Light Dark Matter & Direct Detection

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Based on papers:


Coherent Neutrino Scattering Experiment Workshop - Mitchell Institute, November 12, 2015
OUTLINE

Part I: DM and baryons may have more in common than we think.

- In Asymmetric DM models they share a common origin.
-Prefers 1-10 GeV DM in most cases.
- Need to worry about astro-uncertainties in DD.

Part II: Lack of any clear DM signals may motivate re-thinking standard thermal relic tests.

- Perhaps only DM’s annihilation products couple to SM (similar to boosted DM scenarios).
- Can use DD to probe DM masses as low as 10 MeV.
- Distinctive Recoil spectrum from relativistic scattering.
Miracle WIMP

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The universe expands, and $X$'s cool.

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Miracle WIMP

- At early times, $X$ is in thermal/chemical eq. via $\bar{X}X \leftrightarrow l\bar{l}$
- The universe expands, and $X$'s cool.
- Annihilations “freeze out” around:

\[ H \sim \Gamma_{\text{ann}} \sim \langle \sigma v \rangle n_{eq} \]

\[ \Omega_{DM} h^2 \sim 0.11 \left( \frac{3 \times 10^{-26} \text{ cm}^3/s}{\langle \sigma v \rangle} \right) \]

[Zel’dovich (1965), Zel’dovich, Okun, Pikelner (1965), Chiu (1966), Lee & Weinberg (1977), Wolfram (1979)]
What about baryons?
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- The amounts of dark and visible matter are comparable:

\[ \Omega_{DM} h^2 = 0.1109 \pm 0.0056 \]
\[ \Omega_B h^2 = 0.02258 \pm 0.00057 \]

DMB ratio:

\[ \frac{\Omega_{DM}}{\Omega_B} \approx 5 \]
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  1. A remarkable coincidence.
  3. An indication of an underlying origin.
PART I:
ASYMMETRIC DARK MATTER

Based on papers:

• Perhaps the DM is more like baryons and carries some particle/antiparticle asymmetry.

\[ \eta \equiv \frac{n - \bar{n}}{n_\gamma} \neq 0 \]
Asymmetric Dark Matter

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Other mass scales possible, but ~1-10 GeV is typical.
[Buckley, Randall (2009), Graesser, IMS, Vecchi (2011)]
Generating primordial asymmetries

Sakharov conditions for particle asymmetry are generic:

- Symmetry violation, e.g. baryon number violation.
- C & CP violation.
- Departure from thermal equilibrium.

A. Sakharov 1967
Asymmetry generation: create \textit{either} baryon or dark asymmetry.

\[
\eta_B \neq 0
\]
Invoke standard baryogenesis: EW baryogenesis, leptogenesis, Affleck-Dine.

\[
\eta_X \neq 0
\]
“Darken” a standard mechanism...
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Transfer asymmetry to the other sector

Success!

$\eta_X = a \eta_B$
ADM Thermal History

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Transfer asymmetry to the other sector

\[ \mathcal{O}_{B-L} \mathcal{O}_X \]

Success!

\[ \eta_X = a \eta_B \]

Efficient annihilation removes “symmetric” component until freeze-out.

\[ \frac{\Omega_X}{\Omega_B} = a \frac{m_X}{m_p} \left( \frac{1 + n^-/n^+}{1 - n^-/n^+} \right) \]
Asymmetric Relic Abundance
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symmetric DM

asymmetric DM

\{ 

X \quad X

\}

\[ \bar{X} \quad \bar{X} \]
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\[ \text{annihilate away} \]
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Generically need larger than WIMP annihilation cross sections.
On the origin of asymmetric species

Graesser, IMS, Vecchi (2010)
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- We assume that the particle $X$ carries a $U(1)_X$ charge, and that some asymmetry is generated at high-$T$. 

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$$\frac{d n^\pm}{d t} + 3 H n^\pm = -\langle \sigma_{\text{ann}} v \rangle (n^+ n^- - n_{\text{eq}}^+ n_{\text{eq}}^-)$$

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\]

\[
\langle \sigma_{ann} v \rangle = \sigma_0 \left( \frac{T}{m} \right)^n
\]

\[
n_{eq}^\pm = e^{\pm \mu / T} g \left( \frac{mT}{2\pi} \right)^{3/2} e^{-m/T}
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• Assume no new entropy production $Y^\pm \equiv \frac{n^\pm}{s}$

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• Assume no new entropy production

$$Y^\pm \equiv \frac{n^\pm}{s}$$

• Primordial asymmetry is conserved:

$$\eta_X \equiv Y^+ - Y^- \geq 0$$

Graesser, IMS, Vecchi (2010)
Fractional asymmetry

Convenient to change variables \( (Y^+, Y^-) \rightarrow (\eta, r) \) with

\[
    r \equiv \frac{Y^-}{Y^+}, \quad \eta \equiv Y^+ - Y^-
\]

And use dimensionless variables:

\[
    x \equiv \frac{m_X}{T} \quad \lambda = \left(\frac{\pi}{45}\right)^{1/2} \langle \sigma v \rangle m_X M_{\text{Pl}}
\]

Now only one non-trivial Boltzmann equation:

\[
    \frac{dr}{dx} = -\lambda \eta g^* \frac{1}{2} x^{-n-1/2} \left[ r - r_{\text{eq}} \left( \frac{1 - r}{1 - r_{\text{eq}}} \right)^2 \right]
\]

\[
    \frac{d\eta}{dx} = 0
\]
Annihilation for ADM


The ADM miracle cross section:

\[
\langle \sigma_{\text{ann}} v \rangle_{\text{ADM}} \approx \sqrt{\frac{45}{\pi} \frac{(n + 1) x_f^{n+1} s_0}{\rho_c \Omega_{\text{DM}} M_{\text{Pl}} \sqrt{g_*}}} \log \left( \frac{1}{r_{\infty}} \right)
\]

depends on fractional asymmetry, \(r_{\infty} \equiv \bar{n}/n\)
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ADM and WIMPs are not incompatible!
Present status
Nicole Bell, Shunsaku Horiuchi, IMS, Phys.Rev. D91 (2015) 2, 023505

symmetric limits
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symmetric limits

asymmetric limits

impose

\( \langle \sigma v \rangle_{ADM} \)
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Phys.Rev. D91 (2015) 2, 023505

Symmetric limits

Asymmetric limits

Indirect detection shouldn’t stop at WIMPs!
To be convincing though we need direct detection

For 1-10 GeV DM need both:
  • Low thresholds
  • Also need to have DM astrophysics well-understood since we’re probing the high-v tail of velocity distribution.
Where else might DM be hiding?
PART II:
ON THE DIRECT DETECTION OF DARK MATTER ANNHIILATION

Based on:
Let’s return to thermal relics
Important to keep an open mind

“Always the last place you look!”
Searching for the WIMP miracle directly in direct detection

**Standard Picture**
Searching for the WIMP miracle directly in direct detection

Standard Picture

indirect detection

\[
\begin{align*}
X & \quad \text{SM} \\
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\end{align*}
\]

Not all models obey this dichotomy

direct detection

\[
\begin{align*}
X & \quad X \\
\text{SM} & \quad \text{SM}
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**Standard Picture**

What to do if DM doesn’t couple directly to SM but its annihilation products do?
Searching for the WIMP miracle directly in direct detection

**Standard Picture**

Not all models obey this dichotomy

What to do if DM doesn’t couple directly to SM but its annihilation products do?

*Direct detection of DM annihilation!*

See also: Huang, Zhao [1312.0011]
Agashe, Cui, Necib, Thaler [1405.7370]

Direct Probe of Annihilation

DM annihilation in Galactic Center

LUX
Direct Probe of Annihilation

DM annihilation in Galactic Center

\[ \frac{dR}{dE_R} = \frac{\Phi_Y}{m_N} \int_{E_{\text{min}}(E_R)}^{\infty} dE_Y \frac{dN}{dE_Y} \left( \frac{d\sigma_{YN}}{dE_R} \right) \]
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\[E_{min}(E_R) = \sqrt{m_N E_R/2}\]
	hanks{thanks to relativistic kinematics.}
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Local flux of Y's:
\[ \Phi_Y = 1.6 \times 10^{-2} \text{cm}^{-2}\text{s}^{-1} \left( \frac{\langle \sigma_{XX \rightarrow YY} v_{\text{rel}} \rangle}{5 \times 10^{-26} \text{cm}^3\text{s}^{-1}} \right) \left( \frac{20 \text{ MeV}}{m_X} \right)^2 \]

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Local flux of Y’s:

model-dependent

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Results from LUX data

- Most obvious case for Y: a SM neutrino.

John F. Cherry, Mads T. Frandsen, and IMS,
Results from \textit{LUX} data

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\centering
\includegraphics[width=\linewidth]{image}
\caption{Graph showing annihilation cross section vs. dark matter mass.}
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\[ \mathcal{L} \supset b |\phi|^2 |H|^2 + g \phi \overline{Y} Y \]
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- For sufficiently heavy phi, interaction strength well-described by effective operator:

\[ G_Y(NN)(YY) \]

- Invisible Higgs width constrains:

\[ G_Y = \frac{(g \sin \theta) f_N}{m_\phi} \simeq 7 \times 10^3 \ G_F \ \left( \frac{g \sin \theta}{10^{-2}} \right) \left( \frac{0.2 \text{ GeV}}{m_\phi} \right)^2 \]

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How can we make this more model-independent?
Lightning review of halo-independent methods

Fox, Liu, Weiner [1011.1915]

• For ordinary non-relativistic DM scattering:

\[
\frac{dR}{dE_R} = \frac{A^2 F^2(E_R)}{2\mu_n^2} \times \tilde{g}(v_{\text{min}}) \quad v_{\text{min}} = \sqrt{\frac{m_N E_R}{2\mu_N^2}}
\]

where \( \tilde{g}(v_{\text{min}}) \equiv \frac{\rho_{\text{DM}} \sigma_n}{m_X} \int_{v_{\text{min}}(E_R)}^{\infty} \frac{f(v)}{v} d^3v \)

\[ m_X = 6 \text{ GeV} \]
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• Trade \((m_X, \sigma_n)\) for \((v_{\text{min}}, \tilde{g})\)

at fixed \(m_X\)
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• Trade \((m_X, \sigma_n)\) for \((v_{\text{min}}, \tilde{g})\) at fixed \(m_X\)
• How to construct g-vmin sensitivity plot:
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- How to construct \(g\)-\(v_{\text{min}}\) sensitivity plot:
  
  (1) For signals: \(\tilde{g}(v_{\text{min}}) \equiv 2\mu_n^2 (A^2 F^2(E_R))^{-1} dR/dE_R,\)
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- Trade \((m_X, \sigma_n)\) for \((v_{\text{min}}, \tilde{g})\) at fixed \(m_X\)

- How to construct g-vmin sensitivity plot:

1. For **signals**: \( \tilde{g}(v_{\text{min}}) \equiv 2\mu_n^2(A^2 F^2(E_R))^{-1}dR/dE_R, \)

2. For **constraints**:

   Use \( f(v) \geq 0 \) which implies, \( \tilde{g}(v_{\text{min}}) \geq \tilde{g}(\dot{v}_{\text{min}}) \Theta(\dot{v}_{\text{min}} - v_{\text{min}}) \)

At any given vmin pt., most conservative constraint on velocity integral comes from a step function.
Generalization to relativistic scattering

Apply same “isospin-conserving” assumption:

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Discussion of results:

\[
\begin{align*}
\tilde{g}(E_{\text{min}}) & \equiv 2\mu_n^2 (A^2 F^2(E_R))^{-1} dR/dE_R, \\
& \text{with } E_{\text{min}} \text{ depending on Galactic center, solar interior, etc.}
\end{align*}
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- **This result applies to all DM masses.**

\[ \tilde{g}(E_{\text{min}}) \]
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- No dependence on the DM density distribution.
- No dependence on the assumed form of the Y-nucleus scattering, Y energy spectrum.
- **This result applies to all DM masses.**
- Applies equally well to non-DM direct detection possibilities…

---

Neutrino “backgrounds”

- Solar neutrinos will eventually be a direct detection background.
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- If neutrinos have new interactions, the signal might be closer than expected, see e.g. Pospelov (1103.3261), Pospelov, Pradler (1203.0545), Kopp, Harnik, Machado (1202.6073).
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- If neutrinos have new interactions, the signal might be closer than expected, see e.g. Pospelov (1103.3261), Pospelov, Pradler (1203.0545), Kopp, Harnik, Machado (1202.6073).
- Can annually modulate like DM with appropriate mass splittings:

\[ l_{osc} \sim AU \left( \frac{E}{10 \text{ MeV}} \right) \left( \frac{10^{-10} \text{ eV}^2}{\Delta m^2} \right) \]
Neutrino “backgrounds”

- Solar neutrinos will eventually be a direct detection background.
- If neutrinos have new interactions, the signal might be closer than expected, see e.g. Pospelov (1103.3261), Pospelov, Pradler (1203.0545), Kopp, Harnik, Machado (1202.6073).
- Can annually modulate like DM with appropriate mass splittings:

\[ l_{osc} \sim \text{AU} \left( \frac{E}{10 \text{ MeV}} \right) \left( \frac{10^{-10} \text{ eV}^2}{\Delta m^2} \right) \]

- SuperCDMS now rules out this explanation for DAMA/CDMS-Si for isospin-conserving couplings.
Conclusions

• **Part I:** DM and baryons may have more in common than we think.
  - Shared a common origin in Asymmetric DM models.
  - Prefers 1-10 GeV DM in most cases.
  - Need to worry about astro-uncertainties in DD.

• **Part II:** Lack of any clear DM signals motivates re-thinking thermal relic paradigm.
  - Perhaps only DM’s annihilation products share SM interactions: similar to boosted DM scenarios.
  - Can use DD to probe DM masses as low as 10 MeV.
  - Distinctive recoil spectrum from relativistic scattering.
Extras
WIMP recoil spectrum

RAVE star survey (2006): 498 km/s < $v_{\text{esc}}$ < 608 km/s

$$\frac{dR}{dE_R} \propto \int_{v_{\text{min}}(E_R)}^{v_{\text{esc}}} d^3v \; vf(\vec{v} + \vec{v}_e(t)) \frac{d\sigma}{dE_R}$$

scattering kinematics: $v_{\text{min}} = \sqrt{\frac{m_N E_R}{2\mu^2_N}}$

(elastic)

astrophysics unknown

McMillan, Binney (2009): 230 ±30 km/s

particle physics unknown
LOW-THRESHOLDS WILL BE KEY

The standard plot with uncertainty on circular speed.
LOW-THRESHOLDS WILL BE KEY

The standard plot with uncertainty on circular speed.

\[
\text{filled regions } = v_0 \in [170, 290] \text{ km/s}
\]

\[
\sigma_n(\text{cm}^2)
\]

\[
m_X \text{ (GeV)}
\]
LOW-THRESHOLDS WILL BE KEY

The standard plot with uncertainty on circular speed.

Conventional WIMP needs ever larger targets:

a) LUX, 100 kg-yr.

b) XENON1T, 2 ton-yr.

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LOW-THRESHOLDS WILL BE KEY

The standard plot with uncertainty on circular speed.

Conventional WIMP needs **ever larger targets**:
a) **LUX**, 100 kg-yr.
b) **XENON1T**, 2 ton-yr.

Light WIMPs can yield large improvements by **lowering energy thresholds**:
**MAJORANA DEMONSTRATOR**, 100 kg-yr.

filled regions $= v_0 \in [170, 290] \text{ km/s}$
MARGINALIZE OUT

\[ \int d\sigma_n \; \mathcal{L}(m_X, \sigma_n) \]

\[ \mathcal{L}(m_X) \]
Need to be confident about DM astrophysics in order to infer the DM mass.
Miracle cross section

\[ \Omega_{DM} \sim 0.2 \left( \frac{3 \times 10^{-26} \text{ cm}^3/\text{s}}{\langle \sigma v \rangle} \right) \]

i) heavy WIMP: \((m_X \gg m_\phi)\)

\[ \langle \sigma v \rangle \sim \frac{1}{16\pi} \frac{g^4}{m_X^2} \Rightarrow m_X \sim 1.2 \text{ TeV} \]
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\[ \langle \sigma v \rangle \sim \frac{1}{\pi} \frac{g^4 m_X^2}{m_\phi^4} \quad m_\phi \sim \text{TeV} \quad \Rightarrow \quad m_X \sim 200 \text{ GeV} \]
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More generally a “WIMPless” miracle

[Feng & Kumar (2008)]
Chemical equilibrium

Specify transfer operator, e.g.:

\[ \Delta W_{\text{transfer}} = \frac{XXu^c d^c d^c}{\Lambda^2} \]

[Kaplan, Luty, Zurek (2009)]

(charge neutrality) \[ Q \propto 18\mu_u - 12\mu_d - 6\mu_e = 0 \]

\[ \mu_u - \mu_d = \mu_\nu - \mu_e \]  (W$^\pm$ exchange)

\[ \mu_u + 2\mu_d + \mu_\nu = 0 \]  (EW sphalerons)

\[ 2\mu_X + 3\mu_q = 0 \]  (transfer operator)
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When DM mass is small, i.e. \[ m_X \ll T_{\text{transfer}} \]
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\[ \eta_X \approx 0.3 \eta_B \]
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(charge neutrality) \quad \begin{align*}
Q &\propto 18\mu_u - 12\mu_d - 6\mu_e = 0 \\
\mu_u - \mu_d &= \mu_\nu - \mu_e \quad \text{(W}^\pm \text{ exchange)} \\
\mu_u + 2\mu_d + \mu_\nu &= 0 \\
2\mu_X + 3\mu_q &= 0 \\
\end{align*}

(EW sphalerons)

(transfer operator)

When DM mass is small, i.e. \( m_X \ll T_{\text{transfer}} \)

\[ \eta_X \approx 0.3\eta_B \quad \implies \quad m_X \lesssim 17 \text{ GeV} \]
Annihilation for ADM

Taking d.o.f. constant,

\[ r_\infty \equiv \frac{n_X}{n_X} = \exp \left( \frac{-\eta_X \lambda \sqrt{g_*}}{x_f^{n+1} (n + 1)} \right) \]

Total DM density:

\[ \Omega_{DM} = \Omega_X + \Omega_X = \frac{m_X s_0 \eta_X}{\rho_c} \left( 1 + \frac{2r_\infty}{1 - r_\infty} \right) \]

Take small \( r \) limit:

\[ \eta_X \simeq \rho_c \Omega_{DM} / (m_X s_0) \]

The ADM “miracle” cross section(s)

\[ \langle \sigma_{ann} v \rangle_{ADM} \simeq \sqrt{\frac{45}{\pi}} \frac{(n + 1) x_f^{n+1} s_0}{\rho_c \Omega_{DM} M_{Pl} \sqrt{g_*}} \log \left( \frac{1}{r_\infty} \right) \]
Detectability of certain dark-matter candidates

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(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

Dark matter scatters on detector nuclei, imparting recoil energy

$$E_R \sim \text{keV}$$

Average rate of scattering depends on velocity distribution

$$\frac{dR}{dE_R} = \frac{\rho_{DM}}{m_N m_X} \left\langle v \frac{d\sigma}{dE_R} \right\rangle$$
MASS-DISPERSION DEGENERACY

[IMS, Friedland (2012)]

\[ \sigma_n = 6 \times 10^{-44} \text{ cm}^2 \]
\[ \sigma_n = 10^{-43} \text{ cm}^2 \]
\[ \sigma_n = 1.2 \times 10^{-42} \text{ cm}^2 \]
MASS-DISPERSION DEGENERACY

\[ \int_{v_{\text{min}}}^{\infty} \frac{f(\vec{v} + \vec{v}_e(t))}{v} d^3 v \propto \left[ 1 - \operatorname{erf} \left( \frac{v_{\text{min}} - v_e}{v_0} \right) \right] \]

[IMS, Friedland (2012)]
Extend the canonical fit parameters by one dimension: $(m_X, \sigma_n) \rightarrow (m_X, \sigma_n, \nu_0)$
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Otherwise make “vanilla” assumptions:
1) local \(f(v)\) is MB (but unknown \(v_0\)).
2) Elastic scattering with spin- and momentum-independent cross section (isospin-conserving).
Extend the canonical fit parameters by one dimension: \((m_X, \sigma_n) \rightarrow (m_X, \sigma_n, v_0)\)

Otherwise make “vanilla” assumptions:
1) local \(f(v)\) is MB (but unknown \(v_0\)).
2) Elastic scattering with spin- and momentum-independent cross section (isospin-conserving).

Large statistics makes this goal reasonable:
\((m_X, \sigma_n) = (8\text{ GeV}, 10^{-43} \text{ cm}^2) \Rightarrow N \sim 500\text{ events}\)

\((m_X, \sigma_n) = (7\text{ GeV}, 10^{-42} \text{ cm}^2) \Rightarrow N \sim 3000\text{ events}\)