Introduction to Direct Dark Matter Detection Phenomenology

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Introduction to Direct Dark Matter Detection Phenomenology

Outline

**REVIEW**
Direct Dark Matter detection

**MODEL-INDEPENDENT DATA ANALYSES**
Motivation
Reconstruction of the WIMP velocity distribution
Determination of the WIMP mass
Estimation of the SI WIMP-nucleon coupling
Determinations of ratios of WIMP-nucleon cross sections

**EFFECTS OF RESIDUE BACKGROUND EVENTS**

**AMIDAS PACKAGE AND WEBSITE**

**SUMMARY**
References: direct Dark Matter detection phenomenology

- Velocity distribution


References: direct Dark Matter detection phenomenology

- Mass/SI cross section (maximum likelihood/Bayesian analysis)
References: direct Dark Matter detection phenomenology

- SD cross sections/couplings
References: direct Dark Matter detection phenomenology

- SI and SD cross sections


References: direct Dark Matter detection phenomenology

- **Directional information**


References: our works

- Model-independent data analyses
References: our works

- **Effects of residue background events**
Some words about simulations and phenomenology
Some words about simulations and phenomenology

- In the 1930s Enrico Fermi made some numerical experiments that would now be called Monte Carlo calculations.

  [Monte Carlo Methods, M. H. Kalos and P. A. Whitlock, Chap. 1, p. 3]

- The name Monte Carlo was applied to a class of mathematical methods first by scientists working on the development of nuclear weapons in Los Alamos in the 1940s.

  [Monte Carlo Methods, M. H. Kalos and P. A. Whitlock, Chap. 1, p. 1]

- Relationship between theory, experiment, and numerical simulation: each is distinct, but each is strongly connected to the other two.

Some words about simulations and phenomenology

- Research "triangle"

Theory:
- model building,
- phenomenon predicting

Phenomenology:
- data analyzing,
- model constraining/distinguishing

Experiment:
- detection techniques,
- data taking/analyzing

Simulation:
- data analyzing techniques,
- numerical programming
Some words about simulations and phenomenology

- The process of preparing programs for a digital computer is especially attractive because it not only can be economically and scientifically rewarding, it can also be an aesthetic experience much like composing poetry or music.

  [Donald E. Knuth]

- Numerical methods are an art rather than a science, and acquired as a set of somewhat disconnected methods, clever tricks, and recipes, not as a gloriously complete subject.

- Some of the things I have learnt the hard way through painful experience are given here, in the hope of softening the blow when you meet the same problems.

  [Statistics, B. J. Barlow, Chap. 8, p. 180]
Direct Dark Matter detection
Dark Matter searches

DM should have **small, but non-zero** interactions with SM matter.

⇒ Three different ways to detect DM particles

- **Colliders**
  - $p, e \rightarrow DM, \bar{DM}$

- **Indirect detection**
  - $DM \rightarrow e^+, \bar{p}, \bar{D}$

- **Direct detection**
  - $DM \rightarrow q, \bar{q}$
We start with ...

- direct DM detection (elastic WIMP-nucleus scattering)

  - The event rate depends on
    - the WIMP density near the Earth $\rho_0$
    - the WIMP-nucleus cross sections $\sigma_0^{\text{SI}}$ and $\sigma_0^{\text{SD}}$
    - the WIMP mass $m_\chi$
    - the velocity distribution of incident WIMPs $f_1(v)$

  - The WIMP-nucleus cross section is about $10^{-2} \sim 10^{-6}$ pb
    - the optimistic expected event rate is $\sim 10^{-3}$ events/kg-day
    - but could be $< 1 \text{ event/ton-yr}$

  - An exponential-like recoil energy spectrum
    - Most events would be with energies less than 50 keV.

  - Typical background events due to cosmic rays and ambient radioactivity: signals $\approx \mathcal{O}(10^6) : 1$
We start with ...

- direct detection signals
  - Ionization (charges)
  - Scintillation (light)
  - Heat (phonons)

- Quenching factor
  - Nuclear recoil relative efficiency
  - Measured (electron equivalent) recoil energy $\text{keV}_{ee}$
    $\iff$ true nuclear recoil energy $\text{keV}_r$

- Raw/total mass/exposure
  $\iff$ fiducial mass/exposure

- Combinations of two signals:
  $\implies$ event-by-event background rejection
We start with ...

- **direct detection detectors**
  
  - **Semiconductor/scintillator detectors**
    - Cryogenic
    - Ge, Si, NaI(Tl), CsI(Tl), CaWO₄, TeO₂
  
  - **Liquid noble gas detectors**
    - Single-phase (liquid)
    - Dual-phase (gas-liquid)
    - Xe, Ar, Ne
  
  - **Superheated droplet/gas detectors**
    - Time-projection chamber (TPC)
    - Directional (head-tail) information
    - Xe-CS₂, CF₄, C₃F₈, C₄F₁₀, CF₃I, C₂ClF₅

- For nuclei with \( A \geq 30 \), the SI interaction \( (\propto A^2) \) almost always dominates over the SD interaction.
We start with ...

- direct detection experiments
  - Minimal and maximal cut-off energies $Q_{\text{min, max}}$, $Q_{\text{min, max}, \text{kin}}$
  - Quenching factor $keV_{ee}/keV_r = q(Q)$, energy smearing and resolution
  - Detector materials: Ge ⇐⇒ Si, Xe ⇐⇒ Ar, F ⇐⇒ I
  - Background (discrimination)
  - Excluded/constrained areas on $\sigma_{\chi(p/n)}^{\text{SI/SD}}$ vs. $m_\chi$ planes

We start with ...

- direct detection theory/phenomenology
  - (One-dimensional) velocity distribution function $f(v)$ or $f_1(v)$
  - Local DM density $\rho_0$
  - Escape and the 1-D maximal cut-off velocities $v_{\text{esc}}$ and $v_{\text{max}}$
  - WIMP-nucleon(proton/neutron) couplings
    - SI scalar couplings $f_{(p,n)}$
    - SD axial-vector couplings $a_{(p,n)}$
    - SI vector couplings $b_{(p,n)}$
  - (WIMP-nucleus) scattering form factors $F_{\text{SI}}^2(Q)$ and $F_{\text{SD}}^2(Q)$
  - WIMP mass $m_\chi$ (and mass splitting $\delta$)
We start with ...

- Direct detection theory/phenomenology/experiments
  - **Time-dependence** of the velocity distribution
  - **Annual modulation** of the event rate


- **Diurnal modulation** of the event rate
  - Directionality of the WIMP wind
  - Shielding of the incident WIMP flux by the Earth

We start with ...

- **direct detection theory**
  
  - Predicting **WIMP-nucleon couplings/cross sections**
    
    ![Graph 1](image1)
    ![Graph 2](image2)
    
    [V. Barger, W. Y. Keung, and G. Shaughnessy, PRD 78, 056007 (2008)]

  - Exclusion limits on the (predicted) **WIMP-nucleon cross sections**
    
    ![Graph 3](image3)
    ![Graph 4](image4)
    
    [http://dmtools.berkeley.edu/limitplots/; ZEPLIN Collab., PRL 103, 151302 (2009)]

  - Predicting **velocity distribution function**
We start with ...

- direct detection phenomenology
  - Developing data analysis procedures
  - Constraining/distinguishing particle/astronomical halo models
  - Reconstructing WIMP properties
  - Being combination with and complementarity of indirect DM detection and collider experiments.
  - Packages for Monte-Carlo simulations and/or (real) data analysis
We start with ...

- **direct detection phenomenology**
  - **Exclusion limits on** $\sigma^{SI/SD}_{\chi(p/n)}$ **vs.** $m_\chi$ **planes**
    - S. Yellin
  - **Constraints on** SD WIMP-nucleon couplings
    - D. R. Tovey et al.
    - T. A. Girard and F. Giuliani
  - **Velocity distribution**
    - A. H. G. Peter
    - L. E. Strigari et al.
  - **Maximum likelihood (ML) analysis**
    - A. M. Green and B. Moore
  - **Bayesian + ML analysis**
    - M. Pato et al.
    - J. Billard, F. Mayet, D. Santos et al. (MIMAC Collab.)
  - **Model-independent analysis using the total event rate**
    - P. J. Fox et al.
Model-independent data analyses
Motivation

- **Differential event rate for elastic WIMP-nucleus scattering**

\[
\frac{dR}{dQ} = A F^2(Q) \int_{v_{\text{min}}}^{v_{\text{max}}} \frac{f_1(v)}{v} \, dv
\]

Here

\[
v_{\text{min}} = \alpha \sqrt{Q}
\]

is the minimal incoming velocity of incident WIMPs that can deposit the recoil energy \( Q \) in the detector,

\[
A \equiv \frac{\rho_0 \sigma_0}{2m_\chi m_{r,N}^2}, \quad \alpha \equiv \sqrt{\frac{m_N}{2m_{r,N}^2}}, \quad m_{r,N} = \frac{m_\chi m_N}{m_\chi + m_N}
\]

- \( \rho_0 \): WIMP density near the Earth
- \( \sigma_0 \): total cross section ignoring the form factor suppression
- \( F(Q) \): elastic nuclear form factor
- \( f_1(v) \): one-dimensional velocity distribution of halo WIMPs
Motivation

- Differential event rate for elastic WIMP-nucleus scattering

\[
\frac{dR}{dQ} = \mathcal{A}F^2(Q) \int_{v_{\text{min}}}^{v_{\text{max}}} \left[ \frac{f_1(v)}{v} \right] dv
\]

Here

\[v_{\text{min}} = \alpha \sqrt{Q}\]

is the minimal incoming velocity of incident WIMPs that can deposit the recoil energy \(Q\) in the detector,

\[
\mathcal{A} \equiv \frac{\rho_0 \sigma_0}{2m_\chi m_{r,N}^2}, \quad \alpha \equiv \sqrt{\frac{m_N}{2m_{r,N}^2}}, \quad m_{r,N} = \frac{m_\chi m_N}{m_\chi + m_N}
\]

\(\rho_0\): WIMP density near the Earth
\(\sigma_0\): total cross section ignoring the form factor suppression
\(F(Q)\): elastic nuclear form factor
\(f_1(v)\): one-dimensional velocity distribution of halo WIMPs
Reconstruction of the WIMP velocity distribution

- Normalized one-dimensional WIMP velocity distribution function

\[ f_1(v) = N \left\{ -2Q \cdot \frac{d}{dQ} \left[ \frac{1}{F^2(Q)} \left( \frac{dR}{dQ} \right) \right] \right\}_{Q=v^2/\alpha^2} \]

\[ N = \frac{2}{\alpha} \left\{ \int_0^\infty \frac{1}{\sqrt{Q}} \left[ \frac{1}{F^2(Q)} \left( \frac{dR}{dQ} \right) \right] dQ \right\}^{-1} \]

- Moments of the velocity distribution function

\[ \langle v^n \rangle = N(Q_{\text{thre}}) \left( \frac{\alpha^{n+1}}{2} \right) \left[ \frac{2Q_{\text{thre}}^{(n+1)/2}}{F^2(Q_{\text{thre}})} \left( \frac{dR}{dQ} \right) \right]_{Q=Q_{\text{thre}}} + (n+1)I_n(Q_{\text{thre}}) \]

\[ N(Q_{\text{thre}}) = \frac{2}{\alpha} \left[ \frac{2Q_{\text{thre}}^{1/2}}{F^2(Q_{\text{thre}})} \left( \frac{dR}{dQ} \right) \right]_{Q=Q_{\text{thre}}}^{-1} + I_0(Q_{\text{thre}}) \]

\[ I_n(Q_{\text{thre}}) = \int_{Q_{\text{thre}}}^\infty Q^{(n-1)/2} \left[ \frac{1}{F^2(Q)} \left( \frac{dR}{dQ} \right) \right] dQ \]

[M. Drees and CLS, JCAP 0706, 011 (2007)]
Reconstruction of the WIMP velocity distribution

- **Ansatz:** the measured recoil spectrum in the \( n \)th \( Q \)-bin

\[
\left( \frac{dR}{dQ} \right)_{\text{expt}, \ Q \approx Q_n} = r_n e^{k_n(Q - Q_{s,n})} \quad \quad r_n \equiv \frac{N_n}{b_n}
\]

- **Logarithmic slope and shifted point** in the \( n \)th \( Q \)-bin

\[
Q - Q_n|_n \equiv \frac{1}{N_n} \sum_{i=1}^{N_n} (Q_{n,i} - Q_n) = \left( \frac{b_n}{2} \right) \coth \left( \frac{k_n b_n}{2} \right) - \frac{1}{k_n}
\]

\[
Q_{s,n} = Q_n + \frac{1}{k_n} \ln \left[ \frac{\sinh(k_n b_n/2)}{k_n b_n/2} \right]
\]

- **Reconstructing the one-dimensional WIMP velocity distribution**

\[
f_1(v_{s,n}) = \mathcal{N} \left[ \frac{2Q_{s,n} r_n}{F^2(Q_{s,n})} \right] \left[ \frac{d}{dQ} \ln F^2(Q) \right]_{Q = Q_{s,n}} - k_n
\]

\[
\mathcal{N} = \frac{2}{\alpha} \left[ \sum_a \frac{1}{\sqrt{Q_a} F^2(Q_a)} \right]^{-1} \quad \quad v_{s,n} = \alpha \sqrt{Q_{s,n}}
\]

[M. Drees and CLS, JCAP 0706, 011 (2007)]
Reconstruction of the WIMP velocity distribution

- Reconstructed $f_{1,\text{rec}}(v_s,n)$
  $(^{76}\text{Ge}, \text{500 events}, 5 \text{ bins}, \text{up to 3 bins per window})$

![Graph showing reconstruction of WIMP velocity distribution]

$\chi^2/\text{dof} = 0.73$

- [M. Drees and CLS, JCAP 0706, 011 (2007)]
Determination of the WIMP mass

- Estimating the moments of the WIMP velocity distribution

\[
\langle v^n \rangle = \alpha^n \left[ \frac{2Q_{\text{min}}^{1/2} r_{\text{min}}}{F^2(Q_{\text{min}})} + I_0 \right]^{-1} \left[ \frac{2Q_{\text{min}}^{(n+1)/2} r_{\text{min}}}{F^2(Q_{\text{min}})} + (n+1)I_n \right]
\]

\[
I_n = \sum_a \frac{Q_a^{(n-1)/2}}{F^2(Q_a)}
\]

\[
r_{\text{min}} = \left( \frac{dR}{dQ} \right)_{\text{expt, } Q=Q_{\text{min}}} = r_1 e^{k_1(Q_{\text{min}}-Q_s,1)}
\]

- Determining the WIMP mass

\[
m_{\chi}\big|_{\langle v^n \rangle} = \left( \frac{m_{\chi} m_y}{m_{\chi} m_y} - m_{\chi} R_n \right) \frac{R_n - \sqrt{m_{\chi}/m_y}}}{R_n - \sqrt{m_{\chi}/m_y}}
\]

\[
R_n = \left[ \frac{2Q_{\text{min},X}^{(n+1)/2} r_{\text{min},X}/F_X^2(Q_{\text{min},X}) + (n+1)I_{n,X}}{2Q_{\text{min},X}^{1/2} r_{\text{min},X}/F_X^2(Q_{\text{min},X}) + I_{0,X}} \right]^{1/n}
\]

\[X \rightarrow Y\]^{-1} \quad (n \neq 0)

- Assuming a dominant SI WIMP-nucleus interaction

\[
m_{\chi}\big|_{\sigma} = \left( \frac{m_{\chi} m_y}{m_{\chi} m_y} \right)^{5/2} m_y - m_{\chi} R_{\sigma} \frac{R_{\sigma} - (m_{\chi} m_y)^{5/2}}{R_{\sigma} - (m_{\chi} m_y)^{5/2}}
\]

\[
R_{\sigma} = \frac{\varepsilon_Y}{\varepsilon_X} \left[ \frac{2Q_{\text{min},X}^{1/2} r_{\text{min},X}/F_X^2(Q_{\text{min},X}) + I_{0,X}}{2Q_{\text{min},Y}^{1/2} r_{\text{min},Y}/F_Y^2(Q_{\text{min},Y}) + I_{0,Y}} \right]
\]

[CLS and M. Drees, arXiv:0710.4296]
Determination of the WIMP mass

- $\chi^2$-fitting

$$\chi^2(m_\chi) = \sum_{i,j} (f_{i,x} - f_{i,y}) C_{ij}^{-1} (f_{j,x} - f_{j,y})$$

where

$$f_{i,x} = \alpha^i_X \left[ \frac{2Q_{\min,x}^{(i+1)/2} r_{\min,x} / F_X^2(Q_{\min,x}) + (i + 1)I_{i,x}}{2Q_{\min,x}^{1/2} r_{\min,x} / F_X^2(Q_{\min,x}) + I_{0,x}} \right] \left( \frac{1}{300 \text{ km/s}} \right)^i$$

$$f_{n_{\max} + 1,x} = \mathcal{E}_X \left[ \frac{A_X^2}{2Q_{\min,x}^{1/2} r_{\min,x} / F_X^2(Q_{\min,x}) + I_{0,x}} \right] \left( \frac{\sqrt{m_X}}{m_\chi + m_X} \right)$$

$$C_{ij} = \text{cov}(f_{i,x}, f_{j,x}) + \text{cov}(f_{i,y}, f_{j,y})$$

- Algorithmic $Q_{\max}$ matching

$$Q_{\max,Y} = \left( \frac{\alpha_X}{\alpha_Y} \right)^2 Q_{\max,X} \quad (v_{\text{cut}} = \alpha \sqrt{Q_{\max}})$$

[Ref: M. Drees and CLS, JCAP 0806, 012 (2008)]
Determination of the WIMP mass

- Reconstructed $m_{\chi,\text{rec}}$
  $(^{28}\text{Si} + ^{76}\text{Ge}, Q_{\text{max}} < 100 \text{ keV}, 2 \times 50 \text{ events})$

![Graph showing the relationship between $m_{\chi,\text{rec}}$ and $m_{\chi,\text{in}}$.](image)

[M. Drees and CLS, JCAP 0806, 012 (2008)]
Estimation of the SI WIMP–nucleon coupling

- **Spin-independent (SI) WIMP–nucleus cross section**

\[
\sigma_0^{\text{SI}} = \left( \frac{4}{\pi} \right) m_{r,N}^2 \left[ Z f_p + (A - Z) f_n \right]^2 \approx \left( \frac{4}{\pi} \right) m_{r,N}^2 A^2 |f_p|^2 = A^2 \left( \frac{m_{r,N}}{m_{r,p}} \right)^2 \sigma_{\chi p}^{\text{SI}}
\]

\[
\sigma_{\chi p}^{\text{SI}} = \left( \frac{4}{\pi} \right) m_{r,p}^2 |f_p|^2
\]

\( f_{(p,n)} \): effective SI WIMP–proton/neutron couplings

- **Rewriting the integral of \( f_1(v)/v \) over \( v \)**

\[
\left( \frac{dR}{dQ} \right)_{\text{expt, } Q=Q_{\text{min}}} = \frac{E \rho_0 A^2}{2 m_{\chi} m_{r,p}^2} \left[ \left( \frac{4}{\pi} \right) m_{r,p}^2 |f_p|^2 \right] F^2(Q_{\text{min}}) \left\{ m_{r,N} \sqrt{\frac{2}{m_N}} \left[ \frac{2 Q_{\text{min}}^{1/2} r_{\text{min}}}{F^2(Q_{\text{min}})} + I_0 \right] - 1 \left[ \frac{2 r_{\text{min}}}{F^2(Q_{\text{min}})} \right] \right\}
\]

- **Estimating the SI WIMP–nucleon coupling**

\[
|f_p|^2 = \frac{1}{\rho_0} \left[ \frac{\pi}{4 \sqrt{2}} \left( \frac{1}{E_Z A_Z^2 \sqrt{m_Z}} \right) \right] \left[ \frac{2 Q_{\text{min}}^{1/2} r_{\text{min}} Z}{F_Z^2(Q_{\text{min}} Z)} + I_0 Z \right] (m_{\chi} + m_Z)
\]

Estimation of the SI WIMP-nucleon coupling

- Estimating the SI WIMP-nucleon coupling

\[ |f_p|^2 = \frac{1}{\rho_0} \left[ \frac{\pi}{4\sqrt{2}} \left( \frac{1}{\mathcal{E} A^2 \sqrt{m_Z}} \right) \right] \left[ \frac{2Q_{\min,z}^1 r_{\min,z}}{F_Z^2(Q_{\min,z})} + I_{0,z} \right] (m_\chi + m_z) \]

- \[ |f_p|^2 \ (^{76}\text{Ge} (+^{28}\text{Si} + ^{76}\text{Ge}), \ Q_{\max} < 100 \ \text{keV}, \ \sigma_{\chi p}^{\text{SI}} = 10^{-8} \ \text{pb}, \ 1(3) \times 50 \ \text{events}) \]

[CLS, arXiv:1103.0481]
Estimation of the SI WIMP-nucleon coupling

- Estimating the SI WIMP-nucleon coupling

\[ |f_p|^2 = \frac{1}{\rho_0} \left[ \frac{\pi}{4\sqrt{2}} \left( \frac{1}{E_Z A_Z^2 \sqrt{m_Z}} \right) \right] \left[ \frac{2Q_{\text{min},Z} F_{\text{min},Z}}{F_Z^2(Q_{\text{min},Z})} + I_{0,Z} \right] (m_\chi + m_Z) \]

- \(|f_p|^2\) vs. \(m_\chi\) \((^{76}\text{Ge} + ^{28}\text{Si} + ^{76}\text{Ge})\), \(Q_{\text{max}} < 100 \text{ keV}\), \(\sigma_{X\chi}^{\text{SI}} = 10^{-8} \text{ pb}\), \(1(3) \times 50 \text{ events}\)

[CLS, arXiv:1103.0481]
Determination of the ratio of SD WIMP-nucleon couplings

- **Spin-dependent (SD) WIMP-nucleus cross section**

\[
\sigma_0^{SD} = \left( \frac{32}{\pi} \right) G_F^2 m_{r,N}^2 \left( \frac{J + 1}{J} \right) \left[ \langle S_p \rangle a_p + \langle S_n \rangle a_n \right]^2
\]

\[
\sigma_{\chi p/n}^{SD} = \left( \frac{32}{\pi} \right) G_F^2 m_{r,p/n}^2 \cdot \left( \frac{3}{4} \right) a_{p/n}^2
\]

- J: total nuclear spin
- \( \langle S_{(p,n)} \rangle \): expectation values of the proton/neutron group spin
- \( a_{(p,n)} \): effective SD WIMP-proton/neutron couplings

- **Determining the ratio of two SD WIMP-nucleon couplings**

\[
\left( \frac{a_n}{a_p} \right)^{SD}_{\pm,n} = - \frac{\langle S_p \rangle_x \pm \langle S_p \rangle_y R_{J,n}}{\langle S_n \rangle_x \pm \langle S_n \rangle_y R_{J,n}}
\]

\[
R_{J,n} \equiv \left[ \left( \frac{J_X}{J_X + 1} \right) \left( \frac{J_Y + 1}{J_Y} \right) \frac{R_{\sigma}}{R_n} \right]^{1/2} \quad (n \neq 0)
\]

[M. Drees and CLS, arXiv:0903.3300]
Introduction to Direct Dark Matter Detection Phenomenology
- Model-independent data analyses
- Determinations of ratios of WIMP-nucleon cross sections

Determination of the ratio of SD WIMP-nucleon couplings

- Reconstructed \((a_n/a_p)^{SD}_{rec,1}\)

\[^{73}\text{Ge} + ^{37}\text{Cl}, Q_{\text{min}} > 5 \text{ keV}, Q_{\text{max}} < 100 \text{ keV}, 2 \times 50 \text{ events, } m_\chi = 100 \text{ GeV or } a_n/a_p = 0.7\]

[CLS, JCAP 1107, 005 (2011)]
Determination of the ratio of SD WIMP–nucleon couplings

- Reconstructed \((a_n/a_p)^{SD,1}\)

\((^{19}\text{F} + ^{127}\text{I}, Q_{\text{min}} > 5 \text{ keV}, Q_{\text{max}} < 100 \text{ keV}, 2 \times 50 \text{ events, } m_\chi = 100 \text{ GeV or } a_n/a_p = 0.7)\)

[CLS, JCAP 1107, 005 (2011)]
Determinations of ratios of WIMP-nucleon cross sections

- Differential rate for combined SI and SD cross sections

\[
\frac{dR}{dQ}_{\text{expt}, Q=Q_{\text{min}}} = \mathcal{E} \left( \frac{\rho_0 \sigma_{SI}^0}{2m \chi m_N^2} \right) \left[ F_{SI}^2(Q) + \left( \frac{\sigma_{SD}^0}{\sigma_{SI}^0} \right) C_p F_{SD}^2(Q) \right] \int_{v_{\text{min}}}^{v_{\text{max}}} \left[ \frac{f_1(v)}{v} \right] dv
\]

\[
C_p \equiv \frac{4}{3} \left( J + 1 \right) \left[ \langle S_p \rangle + \left( \frac{a_n}{a_p} \right) \langle S_n \rangle \right]^2
\]

- Determining the ratio of two SI WIMP-proton cross sections

\[
\frac{\sigma_{SD}^0}{\sigma_{SI}^0} = \frac{F_{SI,Y}^2(Q_{\text{min}},Y) R_{m,XY} - F_{SI,X}^2(Q_{\text{min}},X)}{C_p X F_{SD,X}^2(Q_{\text{min}},X) - C_p Y F_{SD,Y}^2(Q_{\text{min}},Y) R_{m,XY}}
\]

\[
R_{m,XY} \equiv \left( \frac{r_{\text{min},X}}{\varepsilon_X} \right) \left( \frac{\varepsilon_Y}{r_{\text{min},Y}} \right) \left( \frac{m_Y}{m_X} \right)^2
\]

- Determining the ratio of two SD WIMP-nucleon couplings

\[
\left( \frac{a_n}{a_p} \right)^{\text{SI+SD}} = - \left( c_p X s_{n/p,X} - c_p Y s_{n/p,Y} \right) \pm \sqrt{c_p X c_p Y \left| s_{n/p,X} - s_{n/p,Y} \right|^2} \left( c_p X s_{n/p,X}^2 - c_p Y s_{n/p,Y}^2 \right)
\]

\[
c_p X \equiv \frac{4}{3} \left( J_X + 1 \right) \left[ \langle S_p \rangle X \right]^2 \left[ F_{SI,Z}^2(Q_{\text{min}},Z) R_{m,YZ} - F_{SI,Y}^2(Q_{\text{min}},Y) \right] F_{SD,X}^2(Q_{\text{min}},X)
\]

[M. Drees and CLS, arXiv:0903.3300]
Determinations of ratios of WIMP-nucleon cross sections

- Reconstructed $(a_n/a_p)^{\text{SI+SD}}_{\text{rec}}$ vs. $(a_n/a_p)^{\text{SD}}_{\text{rec,1}}$

\[ (^{19}\text{F} + ^{127}\text{I} + ^{28}\text{Si}, Q_{\text{min}} > 5 \text{ keV}, Q_{\text{max}} < 100 \text{ keV}, 3 \times 50 \text{ events, } \sigma_{\chi p}^{\text{SI}} = 10^{-8}/10^{-10} \text{ pb, } a_p = 0.1, m_\chi = 100 \text{ GeV}) \]
Determinations of ratios of WIMP-nucleon cross sections

- Reconstructed \( \left( \sigma_{\chi p}^{SD} / \sigma_{\chi p}^{SI} \right)_{\text{rec}} \) and \( \left( \sigma_{\chi n}^{SD} / \sigma_{\chi p}^{SI} \right)_{\text{rec}} \)

\(^{19}\text{F} + ^{127}\text{I} + ^{28}\text{Si} \) vs. \(^{23}\text{Na}/^{131}\text{Xe} + ^{76}\text{Ge} \), \( Q_{\text{min}} > 5 \text{ keV}, Q_{\text{max}} < 100 \text{ keV}, \sigma_{\chi p}^{SI} = 10^{-8} \text{ pb}, a_p = 0.1, m_\chi = 100 \text{ GeV}, 3/2 \times 50 \text{ events} \)

[CLS, JCAP 1107, 005 (2011)]

C.-L. Shan

XJU, May 8, 2013
Effects of residue background events
Effects of residue background events

- Background spectrum
  - Target-dependent exponential background spectrum
    \[ \left( \frac{dR}{dQ} \right)_{bg,ex} = \exp \left( -\frac{Q/\text{keV}}{A^{0.6}} \right) \]
  - Constant background spectrum

- Background window
  - Entire experimental possible energy range (0 – 100 keV)
  - Low energy range (0 – 50 keV)
  - High energy range (50 – 100 keV)

- (Naively) simulate
  - only a few residue background events
  - induced by two or more different sources
AMIDAS package and website
AMIDAS package and website

- **A Model-Independent Data Analysis System** for direct Dark Matter detection experiments

  - DAMNED Dark Matter Web Tool (ILIAS Project)
    - [http://pisrv0.pit.physik.uni-tuebingen.de/darkmatter/amidas/](http://pisrv0.pit.physik.uni-tuebingen.de/darkmatter/amidas/)
    - [CLS, arXiv:0909.1459, 0910.1971]

  - TiResearch (Taiwan interactive Research)

  - Online interactive simulation/data analysis system

  - Full Monte Carlo simulations

  - Theoretical estimations

  - Real/user-uploaded data analyses
Currently running and further projects

- Planned improvements (AMIDAS-II)
  - More well-motivated velocity distributions
  - More more-realistic form factors for each single target
  - Connection to other simulation/data analysis packages for (in)direct detections
  - Dark Matter Les Houches Accord (DLHA)  
    [G. Brooijmans et al., arXiv:1203.1488]
  - User account/setup database system

- Currently running and further projects
  - Data analysis in the inelastic scattering framework
  - Reconstructing modeled velocity distribution functions
  - Analyzing data with directional information
Summary
Summary

- **Direct Dark Matter detection** searches for WIMP particles.

- Direct detection **experiments** aim to observe WIMP-nucleus scattering signals.

- **Theoretical models** predict WIMP candidates.

- **Phenomenological data analyses** would exclude/constrain the parameter space and even extract WIMP properties.

- Our data analysis procedures could extract WIMP properties model-independently by combining data sets with different detector materials.
Summary

- These information will help us to
  - distinguish the (neutralino) LSP from the LKP
    [G. Bertone et al., PRL 99, 151301 (2007); V. Barger et al., PRD 78, 056007 (2008);
    G. Belanger et al., PRD 79, 015008 (2009); R. C. Cotta et al., NJP 11, 105026 (2009)]
  - identify the particle produced at colliders to be indeed halo WIMPs
  - predict the WIMP annihilation cross section $\langle \sigma_{\text{anni}}v \rangle$

- Furthermore, we could
  - determine the local WIMP density $\rho_0$
  - predict the indirect detection event rate $d\Phi/dE$
  - test our understanding of the early Universe
  - ......
Thank you very much for your attention!