Extracting Astrophysical Information about Galactic Dark Matter with and without Astrophysical Prior Knowledge

Chung-Lin Shan

Xinjiang Astronomical Observatory
Chinese Academy of Sciences

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AMIDAS package
Motivation

Reconstruction of the 1-D WIMP velocity distribution
Without astrophysical assumptions
With a model of the WIMP velocity distribution

Summary

AMIDAS package
– **A** **M**odel-**I**ndependent **D**ata **A**nalysis **S**ystem

AMIDAS package

- AMIDAS: A Model-Independent Data Analysis System
  for direct Dark Matter detection experiments and phenomenology

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[CLS, Phys. Dark Univ. 5-6, 240 (2014)]

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  - Full Monte Carlo simulations
  - Theoretical estimations
  - Real/pseudo- data analyses

Motivation

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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,

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

ρ_0: WIMP density near the Earth

σ_0: total cross section ignoring the form factor suppression

$F(Q)$: elastic nuclear form factor

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Particle physics

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Reconstruction of the 1-D WIMP velocity distribution

Without astrophysical assumptions

Reconstruction of the 1-D WIMP velocity distribution

- Normalized one-dimensional WIMP velocity distribution function

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

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

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- 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 (2007)]

Reconstruction of the 1-D WIMP velocity distribution

- Ansatz: the measured recoil spectrum in the nth Q-bin

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

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

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

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

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- Reconstructing the one-dimensional WIMP velocity distribution

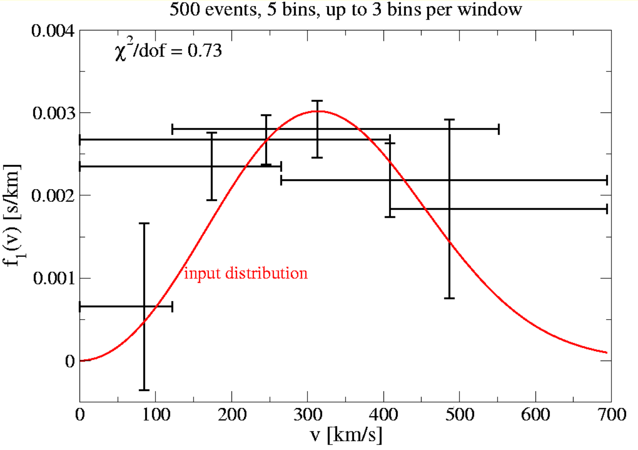
$$f_1(v_{s,n}) = \mathcal{N}\left[\frac{2 Q_{s,n} r_n}{F^2(Q_{s,n})}\right]\left[\frac{d}{dQ} \ln F^2(Q)\Big|_{Q = Q_{s,n}} - k_n\right]$$

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

[M. Drees and CLS, JCAP 0706, 011 (2007)]

Reconstruction of the 1-D WIMP velocity distribution

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



[M. Drees and CLS, JCAP 0706, 011 (2007)]

Reconstruction of $f_1(v)$ with a non-negligible threshold energy

- Consider the non-zero minimal cut-off velocity

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

where

$$\left(\frac{dR}{dQ} \right)_{{\rm expt},\ Q = Q_{\rm min}} = r_1 \, e^{k_1 (Q_{\rm min} - Q_{s,1})} \equiv r(Q_{\rm min})$$

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

$$Q_{\rm max}^* \equiv \min \left(Q_{\rm max},\ \ Q_{\rm max,kin} = \frac{v_{\rm max}^2}{\alpha^2} \right)$$

[CLS, IJMPD 24, 1550090 (2015)]

Reconstruction of $f_1(v)$ with a non-negligible threshold energy

- Height of the velocity distribution at the non-zero minimal cut-off velocity

$$f_{1,\mathrm{rec}}(v_{\mathrm{min}}^*) = \mathcal{N}\left[\frac{2Q_{\mathrm{min}}\, r(Q_{\mathrm{min}})}{F^2(Q_{\mathrm{min}})}\right]\left[\frac{d}{dQ}\ln F^2(Q)\bigg|_{Q=Q_{\mathrm{min}}} - k_1\right] \equiv \mathcal{N}\tilde{f}_{1,\mathrm{rec}}(v_{\mathrm{min}}^*)$$

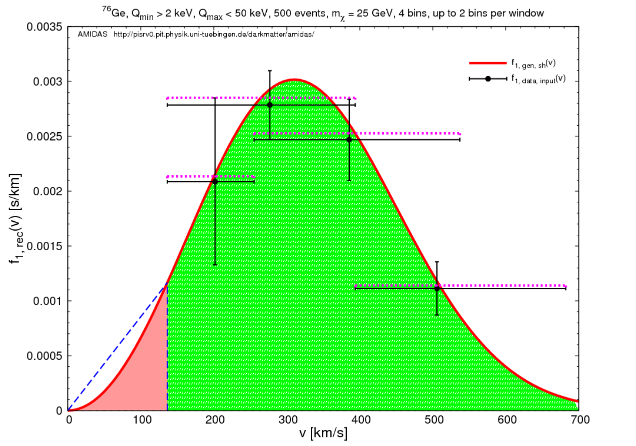
- Consider the contribution below the non-zero minimal cut-off velocity

$$\mathcal{N} = \frac{2}{\alpha}\left[\tilde{f}_{1,\mathrm{rec}}(v_{\mathrm{min}}^*)\, Q_{\mathrm{min}}^{1/2} + \frac{2Q_{\mathrm{min}}^{1/2}}{F^2(Q_{\mathrm{min}})}\left(\frac{dR}{dQ}\right)_{\mathrm{expt},\ Q=Q_{\mathrm{min}}} + I_0(Q_{\mathrm{min}}, Q_{\mathrm{max}}^*)\right]^{-1}$$

[CLS, IJMPD 24, 1550090 (2015)]

Reconstruction of $f_1(v)$ with a non-negligible threshold energy

- Reconstructed $f_{1,\rm rec}(v_{s,n})$ with the input WIMP mass
  (^{76}Ge, 2 - 50 keV, 500 events, $m_\chi = 25$ GeV)



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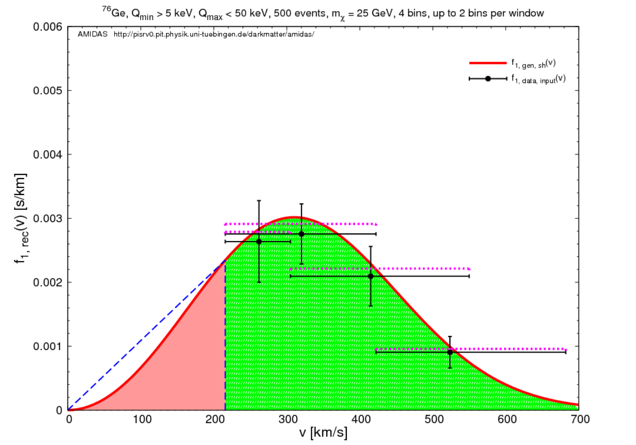

[CLS, IJMPD 24, 1550090 (2015)]

With a model of the WIMP velocity distribution – Bayesian analysis

Bayesian reconstruction of $f_1(v)$

- Bayesian analysis

$$\mathrm{p}(\Theta|\mathrm{data}) = \frac{\mathrm{p}(\mathrm{data}|\Theta)}{\mathrm{p}(\mathrm{data})} \cdot \mathrm{p}(\Theta)$$

  - Θ: $\left\{a_1, a_2, \cdots, a_{N_{\mathrm{Bayesian}}}\right\}$, a specified (combination of the) value(s) of the fitting parameter(s)
  - $\mathrm{p}(\Theta)$: prior probability, our degree of belief about Θ being the true value(s) of fitting parameter(s), often given in form of the (multiplication of the) probability distribution(s) of the fitting parameter(s)
  - $\mathrm{p}(\mathrm{data}|\Theta)$: the probability of the observed result, once the specified (combination of the) value(s) of the fitting parameter(s) happens, usually be described by the "likelihood" function of Θ, $\mathcal{L}(\Theta)$.
  - $\mathrm{p}(\Theta|\mathrm{data})$: posterior probability density function for Θ, the probability of that the specified (combination of the) value(s) of the fitting parameter(s) happens, given the observed result

Bayesian reconstruction of $f_1(v)$

- Probability distribution functions for p(Θ)
  - Without prior knowledge about the fitting parameter
    - Flat-distributed

$$\mathrm{p}_i(a_i) = 1 \qquad \text{for } a_{i,\mathrm{min}} \le a_i \le a_{i,\mathrm{max}}$$

  - With prior knowledge about the fitting parameter
    - Around a theoretical predicted/estimated or experimental measured value $\mu_{a,i}$
    - With (statistical) uncertainties $\sigma_{a,i}$
    - Gaussian-distributed

$$\mathrm{p}_i(a_i; \mu_{a,i}, \sigma_{a,i}) = \frac{1}{\sqrt{2\pi}\,\sigma_{a,i}}\, e^{-(a_i - \mu_{a,i})^2/2\sigma_{a,i}^2}$$

[CLS, JCAP 1408, 009 (2014)]

Bayesian reconstruction of $f_1(v)$

- Likelihood function for p(data|Θ)
  - Theoretical one-dimensional WIMP velocity distribution function: $f_{1,\rm th}(v; a_1, a_2, \cdots, a_{N_{\rm Bayesian}})$
  - Assuming that the reconstructed data points are Gaussian-distributed around the theoretical predictions

$$\mathcal{L}\Big(f_{1,\rm rec}(v_{s,\mu}),\ \mu = 1,\ 2,\ \cdots,\ W;\ a_i,\ i = 1,\ 2,\ \cdots,\ N_{\rm Bayesian}\Big)$$
$$\equiv \prod_{\mu=1}^{W} {\rm Gau}\Big(v_{s,\mu}, f_{1,\rm rec}(v_{s,\mu}), \sigma_{f_1,s,\mu}; a_1, a_2, \cdots, a_{N_{\rm Bayesian}}\Big)$$

with

$${\rm Gau}\Big(v_{s,\mu}, f_{1,\rm rec}(v_{s,\mu}), \sigma_{f_1,s,\mu}; a_1, a_2, \cdots, a_{N_{\rm Bayesian}}\Big)$$
$$\equiv \frac{1}{\sqrt{2\pi}\,\sigma_{f_1,s,\mu}}\, e^{-\left[f_{1,\rm rec}(v_{s,\mu}) - f_{1,\rm th}(v_{s,\mu}; a_1, a_2, \cdots, a_{N_{\rm Bayesian}})\right]^2 / 2\sigma^2_{f_1,s,\mu}}$$

[CLS, JCAP 1408, 009 (2014)]

Bayesian reconstruction of $f_1(v)$

- Input and fitting one-dimensional WIMP velocity distribution functions
  - "One-parameter" shifted Maxwellian velocity distribution

$$f_{1,\mathrm{sh},v_0}(v) = \frac{1}{\sqrt{\pi}} \left(\frac{v}{v_0 v_\mathrm{e}} \right) \left[e^{-(v-v_\mathrm{e})^2/v_0^2} - e^{-(v+v_\mathrm{e})^2/v_0^2} \right] \qquad v_\mathrm{e} = 1.05\, v_0$$

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  - Shifted Maxwellian velocity distribution

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  - "Variated" shifted Maxwellian velocity distribution

$$f_{1,\mathrm{sh},\Delta v}(v) = \frac{1}{\sqrt{\pi}} \left[\frac{v}{v_0 \left(v_0 + \Delta v \right)} \right] \left\{ e^{-[v - (v_0 + \Delta v)]^2/v_0^2} - e^{-[v + (v_0 + \Delta v)]^2/v_0^2} \right\}$$

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  - Simple Maxwellian velocity distribution

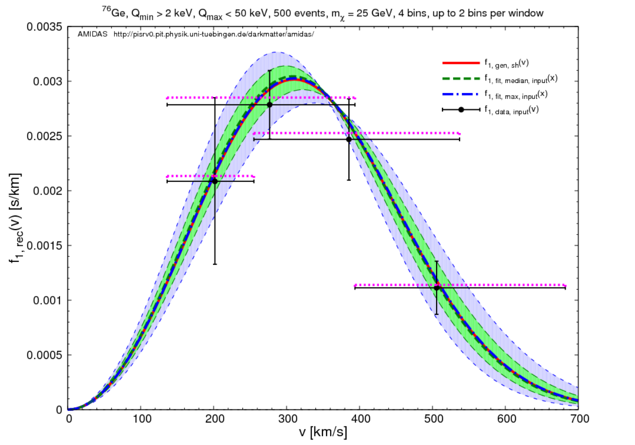
$$f_{1,\mathrm{Gau}}(v) = \frac{4}{\sqrt{\pi}} \left(\frac{v^2}{v_0^3} \right) e^{-v^2/v_0^2}$$

  - "Modified" simple Maxwellian velocity distribution

$$f_{1,\mathrm{Gau},k}(v) = \frac{v^2}{N_{f,k}} \left(e^{-v^2/kv_0^2} - e^{-v_{\max}^2/kv_0^2} \right)^k \qquad \text{for } v \le v_{\max}$$

Bayesian reconstruction of $f_1(v)$

- Reconstructed $f_{1,\text{Bayesian}}(v)$ with the input WIMP mass
  (^{76}Ge, 2 - 50 keV, 500 events, $m_\chi = 25$ GeV, $f_{1,\text{sh},v_0}(v) \Rightarrow f_{1,\text{sh},v_0}(v)$, flat-dist.)



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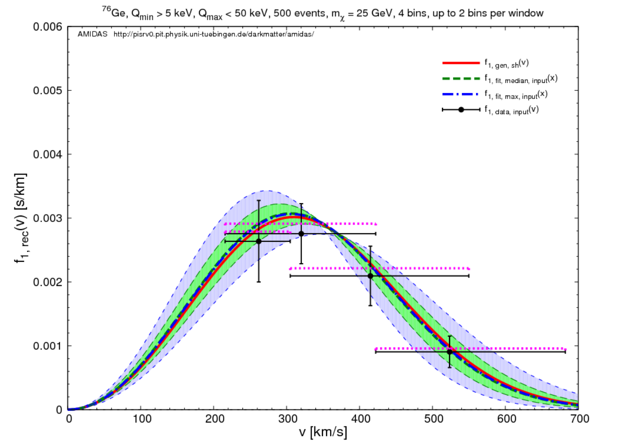

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- Once two or more experiments with different target nuclei observe positive WIMP signals, we could reconstruct
  - WIMP mass m_χ
    [M. Drees and CLS, JCAP 0806, 012 (2008)]
  - 1-D velocity distribution $f_1(v)$
    [M. Drees and CLS, JCAP 0706, 011 (2007); CLS, IJMPD 24, 1550090 (2015)]
  - SI WIMP-proton coupling $|f_\mathrm{p}|^2$ (with an assumed ρ_0)
    [CLS, arXiv:1103.0481]
  - ratio between the SD WIMP-nucleon couplings $a_\mathrm{n}/a_\mathrm{p}$
    [CLS, JCAP 1107, 005 (2011)]
  - ratios between the SD and SI WIMP-nucleon cross sections $\sigma_{\chi(\mathrm{p,n})}^\mathrm{SD}/\sigma_{\chi\mathrm{p}}^\mathrm{SI}$
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- With an assumed $f_{1,{\rm th}}(v)$, one can fit $f_1(v)$ by using Bayesian analysis.
  [CLS, JCAP 1408, 009 (2014)]
- For these analyses the local density, the velocity distribution, and the mass/couplings on nucleons of halo WIMPs are not required priorly.

Further projects

- Extension for directional direct DM detection [Daniel's talk]
  - Combining with 3-D information (e.g. recoil angles, track senses)
  - without assumptions/models
  - with an assumed $f_{\rm th}(\mathbf{v})$

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- Consideration of effects of anisotropic background sources, e.g.
  - gamma-ray burst
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  - gamma-ray burst
  - cosmic-ray/Solar neutrinos
- Information from/analysis results for indirect DM detection (satellite) experiments
  - DAMPE (Purple Mountain Observatory, Chinese Academy of Sciences)
    launched on December 17th, 2015
    http://dpnc.unige.ch/dampe/

Thank you very much for your attention!