar{q}}{m_N} \right) \\
\mathcal{O}_{10} &= -i \tilde{S}_N \cdot \frac{\bar{q}}{m_N} \\
\mathcal{O}_{11} &= -i \tilde{S}_X \cdot \frac{\bar{q}}{m_N} \\
\end{align*}
Astrophysics-independent approach

Compare experiments without assuming a local WIMP density or velocity distribution
Our galaxy is inside a halo of dark matter particles

1 kpc = 2.06×10^{11} AU
Conclusions

- The latest constraints on the local dark matter density give:
  
- Comparing these with the rotation curve implies a near-spherical MW halo at ~8kpc, little dark disc, and a quiescent merger history.

- We have searched for stars accreted along with the dark disc, finding none so far; this supports the "quiescent MW" scenario.

- Gaia will move us into the realm of truly precise measurements of the Local Dark Matter Density.

\[
\rho_{dm} = 0.33^{+0.26}_{-0.075} \text{ GeV cm}^{-3}
\]

\[
\rho_{dm} = 0.25 \pm 0.09 \text{ GeV cm}^{-3}
\]

[volume complete; G12*, R14] [SDSS; Z13]
Astrophysics model: velocity distribution

We know very little about the dark matter velocity distribution near the Sun

Cosmological N-Body simulations including baryons are challenging
The usual approach

\[
\left( \frac{\text{event}}{\text{rate}} \right) = \left( \frac{\text{detector}}{\text{response}} \right) \times \left( \frac{\text{particle}}{\text{physics}} \right) \times \left( \frac{\text{astrophysics}}{\text{physics}} \right)
\]

\text{FIXED} \quad \text{FIXED}

Agnese et al (SuperCDMS) 2014
Astrophysics-independent approach

\[
\frac{\text{event rate}}{\text{detector response}} = \frac{\text{particle physics}}{\text{astrophysics}}
\]

\[
\eta(v_{\text{min}}) = \int_{v_{\text{min}}}^{\infty} \frac{f(v)}{v} \, d^3v
\]

Fox, Liu, Wiener 2011; Gondolo, Gelmini 2012; Del Nobile, Gelmini, Gondolo, Huh 2013-14
Astrophysics-independent approach

Rescaled astrophysics factor

$$\frac{\rho_\chi \sigma_{\chi p}}{m_\chi} \int_{v_{\text{min}}}^{\infty} \frac{f(v)}{v} dv$$

CoGeNT to DAMA with Q = 0.3, $m_\chi = 7$ GeV

$\Delta g(v_{\text{min}})$ [day$^{-1}$]

Fox, Kopp, Lisanti, Weiner 2011

$\Delta g(v_{\text{min}})$ [day$^{-1}$]

$m_\chi = 9$ GeV

Fox, Liu, Weiner 2011

Frandsen et al 2011
### Astrophysics-independent approach

**Recoil energy**

\[
\tilde{\eta}(v_{\text{min}}) = \sigma_{\chi p} \frac{\rho \chi}{m_\chi} \int_{v_{\text{min}}}^{\infty} \frac{f(v)}{v} d^3v
\]

**Rescaled astrophysics factor common to all experiments**

\[
\tilde{\eta}(v_{\text{min}}) = \sigma_{\chi p} \frac{\rho \chi}{m_\chi} \int_{v_{\text{min}}}^{\infty} \frac{f(v)}{v} d^3v
\]

**Minimum WIMP speed**

\[
v_{\text{min}} = \sqrt{\frac{m_T E_R}{2 \mu_T^2}}
\]

**Recoil energy**

\[
\tilde{\eta}(v_{\text{min}}) = \sigma_{\chi p} \frac{\rho \chi}{m_\chi} \int_{v_{\text{min}}}^{\infty} \frac{f(v)}{v} d^3v
\]

**Maxwellian**

\[
e^{-\frac{v_{\text{min}}^2}{2 \sigma_v^2}}
\]

**Stream**

\[
\Theta(v_{\text{min}} - v_{\text{stream}})
\]
Astrophysics-independent approach

Extract $\tilde{\eta}(v_{\text{min}})$ from $dR/dE_R$ (both measurements and upper limits).

Fox, Liu, Weiner 2011

$$\tilde{\eta}(v_{\text{min}}) = \frac{2\mu^2_{\chi p}}{A^2 F^2(E_R)} \frac{dR}{dE_R}$$

Alternative approach: solve the recoil rate equation for $f(v)$

Fox, Kribs, Tait 2010

$$\frac{dR}{dE_R} = \frac{1}{m_T} \frac{\rho_{\chi}}{m_\chi} \int_{v>v_{\text{min}}} v^2 \frac{d\sigma}{dE_R} \frac{f(v)}{v} d^3v$$

Requires derivatives of experimentally measured $dR/dE_R$, which is a notoriously unstable procedure.
Astrophysics-independent approach

All these ideas refer to the recoil spectrum $dR/dE_R$, which is not accessible to experiments because of energy-dependent efficiencies and energy resolution, and the fact that often only part of the recoil energy is actually measured.

$$\frac{dR}{dE} = \int_0^\infty G(E, E_R) \frac{dR}{dE_R} dE_R$$

Use quantities accessible to experiments, i.e., include effective energy response function.

Gondolo Gelmini 1202.6359
Astrophysics-independent approach

Include effective energy response function.

Gondolo Gelmini 1202.6359; Del Nobile, Gelmini, Gondolo, Huh 1304.6183, 1306.5273

Change variables:

\[ v_{\text{min}} = \sqrt{\frac{m_T^2 E_R}{2 \mu_T^2}} \]

\[ \tilde{\eta}(v_{\text{min}}) = \sigma_{\text{ref}} \frac{\rho_\chi}{m_\chi} \int_{v_{\text{min}}}^{\infty} \frac{f(v)}{v} d^3v \]

Minimum WIMP speed to impart recoil energy \( E_R \)

Constant reference cross section

Astrophysics factor, same for all direct detection experiments

And integrate over measured energy intervals:

\[ R_{[E_1, E_2]} = \int_{E_1}^{E_2} dE \frac{dR}{dE} \]
Astrophysics-independent approach

Include effective energy response function.

Gondolo Gelmini 1202.6359; Del Nobile, Gelmini, Gondolo, Huh 1304.6183, 1306.5273

• The measured rate is a “weighted average” of the astrophysical factor.

\[ R = \int_0^\infty dv \mathcal{R}(v) \tilde{\eta}(v) \]

• Every experiment is sensitive to a “window in velocity space” given by the response function.

\[ \mathcal{R}[E_1, E_2](v) = \int_{E_1}^{E_2} dE \frac{\partial}{\partial v} \int_0^{2\mu_T^2 v^2/m_T} dE_R \mathcal{G}(E, E_R) \frac{v^2}{\sigma_{\text{ref}} m_T} \frac{d\sigma}{dE_R} \]
Astrophysics-independent approach

Examples of response functions

Del Nobile, Gelmini, Gondolo, Huh 2013
Astrophysics-independent approach

Measure or bound astrophysics factor in velocity interval $[v_1, v_2]$

\[
\tilde{\eta}[v_1, v_2] = \frac{R_{\text{measured}}[E_1, E_2]}{\int_0^\infty R[E_1, E_2](v_{\text{min}}) \, dv_{\text{min}}}
\]

\[
\tilde{\eta}(v) < \frac{R_{\text{upper limit}}[E_1, E_2]}{\int_0^v R[E_1, E_2](v_{\text{min}}) \, dv_{\text{min}}}
\]

Gondolo Gelmini 1202.6359; Del Nobile, Gelmini, Gondolo, Huh 1304.6183, 1306.5273

Include effective energy response function.
Spin-independent isoscalar interactions

\[ \sigma_{\chi A} = A^2 \sigma_{\chi p} \mu_{\chi A}^2 / \mu_{\chi p}^2 \]

Astrophysics-independent approach

Halo modifications alone cannot save the SI signal regions from the Xe and Ge bounds

Still depends on particle model

Del Nobile, Gelmini, Gondolo, Huh 2014
Spin-independent isoscalar interactions

$$\sigma_{\chi A} = A^2 \sigma_{\chi p} \mu_{\chi A}^2 / \mu_{\chi p}^2$$

Halo modifications alone cannot save the SI signal regions from the Xe and Ge bounds

CDMS-Si event rate is similar to yearly modulated rates

Still depends on particle model

Del Nobile, Gelmini, Gondolo, Huh 2014
Spin-independent nonisoscalar interactions

\[ \sigma_{\chi A} = \left[ Z + (A - Z) \frac{f_n}{f_p} \right]^2 \frac{\sigma_{\chi p} \mu_{\chi A}^2}{\mu_{\chi p}^2} \]

Astrophysics-independent approach

Dark matter coupled differently to protons and neutrons may have a slim chance

Still depends on particle model

Del Nobile, Gelmini, Gondolo, Huh 2014
Spin-independent nonisoscalar interactions

\[
\sigma_{\chi A} = \left[ Z + (A - Z) \frac{f_n}{f_p} \right]^2 \frac{\sigma_{\chi p} \mu_{\chi A}^2}{\mu_{\chi p}^2}
\]

Astrophysics-independent approach

Dark matter coupled differently to protons and neutrons may have a slim chance

The CDMS-Si events lie “below” the CoGeNT/DAMA modulation amplitudes

Still depends on particle model

Del Nobile, Gelmini, Gondolo, Huh 2014
In the next episodes
In the next episodes..... More DAMA

DAMA/LIBRA phase2 - running

Quantum Efficiency features

- Q.E. @ peak (%)
- Q.E. @ 420 nm (%)

Second upgrade on end of 2010:
all PMTs replaced with new ones of higher Q.E.

Mean value:
- 7.5%(0.6% RMS)
- 6.7%(0.5% RMS)

Previous PMTs: 5.5-7.5 ph.e./keV
New PMTs: up to 10 ph.e./keV

- To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects
- Special data taking for other rare processes
In the next episodes..... Giant detectors

SuperCDMS, XENON1T, XENONnT, Darwin, .......

Spin-independent sensitivity

Measurement of coherent scattering
In the next episodes..... All interactions

WIMP-nucleus effective theory

- Analyze all WIMP-nucleus currents in the spirit of the 1960’s analysis of weak currents (Haxton)

- Velocity- and momentum-dependent operators

- Expected developments
  - long-distance operators
  - improved nuclear physics
  - improved comparison to data
  - astrophysics-independent analysis
In the next episodes..... WIMP astronomy

• Directional direct detection
  - measure direction of nuclear recoil

• Several R&D efforts
  - DRIFT
  - Dark Matter TPC
  - NEWAGE
  - MIMAC
  - D3
  - Emulsion Dark Matter Search
  - Columnar recombination

Only ~10 events needed to confirm extraterrestrial signal
In the next episodes..... WIMP astronomy

Aberration of WIMPs

Photon arrival direction
20 arcsec

WIMP arrival direction
10 degrees

Bozorgnia, Gelmini, Gondolo 2012
Synopsis

- **The forbidden fruit**
  - *WIMP interaction rates in direct searches are very small.*
  - *No bananas in the lab.*

- **Confusion of the mind**
  - *Some experiments claim WIMP detection while others exclude it.*
  - *The comparison depends heavily on particle astrophysics models.*

- **Treason and murder**
  - *Analysis of CoGeNT’s public data disagrees with official result.*
  - *Improved CRESST-II data reject previous CRESST excess.*

- **That which does not kill us makes us stronger**
  - *Move to consider all possible WIMP-nucleus currents.*
  - *Do not assume any specific dark halo model.*