Data Analysis in Direct Searches for Inelastic Dark Matter

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Institute of Physics, Academia Sinica

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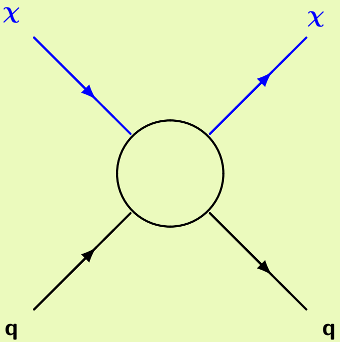
Motivation

- WIMP-nucleus scattering



Elastically

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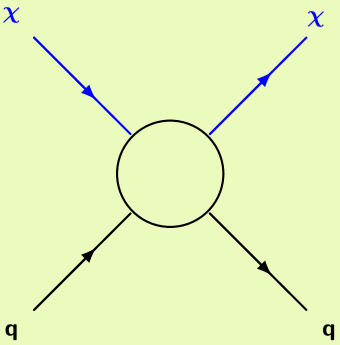

Elastically

- DAMA: 11-year annual modulation observation

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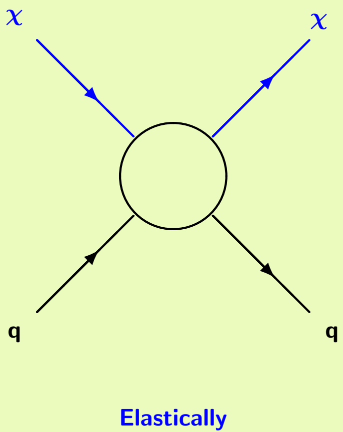

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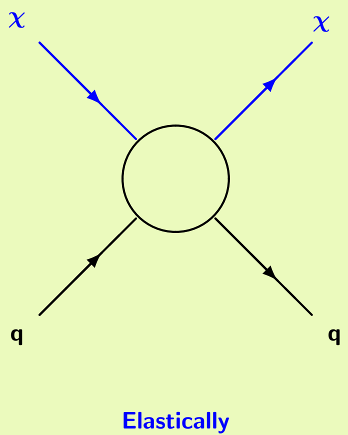

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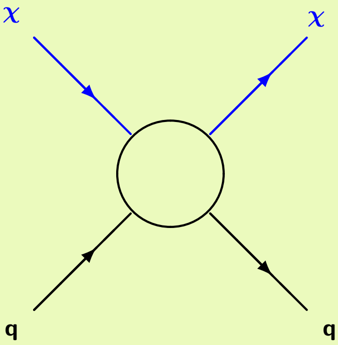

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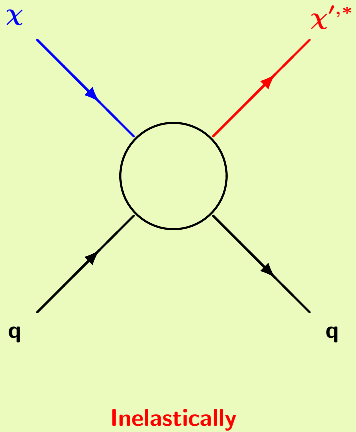

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- Differential event rate for elastic WIMP-nucleus scattering

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

Here

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

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

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Reconstruction of the WIMP velocity distribution - inelastic scattering

- Normalized one-dimensional WIMP velocity distribution function

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

with

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- Determining m_χ and δ (by combining two targets)

$$m_\chi = \frac{Q_{v_{\rm thre},Y}\, m_Y - Q_{v_{\rm thre},X}\, m_X}{Q_{v_{\rm thre},X} - Q_{v_{\rm thre},Y}}$$

$$\delta = \frac{Q_{v_{\rm thre},X}\, Q_{v_{\rm thre},Y}\,(m_Y - m_X)}{Q_{v_{\rm thre},Y}\, m_Y - Q_{v_{\rm thre},X}\, m_X}$$

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Reconstruction of the recoil spectrum - elastic scattering

- Integrals over two simplest theoretical velocity distributions

$$\left(\frac{dR}{dQ}\right)_{\rm Gau} \propto F^2(Q)\, e^{-\alpha^2 Q/v_0^2}$$

$$\left(\frac{dR}{dQ}\right)_{\rm sh} \propto F^2(Q)\left[\text{erf}\left(\frac{\alpha\sqrt{Q}+v_e}{v_0}\right) - \text{erf}\left(\frac{\alpha\sqrt{Q}-v_e}{v_0}\right)\right]$$

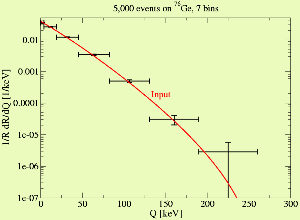
- Exponential ansatz for reconstructing the measured recoil spectrum (in the nth Q-bin)

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

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

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

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



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

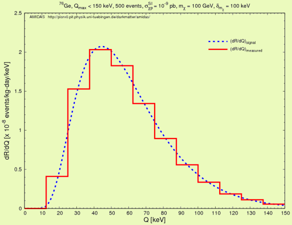
Reconstruction of the recoil spectrum - inelastic scattering

- Integrals over two simplest theoretical velocity distributions

$$\left(\frac{dR}{dQ}\right)_{\rm in,\ Gau} \propto F^2(Q)\, e^{-\left(\alpha^2 Q \,+\, \alpha_\delta^2/Q\right)/v_0^2}$$

$$\left(\frac{dR}{dQ}\right)_{\rm in,\ sh} \propto F^2(Q)\left[\mathrm{erf}\left(\frac{\alpha\sqrt{Q}+\alpha_\delta/\sqrt{Q}+v_e}{v_0}\right) - \mathrm{erf}\left(\frac{\alpha\sqrt{Q}+\alpha_\delta/\sqrt{Q}-v_e}{v_0}\right)\right]$$

- Typical recoil spectrum



- Ansatz for reconstructing the measured recoil spectrum

$$\left(\frac{dR}{dQ}\right)_{\rm in,\ expt} = r_0\, e^{-kQ-k'/Q}$$

Reconstruction of the recoil spectrum - inelastic scattering

- Moments of the measured recoil energies

$$\int_{x_1}^{x_2} \frac{1}{\sqrt{x}}\, e^{-ax-b/x}\, dx = \frac{1}{2}\sqrt{\frac{\pi}{a}}\left\{e^{2\sqrt{a}\sqrt{b}}\left[\mathrm{erf}\left(\sqrt{a}\sqrt{x_2}+\frac{\sqrt{b}}{\sqrt{x_2}}\right)-\mathrm{erf}\left(\sqrt{a}\sqrt{x_1}+\frac{\sqrt{b}}{\sqrt{x_1}}\right)\right]\right.$$
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$$\int_{x_1}^{x_2} \sqrt{x}\, e^{-ax-b/x}\, dx$$
$$= \frac{1}{2}\sqrt{\frac{\pi}{a}}\left\{\frac{1}{2a}\left\{e^{2\sqrt{a}\sqrt{b}}\left[\mathrm{erf}\left(\sqrt{a}\sqrt{x_2}+\frac{\sqrt{b}}{\sqrt{x_2}}\right)-\mathrm{erf}\left(\sqrt{a}\sqrt{x_1}+\frac{\sqrt{b}}{\sqrt{x_1}}\right)\right]\right.\right.$$
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$$-\sqrt{\frac{b}{a}}\left\{e^{2\sqrt{a}\sqrt{b}}\left[\mathrm{erf}\left(\sqrt{a}\sqrt{x_2}+\frac{\sqrt{b}}{\sqrt{x_2}}\right)-\mathrm{erf}\left(\sqrt{a}\sqrt{x_1}+\frac{\sqrt{b}}{\sqrt{x_1}}\right)\right]\right.$$
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$$-\frac{1}{a}\left(\sqrt{x_2}\, e^{-ax_2-b/x_2}-\sqrt{x_1}\, e^{-ax_1-b/x_1}\right)$$

Reconstruction of the recoil spectrum - inelastic scattering

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$$k = \frac{1}{2} \left(\frac{\left\langle Q^{-1/2} \right\rangle \left\langle Q^{-3/2} \right\rangle}{\left\langle Q^{1/2} \right\rangle \left\langle Q^{-3/2} \right\rangle - \left\langle Q^{-1/2} \right\rangle^2} \right) \qquad k' = \frac{1}{2} \left(\frac{\left\langle Q^{-1/2} \right\rangle \left\langle Q^{-3/2} \right\rangle}{\left\langle Q^{-1/2} \right\rangle \left\langle Q^{-5/2} \right\rangle - \left\langle Q^{-3/2} \right\rangle^2} \right)$$

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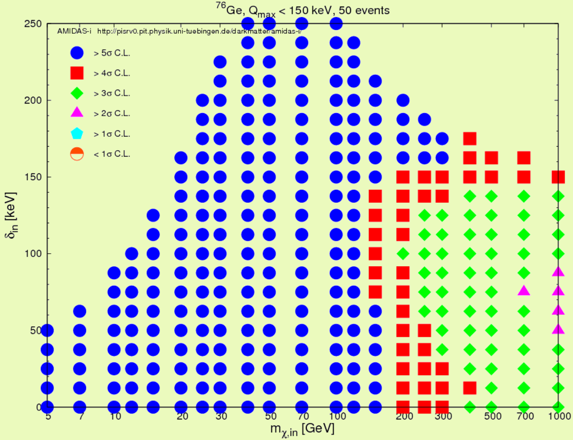
- Equation for solving $Q_{v_{\text{thre}}}$

$$\left(k - \frac{k'}{Q_{v_{\text{thre}}}^2} \right) + \frac{2}{F\left(Q_{v_{\text{thre}}}\right)} \left(\frac{dF}{dQ} \right)_{Q = Q_{v_{\text{thre}}}} = 0$$

Reconstruction of the recoil spectrum - inelastic scattering

- Checking whether $Q_{v_{\rm thre},\rm rec} > 0$
  (^{76}Ge, $0 - 150$ keV, 50 events)



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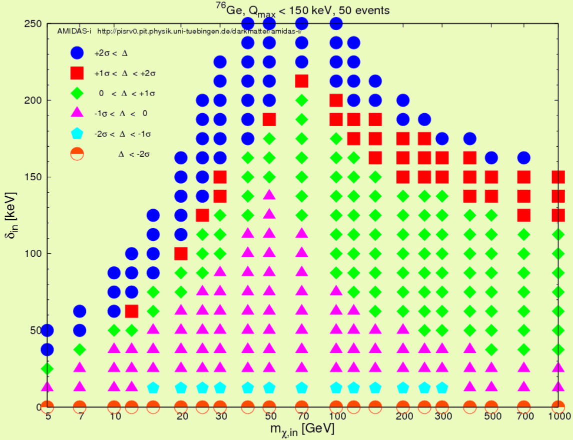

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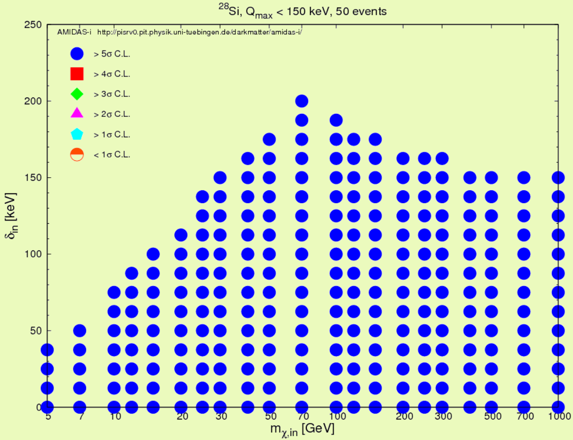

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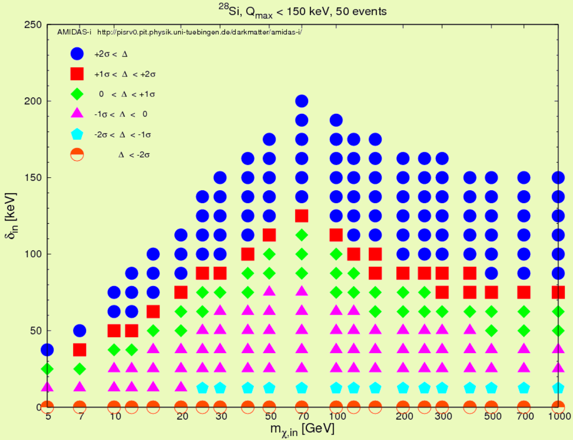

Determinations of the WIMP mass and the mass splitting

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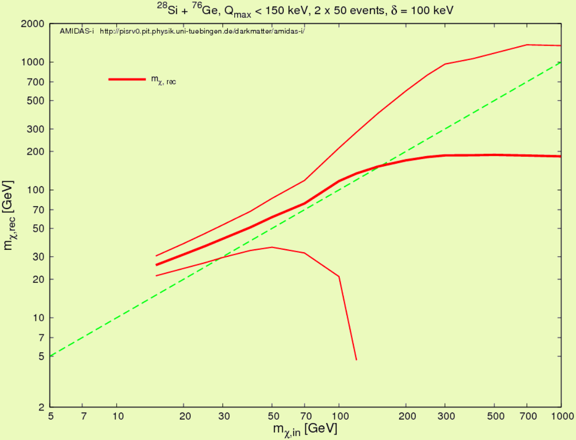

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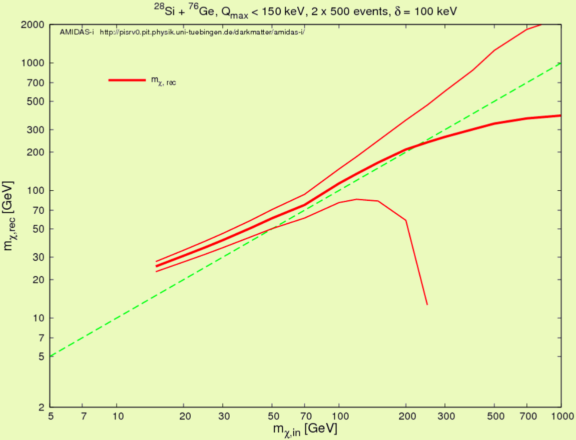

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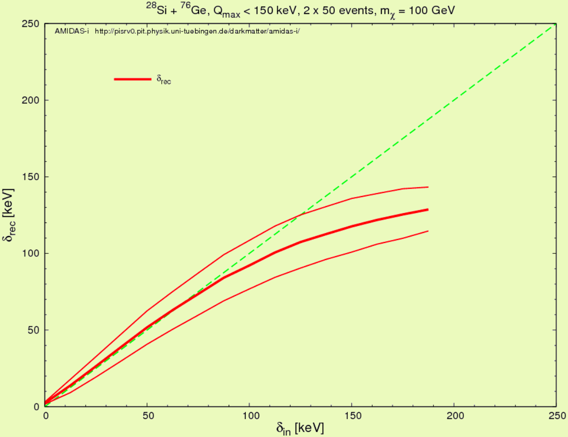

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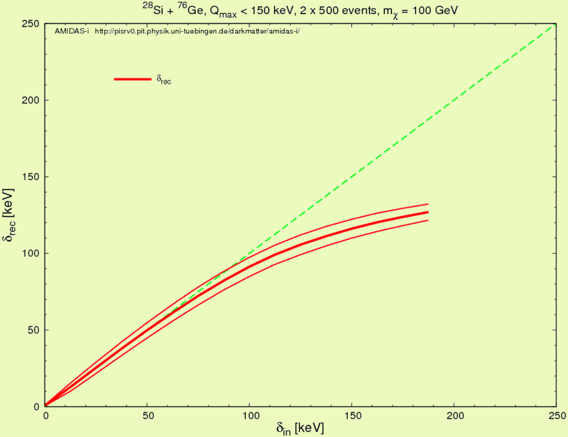

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- For elastic ($\delta = 0$) case, we could observe
  - very small, but non-zero positive $Q_{v_{\rm thre}}$...
  - very small, but non-zero positive δ...
  - (unphysically) negative m_χ: the larger the input m_χ, the larger the absolute value of the reconstructed m_χ

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Reconstruction of the WIMP velocity distribution - inelastic scattering

- Normalized one-dimensional WIMP velocity distribution function

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

$$= \mathcal{N}\left\{\left(\alpha\sqrt{Q}+\frac{\alpha_\delta}{\sqrt{Q}}\right)\left(\alpha\sqrt{Q}-\frac{\alpha_\delta}{\sqrt{Q}}\right)^{-1} \times\left\{\frac{2Q}{F^2(Q)}\left[\frac{d}{dQ}\ln F^2(Q)+\left(k-\frac{k'}{Q^2}\right)\right]\left(\frac{dR}{dQ}\right)\right\}\right\}$$

with

$$Q(v) = \frac{v^2-2\alpha\alpha_\delta \pm v\sqrt{v^2-4\alpha\alpha_\delta}}{2\alpha^2}$$

and

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

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Thank you very much for your attention!