Constraining the Spin-Independent WIMP-Nucleon Coupling from Direct Dark Matter Detection Data

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in collaboration with M. Drees

Review: what can we do with direct DM detection data

- Differential event rate for elastic WIMP-nucleus scattering

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

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.

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

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

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- Determining the moments of the WIMP velocity distribution

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

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

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

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- 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]

Review: what can we do with direct DM detection data

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

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

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

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

- Determining the WIMP mass

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

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

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

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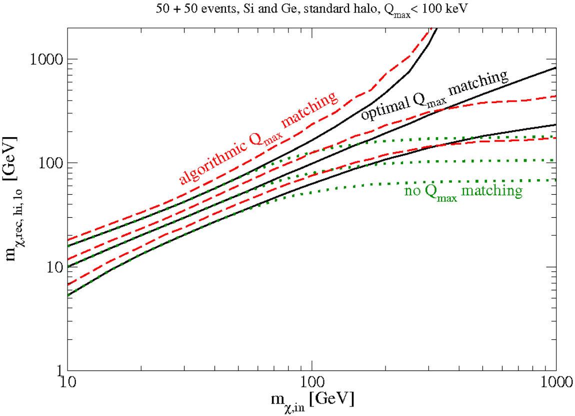
- Reconstructed m_χ
  ($Q_{\rm max} < 100$ keV, ^{76}Ge + ^{28}Si, 50 + 50 events)



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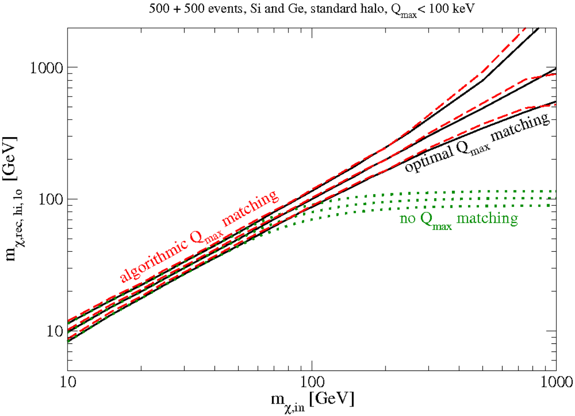

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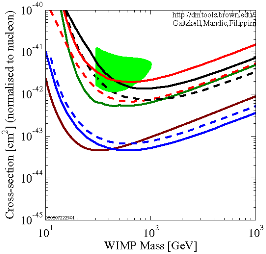

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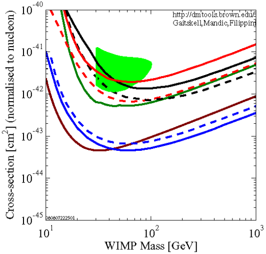

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- Determining the local WIMP density?

Estimating ratios of WIMP-nucleon cross sections

- −1-st moment of the WIMP velocity distribution

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

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

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- 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]

Only the SD cross section

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

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

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

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

- $m_\chi^{\rm SD} = m_\chi$

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

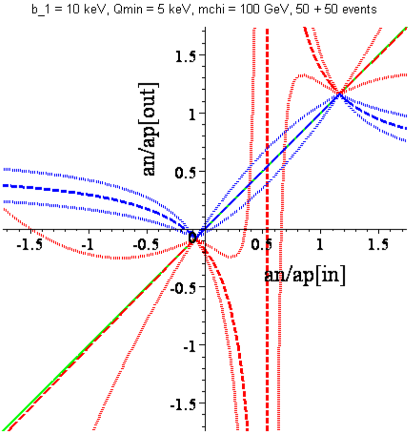
- Determining the ratio of two SD WIMP-nucleon couplings

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

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

Only the SD cross section

- Reproduced $(a_n/a_p)^{SD}_{\pm}$
  ($5 - 15$ keV, ^{73}Ge + ^{37}Cl, $50 + 50$ events, $m_\chi = 100$ GeV$/c^2$)



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

Combining the SI and SD cross sections

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

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

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

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- 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

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

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

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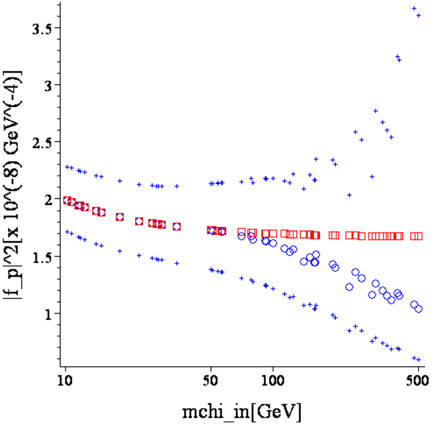
$$f_{\rm p}^2 = \frac{1}{\rho_0} \left[\frac{\pi}{4\sqrt{2}} \left(\frac{1}{\mathcal{E} A^2 \sqrt{m_{\rm N}}}\right)\right] (m_\chi + m_{\rm N}) \left[\frac{2 Q_{\rm min}^{1/2} r_{\rm min}}{F_{\rm SI}^2(Q_{\rm min})} + I_0\right]$$

Constraining the SI WIMP-nucleon coupling

- Reconstructed $f_{\rm p}^2$
  ($\sigma_{\chi {\rm p}}^{\rm SI} = 10^{-8}$ pb, $Q_{\rm max} < 100$ keV, $^{76}{\rm Ge} + ^{28}{\rm Si} + ^{76}{\rm Ge}$, 3×50 events)



[M. Drees and CLS, in progress]

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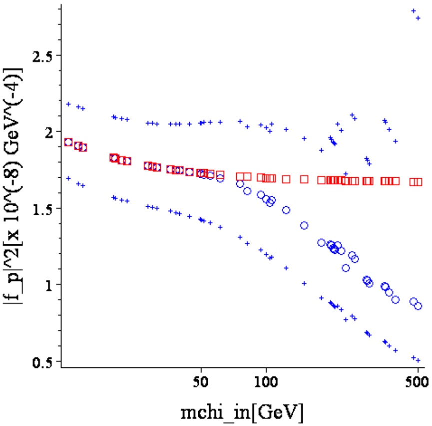

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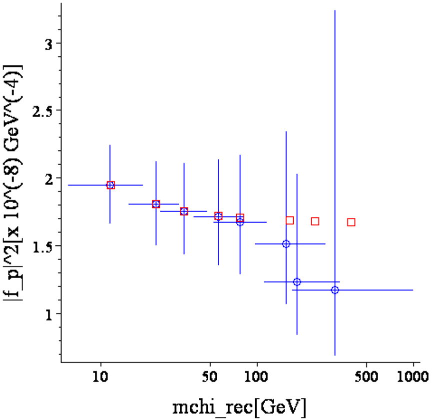

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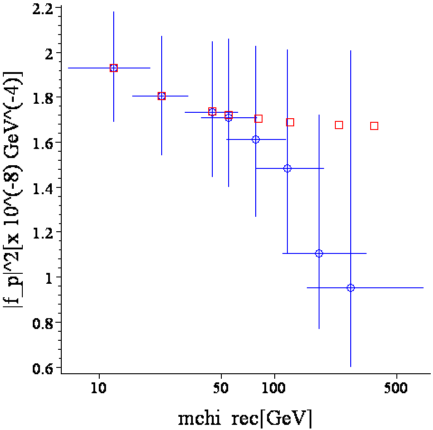

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- For a WIMP mass of 100 GeV the SI coupling could be estimated with an error of $\sim$ 30% with only 50 events from each experiment.
- In spite of the uncertainty of the local Dark Matter density, at least an upper limit on the SI coupling could be given.
- A full Monte Carlo simulation is now in progress.

Outlook

- With measured recoil energies 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, $a_{\rm n} / a_{\rm p}$

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- These information will help us to
  - constrain the (SUSY) parameter space
  - identify the particle produced at colliders to be indeed Dark Matter
  - predict the WIMP annihilation cross section $\langle\sigma_{\rm anni} v\rangle$

Outlook

- With measured recoil energies 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, $a_{\rm n} / a_{\rm p}$
- These information will help us to
  - constrain the (SUSY) parameter space
  - 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 $d\Phi / dE$

Thank you very much for your attention