Identifying Weakly Interacting Massive Particles from Direct Dark Matter Detection Data

Chung-Lin Shan

School of Physics and Astronomy, Seoul National University

IPMU, November 6, 2008

in collaboration with M. Drees and M. Kakizaki

- Introduction
  - Evidence and candidates for Dark Matter
  - Direct Dark Matter detection
  - Motivation
- Reconstructing the velocity distribution of halo WIMPs
- Determining the WIMP mass
- Determining the WIMP-nucleon couplings
  - Determining ratios of WIMP-nucleon cross sections
  - Estimating the SI WIMP-nucleon coupling
- Summary and outlook

References

- ☐ G. Jungman, M. Kamionkowski, and K. Griest, *"Supersymmetric Dark Matter"*, *Phys. Rep.* **267**, 195 (1996).

- ☐ G. Bertone, D. Hooper, and J. Silk, *"Particle Dark Matter: Evidence, Candidates and Constraints"*, *Phys. Rep.* **405**, 279 (2005).

- ☐ C. Amsler *et al.*, *"Review of Particle Physics"*, *Phys. Lett.* **B 667**, 1 (2008):
  K. A. Olive and J. A. Peacock, *19. Big-Bang Cosmology*;
  B. D. Fields and S. Sarkar, *20. Big-Bang Nucleosynthesis*;
  O. Lahav and A. R. Liddle, *21. The Cosmological Parameters*;
  M. Drees and G. Gerbier, *22. Dark Matter*;
  D. Scott and G. F. Smoot, *23. Cosmic Microwave Background*.

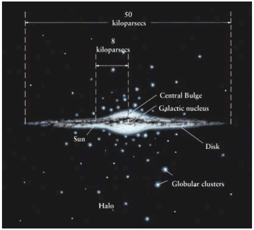
- ☐ C. L. Shan, Ph.D. Thesis, *"Theoretical Interpretation of Experimental Data from Direct Dark Matter Detection"*, `arXiv:0707.0488` (2007).

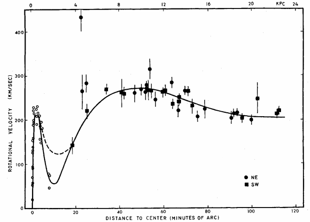
- ☐ F. D. Steffen, *"Supersymmetric Dark Matter Candidates: The lightest neutralino, the gravitino, and the axino"*, `arXiv:0711.1240` (2007).

- ☐ L. Baudis, *"Direct Detection of Cold Dark Matter"*, `arXiv:0711.3788` (2007).

Evidence for Dark Matter

- Dark: neither emits nor absorbs electromagnetic radiation.
- The observational evidence for the existence of Dark Matter is gravitational.
- Rotation curves of spiral galaxies



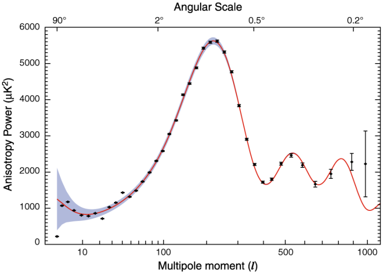


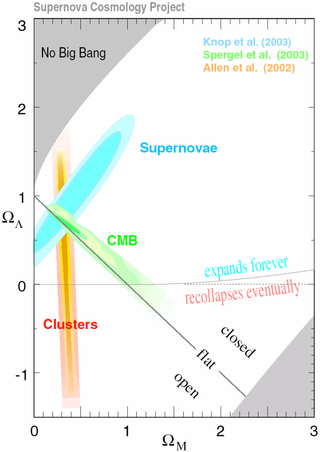
[V. C. Rubin and W. K. Ford, *Astrophys. J.* **159**, 379 (1970)]

- The observed luminous objects can not have enough mass to support the observed gravitational effects.

Evidence for Dark Matter

- Astronomical measurements





[NASA/WMAP Science Team; Supernova Cosmology Project]

Evidence for Dark Matter

- A large fraction of the mass/energy in our Universe is Dark!
  - Dark Energy: 73%
  - Dark Matter: $\approx$ 20%
  - Ordinary baryonic matter: $\approx$ 4%
  - Luminous matter: $\simeq$ 1%
  - Stars: 0.2% $\sim$ 0.5%
  - CMB photons: $\approx$ 0.0046%
  - Neutrinos: 0.1% $\sim$ 5%

[Review of Particle Physics 2008]

Candidates for Dark Matter

- Non-luminous, non-baryonic, non-relativistic (cold), collisionless elementary particles which have not yet been discovered.
  - Dark Matter should move non-relativistically in the early Universe in order to allow it to merge to galactic scale structures.
  - So far we can observe (or "feel") the existence of Dark Matter only through its gravitational effects.
  - Dark Matter forms halos with an approximately spherical distribution around galaxies.
  - Dark Matter must be stable on the cosmological time scale.
  - Dark Matter must have the right relic cosmological density.

Candidates for Dark Matter

- Weakly Interacting Massive Particles (WIMPs) χ
  - arise in several extensions of the Standard Model of electroweak interactions.
  - are stable particles and interact with ordinary matter only via weak interactions.
  - have masses roughly between 10 GeV and a few TeV.

- Neutralinos
  - are linear combinations of photino, Z-ino and neutral higgsinos.
  - The lightest neutralino is the most widely studied candidate for WIMP Dark Matter.
  - has the desired thermal relic density in at least four distinct regions of parameter space.

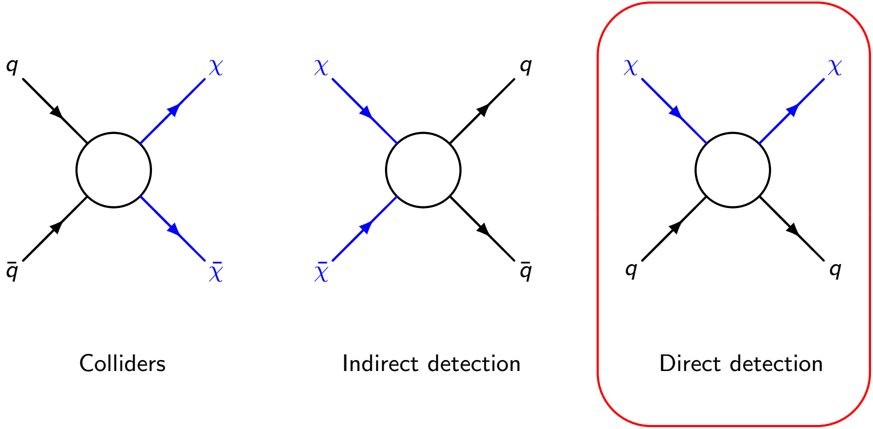
Candidates for Dark Matter

Particles of typical supersymmetric models

Normal particles		SUSY partners		
Name	Symbol	Name		Symbol
up-quarks	$u,\ c,\ t$	up-squarks		$\tilde{u}_L,\ \tilde{u}_R,\ \tilde{c}_L,\ \tilde{c}_R,\ \tilde{t}_L,\ \tilde{t}_R$
down-quarks	$d,\ s,\ b$	down-squarks		$\tilde{d}_L,\ \tilde{d}_R,\ \tilde{s}_L,\ \tilde{s}_R,\ \tilde{b}_L,\ \tilde{b}_R$
leptons	$e,\ \mu,\ \tau$	sleptons		$\tilde{e}_L,\ \tilde{e}_R,\ \tilde{\mu}_L,\ \tilde{\mu}_R,\ \tilde{\tau}_L,\ \tilde{\tau}_R$
neutrinos	$\nu_e,\ \nu_\mu,\ \nu_\tau$	sneutrinos		$\tilde{\nu}_e,\ \tilde{\nu}_\mu,\ \tilde{\nu}_\tau$
gluons	g	gluinos		$\tilde{g}$
photon	γ	photino $\tilde{\gamma}$	neutralinos	$\tilde{\chi}_1^0,\ \tilde{\chi}_2^0,\ \tilde{\chi}_3^0,\ \tilde{\chi}_4^0$
Z boson	Z^0	Z-ino $\tilde{Z}$		
light scalar Higgs	h^0	neutral higgsinos $\tilde{h}^0,\ \tilde{H}^0$		
heavy scalar Higgs	H^0			
pseudoscalar Higgs	A^0			
charged Higgs	$H^\pm$	charged higgsinos $\tilde{H}^\pm$	charginos	$\tilde{\chi}_1^\pm,\ \tilde{\chi}_2^\pm$
W bosons	$W^\pm$	W-inos $\tilde{W}^\pm$		
graviton	G	gravitino		$\tilde{G}$
axion	a	axino		$\tilde{a}$

Dark Matter searches

WIMPs should have small, but non-zero couplings to ordinary matter.



Colliders

Indirect detection

Direct detection

Direct detection: elastic WIMP-nucleus scattering

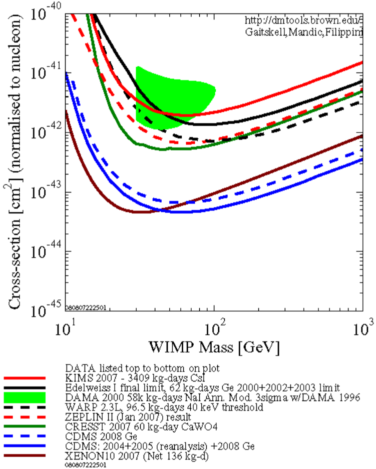
- WIMPs could scatter elastically off target nuclei and produce nuclear recoils which deposit energy in the detector.
    - The event rate depends on the WIMP density near the Earth, the WIMP-nucleus cross section, the WIMP mass and the velocity distribution of the incident WIMPs.
    - In typical SUSY models with neutralino WIMPs, WIMP-nucleus cross section is about $10^{-6} \sim 10^{-4}$ pb, the optimistical expected event rate is then $\sim 10^{-3}$ events/kg/day, but could be less than 1 event/ton/yr.
    - The event rate drops approximately exponentially and most events should be with energies less than 40 keV.
    - Typical background noise due to cosmic rays and ambient radioactivity is much larger.

Direct detection: elastic WIMP-nucleus scattering

- Target material dependence
  - Spin-independent (SI) coupling
    a scalar (and/or vector) interaction, the cross section for scalar interaction is approximately proportional to the square of the mass of the nucleus, thus higher mass nuclei, e.g. Ge or Xe, are more suitable.
  - Spin-dependent (SD) coupling
    an axial-vector (spin-spin) interaction, the useful target nuclei are ^{19}F and ^{127}I.
  - For nuclei with $A \geq 30$, the SI interaction almost always dominates the spin interaction.
  - The scattering event rate depends on the mass of the target material directly.

Direct detection: elastic WIMP-nucleus scattering

- Exclusion limits on the SI WIMP-nucleon cross section



[http://dmtools.berkeley.edu/limitplots/]

Motivation

- Differential event rate for elastic WIMP-nucleus scattering

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

Here

Astrophysics

$$v_{\rm min} = \alpha\sqrt{Q}$$

is the minimal incoming velocity of incident WIMPs that can deposit the recoil energy Q in the detector.

$$\mathcal{A} \equiv \frac{\boxed{\rho_0}\boxed{\sigma_0}}{2\boxed{m_\chi m_{\rm r,N}^2}} \qquad \alpha \equiv \sqrt{\frac{m_{\rm N}}{2m_{\rm r,N}^2}} \qquad m_{\rm r,N} = \frac{m_\chi m_{\rm N}}{m_\chi + m_{\rm N}}$$

Particle Physics

ρ_0: WIMP density near the Earth

σ_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

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

Here

$$v_{\rm min} = \alpha\sqrt{Q}$$

is the minimal incoming velocity of incident WIMPs that can deposit the recoil energy Q in the detector.

$$\mathcal{A} \equiv \frac{\rho_0\sigma_0}{2m_\chi m_{\rm r,N}^2} \qquad \alpha \equiv \sqrt{\frac{m_{\rm N}}{2m_{\rm r,N}^2}} \qquad m_{\rm r,N} = \frac{m_\chi m_{\rm N}}{m_\chi + m_{\rm N}}$$

ρ_0: WIMP density near the Earth

σ_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

Reconstructing the velocity distribution of halo WIMPs

- Normalized one-dimensional velocity distribution function

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

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

- Moments of the velocity distribution function

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

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

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

[M. Drees and CLS, JCAP 0706, 011]

Reconstructing the velocity distribution of halo WIMPs

- Ansatz: in the nth Q-bin

$$\left(\frac{dR}{dQ}\right)_{Q \simeq Q_n} \equiv r_n \, e^{k_n (Q - Q_{s,n})} \qquad r_n \equiv \frac{N_n}{b_n}$$

- Logarithmic slope and shifted point in the nth Q-bin

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

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

- Reconstructing the one-dimensional velocity distribution

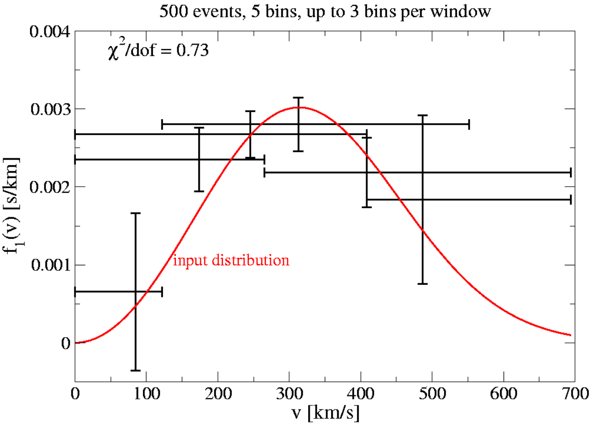
$$f_{1,r}(v_{s,n}) = \mathcal{N}\left[\frac{2 Q_{s,n} r_n}{F^2(Q_{s,n})}\right]\left[\frac{d}{dQ} \ln F^2(Q)\bigg|_{Q=Q_{s,n}} - k_n\right]$$

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

[M. Drees and CLS, JCAP 0706, 011]

Reconstructing the velocity distribution of halo WIMPs

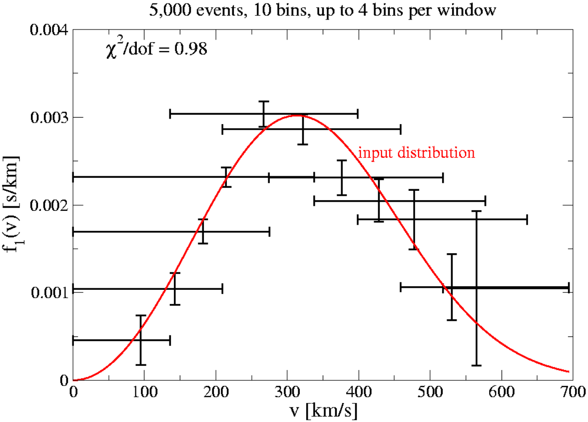
- Reconstruction with simulated experimental data (500 events, 5 bins, up to 3 bins per window)



[M. Drees and CLS, JCAP 0706, 011]

Reconstructing the velocity distribution of halo WIMPs

- Reconstruction with simulated experimental data (5,000 events, 10 bins, up to 4 bins per window)



[M. Drees and CLS, JCAP 0706, 011]

Determining the WIMP mass

- Determining the moments of the WIMP velocity distribution

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

$$I_n = \sum_a \frac{Q_a^{(n-1)/2}}{F^2(Q_a)} \qquad r_{\rm min} = \left(\frac{dR}{dQ} \right)_{Q=Q_{\rm min}}$$

[M. Drees and CLS, JCAP 0706, 011]

- Determining the WIMP mass

$$m_\chi = \frac{\sqrt{m_X m_Y} - m_X \mathcal{R}_n}{\mathcal{R}_n - \sqrt{m_X/m_Y}}$$

$$\mathcal{R}_n \equiv \frac{\alpha_Y}{\alpha_X}$$

$$= \left[\frac{2Q_{{\rm min},X}^{(n+1)/2} r_{{\rm min},X}/F_X^2(Q_{{\rm min},X}) + (n+1) I_{n,X}}{2Q_{{\rm min},X}^{1/2} r_{{\rm min},X}/F_X^2(Q_{{\rm min},X}) + I_{0,X}} \right]^{1/n} \Big(X \longrightarrow Y \Big)^{-1} \qquad (n \neq 0)$$

[M. Drees and CLS, JCAP 0806, 012]

Determining the WIMP mass

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

$$\sigma_0^{\rm SI} = \left(\frac{4}{\pi}\right) m_{\rm r,N}^2 \Big[Z f_{\rm p} + (A - Z) f_{\rm n}\Big]^2 \simeq \left(\frac{4}{\pi}\right) m_{\rm r,N}^2 A^2 |f_{\rm p}|^2 = A^2 \left(\frac{m_{\rm r,N}}{m_{\rm r,p}}\right)^2 \sigma_{\chi{\rm p}}^{\rm SI}$$

$$\sigma_{\chi{\rm p}}^{\rm SI} \equiv \left(\frac{4}{\pi}\right) m_{\rm r,p}^2 |f_{\rm p}|^2$$

$f_{\rm p}$, $f_{\rm n}$: effective WIMP-proton/neutron SI coupling

- Determining the WIMP mass

$$m_\chi^{\rm SI} = \frac{(m_X/m_Y)^{5/2}\, m_Y - m_X \mathcal{R}_\sigma}{\mathcal{R}_\sigma - (m_X/m_Y)^{5/2}} = \frac{\sqrt{m_X m_Y} - m_X \mathcal{R}_\sigma^{\rm SI}}{\mathcal{R}_\sigma^{\rm SI} - \sqrt{m_X/m_Y}}$$

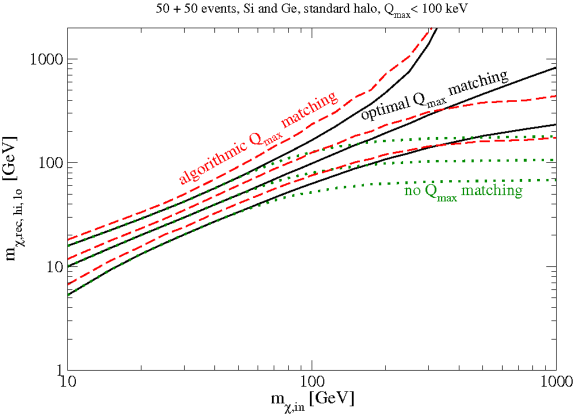
$$\mathcal{R}_\sigma^{\rm SI} \equiv \left(\frac{m_Y}{m_X}\right)^2 \mathcal{R}_\sigma$$

$$\mathcal{R}_\sigma = \frac{\mathcal{E}_Y}{\mathcal{E}_X} \left[\frac{2 Q_{{\rm min},X}^{1/2} r_{{\rm min},X} / F_X^2(Q_{{\rm min},X}) + I_{0,X}}{2 Q_{{\rm min},Y}^{1/2} r_{{\rm min},Y} / F_Y^2(Q_{{\rm min},Y}) + I_{0,Y}}\right]$$

[M. Drees and CLS, JCAP 0806, 012]

Determining the WIMP mass

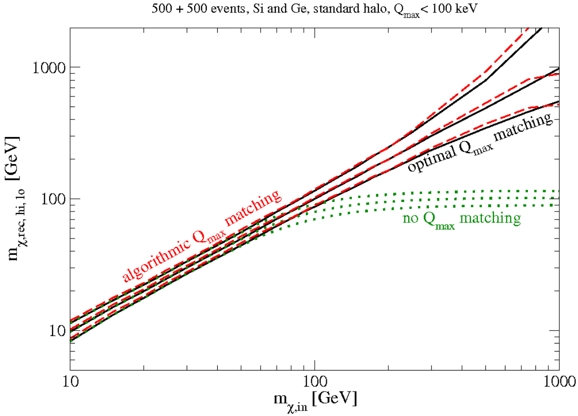
- Reconstructed $m_{\chi,\mathrm{rec}}$
  ($Q_{\max} < 100$ keV, ^{76}Ge + ^{28}Si, 50 events each)



[M. Drees and CLS, JCAP 0806, 012]

Determining the WIMP mass

- Reconstructed $m_{\chi,\mathrm{rec}}$
  ($Q_{\mathrm{max}} < 100$ keV, ^{76}Ge + ^{28}Si, 500 events each)



[M. Drees and CLS, JCAP 0806, 012]

Determining ratios of WIMP-nucleon cross sections

- -1-st moment of the WIMP velocity distribution

$$\left(\frac{dR}{dQ}\right)_{Q=Q_{\rm min}} = \mathcal{E}\mathcal{A}F^2(Q_{\rm min})\int_{v_{\rm min}(Q_{\rm min})}^{v_{\rm esc}}\left[\frac{f_1(v)}{v}\right]dv$$

$$= \mathcal{E}\left(\frac{\rho_0\sigma_0}{2m_\chi m_{\rm r,N}^2}\right)F^2(Q_{\rm min})\cdot\frac{1}{\alpha}\left[\frac{2r_{\rm min}}{2Q_{\rm min}^{1/2}r_{\rm min}+I_0F^2(Q_{\rm min})}\right]$$

- Product of the local density times the WIMP-nucleus cross section

$$\rho_0\sigma_0 = \left(\frac{1}{\mathcal{E}}\right)m_\chi m_{\rm r,N}\sqrt{\frac{m_{\rm N}}{2}}\left[\frac{2Q_{\rm min}^{1/2}r_{\rm min}}{F^2(Q_{\rm min})}+I_0\right]$$

- Ratio of two WIMP-nucleus cross sections

$$\frac{\sigma_{0,X}}{\sigma_{0,Y}} = \left(\frac{\mathcal{E}_Y}{\mathcal{E}_X}\right)\frac{m_{{\rm r},X}\sqrt{m_X}}{m_{{\rm r},Y}\sqrt{m_Y}}\left[\frac{2Q_{{\rm min},X}^{1/2}r_{{\rm min},X}+I_{0,X}F_X^2(Q_{{\rm min},X})}{2Q_{{\rm min},Y}^{1/2}r_{{\rm min},Y}+I_{0,Y}F_Y^2(Q_{{\rm min},Y})}\right]\left[\frac{F_Y^2(Q_{{\rm min},Y})}{F_X^2(Q_{{\rm min},X})}\right]$$

[M. Drees, M. Kakizaki and CLS, UCLA Dark Matter 2008]

SD cross section dominates

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

$$\sigma_0^{\rm SD} = \left(\frac{32}{\pi}\right) G_F^2\, m_{\rm r,N}^2 \left(\frac{J+1}{J}\right) \Big[a_{\rm p} \langle S_{\rm p} \rangle + a_{\rm n} \langle S_{\rm n} \rangle\Big]^2$$

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

J: total nuclear spin

$\langle S_{\rm p} \rangle$, $\langle S_{\rm n} \rangle$: expectation value of the proton/neutron group spin

$a_{\rm p}$, $a_{\rm n}$: effective WIMP-proton/neutron SD coupling

- ❑ $m_\chi^{\rm SD} = m_\chi$

$$\mathcal{R}_\sigma^{\rm SD} \equiv \left(\frac{J_X}{J_X+1}\right) \left(\frac{J_Y+1}{J_Y}\right) \left[\frac{a_{\rm p} \langle S_{\rm p} \rangle_Y + a_{\rm n} \langle S_{\rm n} \rangle_Y}{a_{\rm p} \langle S_{\rm p} \rangle_X + a_{\rm n} \langle S_{\rm n} \rangle_X}\right]^2 \mathcal{R}_\sigma = \mathcal{R}_n$$

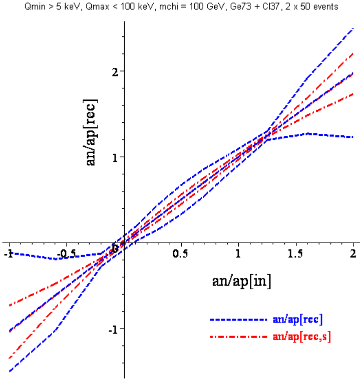
- ❑ Determining the ratio of two SD WIMP-nucleon couplings

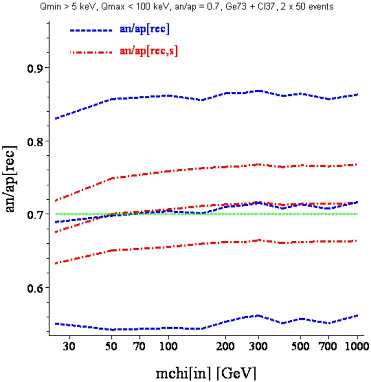
$$\left(\frac{a_{\rm n}}{a_{\rm p}}\right)_\pm^{\rm SD} = -\frac{\langle S_{\rm p} \rangle_X \pm \langle S_{\rm p} \rangle_Y \mathcal{R}_J}{\langle S_{\rm n} \rangle_X \pm \langle S_{\rm n} \rangle_Y \mathcal{R}_J} \qquad \mathcal{R}_J \equiv \left[\left(\frac{J_X}{J_X+1}\right) \left(\frac{J_Y+1}{J_Y}\right) \frac{\mathcal{R}_\sigma}{\mathcal{R}_n}\right]^{1/2}$$

[M. Drees, M. Kakizaki and CLS, UCLA Dark Matter 2008]

SD cross section dominates

- Reconstructed $(a_{\rm n}/a_{\rm p})^{\rm SD}_{\rm rec}$
  ($Q_{\rm min} > 5$ keV, $Q_{\rm max} < 100$ keV, ^{73}Ge + ^{37}Cl, 50 events each,
  $m_\chi = 100$ GeV or $an/ap = 0.7$)


Qmin > 5 keV, Qmax < 100 keV, mchi = 100 GeV, Ge73 + Cl37, 2 x 50 events

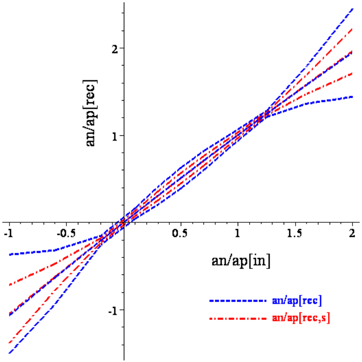

Qmin > 5 keV, Qmax < 100 keV, an/ap = 0.7, Ge73 + Cl37, 2 x 50 events

[M. Drees, M. Kakizaki and CLS, in progress]

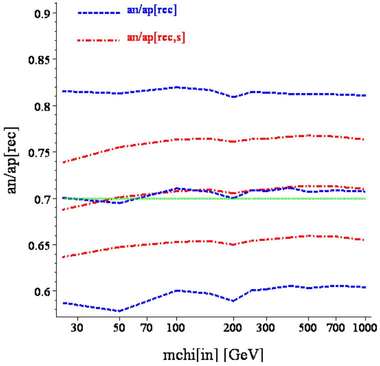
SD cross section dominates

- Reconstructed $(a_n/a_p)^{SD}_{rec}$
  ($Q_{min} > 1$ keV, $Q_{max} < 100$ keV, ^{73}Ge + ^{37}Cl, 50 events each,
  $m_\chi = 100$ GeV or $an/ap = 0.7$)

Qmin > 1 keV, Qmax < 100 keV, mchi = 100 GeV, Ge73 + Cl37, 2 x 50 events



Qmin > 1 keV, Qmax < 100 keV, an/ap = 0.7, Ge73 + Cl37, 2 x 50 events



[M. Drees, M. Kakizaki and CLS, in progress]

Combining the SI and SD cross sections

- Differential rate for the combination of the SI and SD cross sections

$$\left(\frac{dR}{dQ}\right)_{Q=Q_{\rm min}} = \mathcal{E}\left(\frac{\rho_0\sigma_0^{\rm SI}}{2m_\chi m_{\rm r,N}^2}\right) F_{\rm SI}'^2(Q_{\rm min})\cdot\frac{1}{\alpha}\left[\frac{2r_{\rm min}}{2Q_{\rm min}^{1/2}r_{\rm min}+I_0 F_{\rm SI}'^2(Q_{\rm min})}\right]$$

$$F_{\rm SI}'^2(Q)\equiv F_{\rm SI}^2(Q)+\left(\frac{\sigma_{\chi\rm p}^{\rm SD}}{\sigma_{\chi\rm p}^{\rm SI}}\right)\mathcal{C}_{\rm p}F_{\rm SD}^2(Q) \qquad \mathcal{C}_{\rm p}\equiv\frac{4}{3}\left(\frac{J+1}{J}\right)\left[\frac{\langle S_{\rm p}\rangle+(a_{\rm n}/a_{\rm p})\langle S_{\rm n}\rangle}{A}\right]^2$$

- Determining the ratio of two WIMP-proton cross sections

$$\frac{\sigma_{\chi\rm p}^{\rm SD}}{\sigma_{\chi\rm p}^{\rm SI}}=\frac{F_{{\rm SI},Y}^2(Q_{{\rm min},Y})\mathcal{R}_{m,XY}-F_{{\rm SI},X}^2(Q_{{\rm min},X})}{\mathcal{C}_{{\rm p},X}F_{{\rm SD},X}^2(Q_{{\rm min},X})-\mathcal{C}_{{\rm p},Y}F_{{\rm SD},Y}^2(Q_{{\rm min},Y})\mathcal{R}_{m,XY}}$$

$$\mathcal{R}_{m,XY}\equiv\left(\frac{r_{{\rm min},X}}{\mathcal{E}_X}\right)\left(\frac{\mathcal{E}_Y}{r_{{\rm min},Y}}\right)\left(\frac{m_Y}{m_X}\right)^2$$

- Determining the ratio of two SD WIMP-nucleon couplings

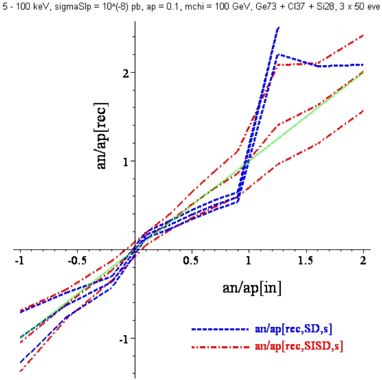
$$\left(\frac{a_{\rm n}}{a_{\rm p}}\right)_{\pm}^{\rm SI+SD}=-\frac{\sqrt{c_{{\rm p},X}}\mp\sqrt{c_{{\rm p},Y}}}{\sqrt{c_{{\rm p},X}}\,s_{{\rm n/p},X}\mp\sqrt{c_{{\rm p},Y}}\,s_{{\rm n/p},Y}} \qquad \left(s_{{\rm n/p},X}>s_{{\rm n/p},Y},\ s_{\rm n/p}\equiv\langle S_{\rm n}\rangle/\langle S_{\rm p}\rangle\right)$$

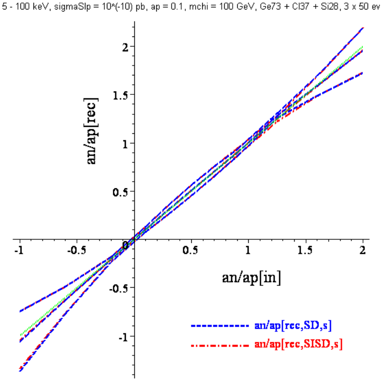
$$c_{{\rm p},X}\equiv\frac{4}{3}\left(\frac{J_X+1}{J_X}\right)\left[\frac{\langle S_{\rm p}\rangle_X}{A_X}\right]^2\left[F_{{\rm SI},Z}^2(Q_{{\rm min},Z})\mathcal{R}_{m,YZ}-F_{{\rm SI},Y}^2(Q_{{\rm min},Y})\right]F_{{\rm SD},X}^2(Q_{{\rm min},X})$$

[M. Drees, M. Kakizaki and CLS, UCLA Dark Matter 2008]

Combining the SI and SD cross sections

- Reconstructed $(a_n/a_p)_{\rm rec}^{\rm SI+SD}$ vs $(a_n/a_p)_{\rm rec}^{\rm SD}$
  ($Q_{\rm min} > 5$ keV, $Q_{\rm max} < 100$ keV, ^{73}Ge + ^{37}Cl + ^{28}Si, 50 events each,
  $\sigma_{\chi p}^{\rm SI} = 10^{-8}$ / 10^{-10} pb, $a_p = 0.1$, $m_\chi = 100$ GeV)

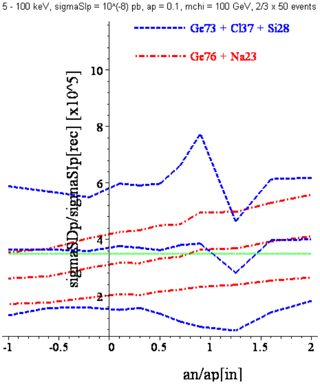


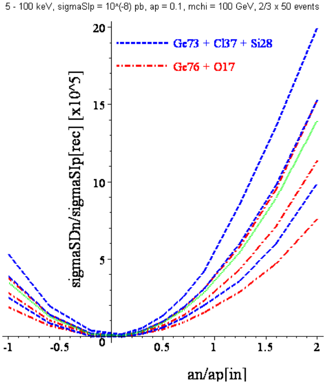


[M. Drees, M. Kakizaki and CLS, in progress]

Combining the SI and SD cross sections

- Reconstructed $\left(\sigma_{\chi p}^{SD}/\sigma_{\chi p}^{SI}\right)_{rec}$ and $\left(\sigma_{\chi n}^{SD}/\sigma_{\chi p}^{SI}\right)_{rec}$ $\left(Q_{min} > 5\ \text{keV},\ Q_{max} < 100\ \text{keV},\ {}^{73}\text{Ge} + {}^{37}\text{Cl} + {}^{28}\text{Si}\ \text{vs}\ {}^{76}\text{Ge} + {}^{23}\text{Na}/{}^{17}\text{O},\ \sigma_{\chi p}^{SI} = 10^{-8}\ \text{pb},\ a_p = 0.1,\ m_\chi = 100\ \text{GeV},\ 50\ \text{events each}\right)$

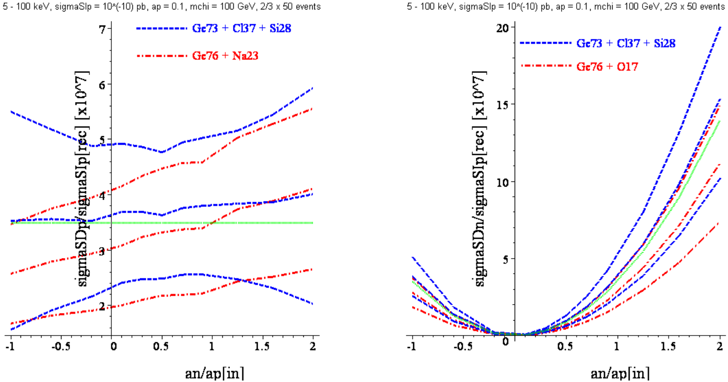




[M. Drees, M. Kakizaki and CLS, in progress]

Combining the SI and SD cross sections

- Reconstructed $(\sigma_{\chi p}^{SD}/\sigma_{\chi p}^{SI})_{rec}$ and $(\sigma_{\chi n}^{SD}/\sigma_{\chi p}^{SI})_{rec}$ ($Q_{min} > 5$ keV, $Q_{max} < 100$ keV, ^{73}Ge + ^{37}Cl + ^{28}Si vs ^{76}Ge + ^{23}Na/^{17}O, $\sigma_{\chi p}^{SI} = 10^{-10}$ pb, $a_p = 0.1$, $m_\chi = 100$ GeV, 50 events each)



[M. Drees, M. Kakizaki and CLS, in progress]

Estimating the SI WIMP-nucleon coupling

- We can estimate ratios of each two of the three WIMP-nucleon cross sections model-independently.
  - Can we estimate any one of them further?
  - Unfortunately, no!
  - But, if we release some constraints or add some assumptions?
  - Let's go back to look at the expression for the product of the local density times the WIMP-nucleus cross section:

$$\rho_0 \sigma_0^{\rm SI} = \left(\frac{1}{\mathcal{E}}\right) m_\chi m_{\rm r,N} \sqrt{\frac{m_{\rm N}}{2}} \left[\frac{2 Q_{\rm min}^{1/2} r_{\rm min}}{F_{\rm SI}^2(Q_{\rm min})} + I_0\right]$$

  - If we accept the standard assumption for the local DM density...

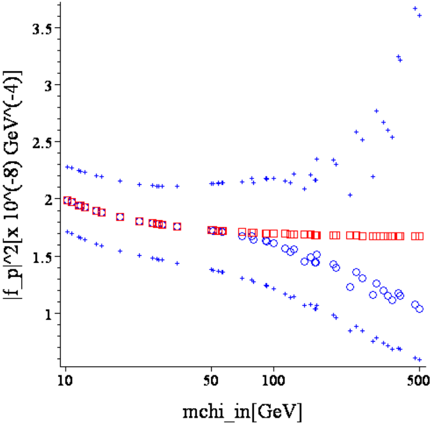
- Estimating the SI WIMP-nucleon coupling

$$|f_{\rm p}|^2 = \frac{1}{\rho_0} \left[\frac{\pi}{4\sqrt{2}} \left(\frac{1}{\mathcal{E} A^2 \sqrt{m_{\rm N}}}\right)\right] (m_\chi + m_{\rm N}) \left[\frac{2 Q_{\rm min}^{1/2} r_{\rm min}}{F_{\rm SI}^2(Q_{\rm min})} + I_0\right]$$

[M. Drees and CLS, arXiv:0809.2441]

Estimating the SI WIMP-nucleon coupling

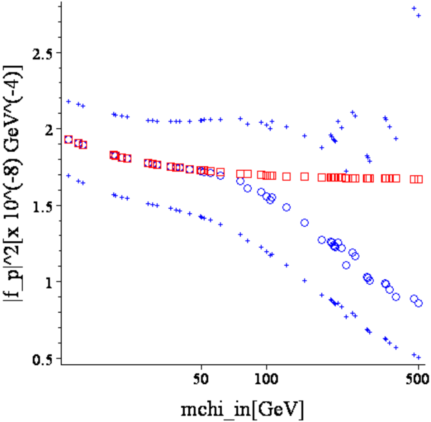
- Reconstructed $|f_{\rm p}|^2_{\rm rec}$
  $\left(\sigma_{\chi {\rm p}}^{\rm SI} = 10^{-8}\ {\rm pb},\ Q_{\rm max} < 100\ {\rm keV},\ {}^{76}{\rm Ge} + {}^{28}{\rm Si} + {}^{76}{\rm Ge}\right.$, 50 events each$\left.\right)$



[M. Drees and CLS, arXiv:0809.2441; in progress]

Estimating the SI WIMP-nucleon coupling

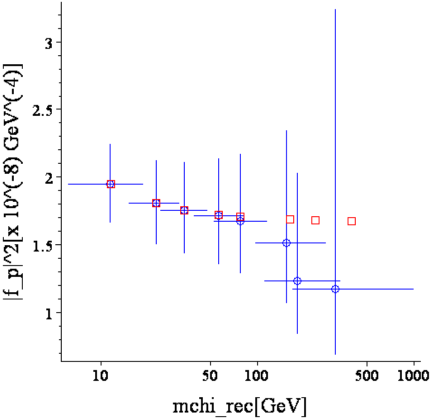
- Reconstructed $|f_{\rm p}|^2_{\rm rec}$
  $\left(\sigma_{\chi{\rm p}}^{\rm SI} = 10^{-8}~{\rm pb},~Q_{\rm max} < 100~/~75~{\rm keV},~^{76}{\rm Ge} + ^{28}{\rm Si} + ^{136}{\rm Xe},~50~{\rm events~each}\right)$



[M. Drees and CLS, arXiv:0809.2441; in progress]

Estimating the SI WIMP-nucleon coupling

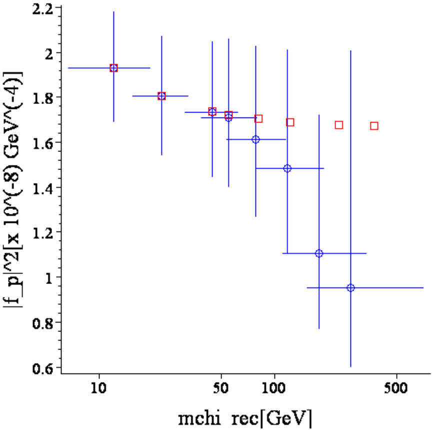
- Reconstructed $|f_{\rm p}|^2_{\rm rec}$ vs. reconstructed $m_{\chi,{\rm rec}}$
  $\left(\sigma_{\chi {\rm p}}^{\rm SI} = 10^{-8}\ {\rm pb},\ Q_{\rm max} < 100\ {\rm keV},\ {}^{76}{\rm Ge} + {}^{28}{\rm Si} + {}^{76}{\rm Ge},\ 50\ \text{events each}\right)$



[M. Drees and CLS, arXiv:0809.2441; in progress]

Estimating the SI WIMP-nucleon coupling

- Reconstructed $|f_{\rm p}|^2_{\rm rec}$ vs. reconstructed $m_{\chi,{\rm rec}}$
  $\left(\sigma_{\chi{\rm p}}^{\rm SI} = 10^{-8}\ {\rm pb},\ Q_{\rm max} < 100\ /\ 75\ {\rm keV},\ {}^{76}{\rm Ge} + {}^{28}{\rm Si} + {}^{136}{\rm Xe},\ 50\ \text{events each}\right)$



[M. Drees and CLS, arXiv:0809.2441; in progress]

Summary and outlook

- Once two or more experiments with different target nuclei obtain WIMP signals, we could estimate
  - WIMP mass m_χ
  - SI WIMP-nucleon coupling $|f_{\rm p}|^2$
  - ratio of the SD WIMP-proton cross section to the SI one, $\sigma_{\chi{\rm p}}^{\rm SD}/\sigma_{\chi{\rm p}}^{\rm SI}$
  - ratio of the SD WIMP coupling on neutrons to that on protons, $a_{\rm n}/a_{\rm p}$

- Our methods are independent of the velocity distribution, the local dentity, and the mass/couplings on nucleons of halo WIMPs (none of them is yet known).

- For a WIMP mass of 100 GeV these quantities could be estimated with statistical errors of 10 – 40% with only 50 events from each experiment.

Summary and outlook

- ❑ These information will help us to
    - ➢ constrain the parameter space
    - ➢ distinguish the (neutralino) LSP from the (first KK hypercharge) LKP

      G. Bertone *et al.*, PRL 99, 151301 (2007); G. Belanger *et al.*, `arXiv:0810.1362` (2008)
    - ➢ identify the particle produced at colliders to be indeed Dark Matter
    - ➢ predict the WIMP annihilation cross section $\langle \sigma_{\rm anni} v \rangle$
    - ➢ ......

- ❑ Furthermore, we could
    - ➢ determine the local WIMP density ρ_0
    - ➢ predict the indirect detection event rate $d\Phi/dE$
    - ➢ test our understanding of the early Universe
    - ➢ ......

Current projects and related research interests

- With direct DM detection experiments
  - Identifying the annual modulation of WIMP signals
  - Applying/extracting directional information of WIMP events

- With indirect DM detection experiments
  - Information on the spin-dependent WIMP-proton coupling
  - Information on (the anisotropy of) the halo structure

- With collider experiments
  - Identifying DM particles produced at colliders
  - Determining the properties of DM particles (more precisely)

Thank you very much for your attention

`[http://dmrc.snu.ac.kr/∼cshan/]`