Reconstructing Properties of Galactic Dark Matter Particles by Using Direct Detection Data

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Review
Direct Dark Matter detection

Model-independent data analyses
Motivation
Reconstruction of the WIMP velocity distribution
Determination of the WIMP mass

AMIDAS package and website

Summary
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**
  - \( p, e \) to DM
  - DM to \( p, e^+ \)

- **Indirect detection**
  - DM to e, \( \nu_\mu, \gamma \)
  - e\(^+\), \( \bar{p}, \bar{D} \)

- **Direct detection**
  - DM to DM\(^{('), (*)}\)
  - q to q
Review

- **Existence of Dark Matter (DM)**
  - **Clusters of galaxies**
    - [Coma cluster of galaxies; F. Zwicky (1933)]
  - **Bullet Cluster**
    - [http://chandra.harvard.edu/photo/2006/1e0657/]
  - **Abundances of D, $^3$He, $^4$He**
    - [Review of Particle Physics 2006]

- **Galactic rotation curves**

- **CMBR anisotropy**
  - [NASA/WMAP Science Team, WMAP5 (2008)]

- **SNe Ia observations at high-z**
  - [Supernova Cosmology Project 2010]
Review

- Majority of **Cold Dark Matter (CDM)**
  - moved *non-relativistically* when galaxies could just start to form (matter-radiation decoupling time).
  - would form some **small galactic scale structures** due to their relatively slower velocities (*botton-up*).

  ⇧

- **Hot Dark Matter (HDM)**
  - moved *relativistically* at the matter-radiation decoupling time.
  - would cover great(er) distances and form some **very large scale structures** (*top-down*).

- **Warm Dark Matter (WDM)**

- **Dark baryons**
Review

- Weakly Interacting Massive Particles (WIMPs) $\chi$
  - Dark Matter relic density
    $$ \Omega_\chi h^2 \sim \frac{3 \times 10^{-27} \text{ cm}^3/\text{s}}{\langle \sigma_{\text{anni}} \nu \rangle} = 0.112 \pm 0.006 $$
    $$ \Rightarrow \langle \sigma_{\text{anni}} \nu \rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s} $$
    $$ \Rightarrow \text{weak interaction} $$

  - Gravitational, EM, strong interactions
  - Mass ranges roughly between 10 GeV and a few TeV.
    $$ v_\chi \sim 10^{-3} \text{c} \Rightarrow Q \sim \left( \frac{10^{-6}}{2} \right) m_\chi $$
    $$ \Leftrightarrow \text{Gravitino, axion, axino} $$
Review

- 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 $< 1$ 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 $\approx \mathcal{O}(10^6) : 1$
Review

- Direct DM detection (elastic WIMP-nucleus scattering)
  - 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.
Review

- Direct DM detection (elastic WIMP-nucleus scattering)
  - 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
Model-independent data analyses
**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,

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

- \(\rho_0\): 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
Reconstructing Properties of Galactic Dark Matter Particles by Using Direct Detection Data

- Model-independent data analyses
- Reconstruction of the WIMP velocity distribution

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

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

\[
N(Q_{\text{thre}}) = \frac{2}{\alpha} \left[ \frac{2Q_{\text{thre}}^{1/2}}{F^2(Q_{\text{thre}})} \left( \frac{dR}{dQ} \right) \right]_{Q = Q_{\text{thre}}}^{-1} + l_0(Q_{\text{thre}})
\]

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

[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

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

\[ r_n \equiv \frac{N_n}{b_n} \]

- 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

\[
f_1(v_{s,n}) = \mathcal{N} \left[ \frac{2 Q_{s,n} r_n}{F^2(Q_{s,n})} \right] \left[ \frac{1}{dQ} \ln F^2(Q) \bigg|_{Q=Q_{s,n}} - k_n \right]
\]

\[
\mathcal{N} = \frac{2}{\alpha} \left[ \sum_{a} \frac{1}{\sqrt{Q_a} F^2(Q_a)} \right]^{-1}
\]

\[ v_{s,n} = \alpha \sqrt{Q_{s,n}} \]

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

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

\[ \chi^2 / \text{dof} = 0.73 \]

Determination of the WIMP mass

- Estimating the moments of the WIMP velocity distribution

\[ \langle v^n \rangle = \alpha^n \left[ \frac{2Q_{\text{min}}^{1/2} r_{\text{min}}}{F^2(Q_{\text{min}})} + l_0 \right]^{-1} \left[ \frac{2Q_{\text{min}}^{(n+1)/2} r_{\text{min}}}{F^2(Q_{\text{min}})} + (n + 1) l_n \right] \]

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

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

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

- Determining the WIMP mass

\[ m_\chi |_{\langle v^n \rangle} = \frac{\sqrt{m_\chi m_\gamma} - m_\chi R_n}{R_n - \sqrt{m_\chi/m_\gamma}} \]

\[ R_n = \left[ \frac{2Q_{\text{min},X}^{(n+1)/2} r_{\text{min},X} / F_X^2(Q_{\text{min},X}) + (n + 1) l_n,X}{2Q_{\text{min},X}^{1/2} r_{\text{min},X} / F_X^2(Q_{\text{min},X}) + l_0,X} \right]^{1/n} \]

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

[CLS and M. Drees, arXiv:0710.4296]

- Assuming a dominant SI WIMP-nucleus interaction

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

\[ R_\sigma = \frac{E_\gamma}{E_X} \left[ \frac{2Q_{\text{min},X}^{1/2} r_{\text{min},X} / F_X^2(Q_{\text{min},X}) + l_0,X}{2Q_{\text{min},Y}^{1/2} r_{\text{min},Y} / F_Y^2(Q_{\text{min},Y}) + l_0,Y} \right] \]

[M. Drees and CLS, JCAP 0806, 012 (2008)]
Reconstructing Properties of Galactic Dark Matter Particles by Using Direct Detection Data

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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

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

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

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

- Algorithmic $Q_{\max}$ matching

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

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

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

\[ \text{[M. Drees and CLS, JCAP 0806, 012 (2008)]} \]
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/)
  - 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
  - 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.

- Our data analysis procedures could extract WIMP properties **model-independently** by combining data sets with different detector materials without knowing the local density, the velocity distribution, and the mass/couplings on nucleons of halo WIMPs priorly.

- Once two or more experiments with different target nuclei observe positive WIMP signals, we could determine:
  - WIMP mass \( m_\chi \)
  - 1-D velocity distribution \( f_1(v) \)
  - SI WIMP-proton coupling \( |f_p|^2 \)
  - ratio between the SD WIMP-nucleon couplings \( a_n/a_p \)
  - ratios between the SD and SI WIMP-nucleon cross sections \( \sigma^{SD}_{\chi(p,n)}/\sigma^{SI}_{\chi p} \)
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 $\langle \sigma_{\text{anni}} \rangle$

- 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!