Interpreting direct detection searches

Christopher McCabe

with Oliver Buchmueller, Matthew Dolan and Sarah Alam Malik

JHEP 1401 025 (arXiv:1308.6799) and work in progress

Dark matter brainstorming meeting, Imperial College – 29th May 2014
Outline of this talk

• Standard interpretation of direct detection results
• Application to simple models
• Comparing direct detection and LHC limits
Direct detection results

Spin-independent

Spin-dependent
Why constrain these parameters?

- Interactions that dark matter might have with quarks

<table>
<thead>
<tr>
<th>Name</th>
<th>Operator</th>
<th>Coefficient</th>
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<tbody>
<tr>
<td>D1</td>
<td>$\bar{\chi} \chi \bar{q} q$</td>
<td>$m_q / M_*^3$</td>
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<tr>
<td>D2</td>
<td>$\bar{\chi} \gamma^5 \chi \bar{q} q$</td>
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<td>$\bar{\chi} \chi \bar{q} \gamma^5 q$</td>
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<td>D10</td>
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<td>$\alpha_s / 4M_*^3$</td>
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<td>$\alpha_s / 4M_*^2$</td>
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<td>$\chi^\dagger \chi G_{\mu \nu} \tilde{G}^{\mu \nu}$</td>
<td>$i\alpha_s / 4M_*^2$</td>
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<td>$\chi^2 \bar{q} q$</td>
<td>$m_q / 2M_*^2$</td>
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Goodman et al:1008.1783

- Using operators excellent approximation when $M_{\text{med}} > 500$ MeV
Why constrain these parameters?

- In the non-relativistic limit ($\nu_{\text{DM}} \sim 10^{-3}$)

$$u = \left( \frac{\sqrt{p \cdot \sigma \xi}}{\sqrt{p \cdot \bar{\sigma} \xi}} \right) \xrightarrow{\text{NR limit}} \sqrt{m} \begin{pmatrix} \xi \\ \bar{\xi} \end{pmatrix} \quad v = \left( \frac{\sqrt{p \cdot \sigma \eta}}{-\sqrt{p \cdot \bar{\sigma} \eta}} \right) \xrightarrow{\text{NR limit}} \sqrt{m} \begin{pmatrix} \eta \\ -\eta \end{pmatrix}$$

$$\bar{\chi} \chi \bar{q} q \propto \mathbb{I} + \mathcal{O}(\nu_{\text{DM}}^2) \quad \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu \gamma^5 q \propto \vec{s}_{\text{DM}} \cdot \vec{s}_N + \mathcal{O}(\nu_{\text{DM}}^2)$$

$$\bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q \propto \mathbb{I} + \mathcal{O}(\nu_{\text{DM}}^2) \quad \bar{\chi} \gamma^5 \chi \bar{q} \gamma^5 q \propto \vec{s}_{\text{DM}} \cdot \vec{s}_N \nu_{\text{DM}}^2 + \mathcal{O}(\nu_{\text{DM}}^4)$$

- All interactions fall into two categories: spin-independent or spin-dependent
Direct detection results

- Constrain the cross-section to scatter with nucleon
Why constrain these parameters?

- Dark matter scatters off the whole nucleus ...but different experiments use different target nuclei

- Parameterising in terms of the nucleon cross-section allows an easy comparison of different experiments

- SI limits assume $\sigma_N \propto A^2 \sigma_n$
  - more generally $\sigma_N \propto (f_p Z + f_n (A - Z))^2 \sigma_n$

- SD limits assume the DM couples either to neutron or proton only – good approximation
Why constrain these parameters?
Mini summary

• All interactions are either spin-independent or spin-dependent
  – Experiments place separate constraints on each

• Limit is on the cross-section to scatter of a nucleon (not the whole nucleus)

• SI limit – assumes equal coupling to protons and neutrons
• SD limit – separate limit for scattering on proton and neutron
Uncertainties?

• How robust are these limits?

• Sources of uncertainty come from
  – Astrophysical parameters
  – Response of the detector
  – Nuclear physics
Astrophysical parameters

- Cross-section is degenerate with the local DM density:
  \[ N_{\text{events}} \propto \rho_{\text{DM}} \sigma_n \quad \text{where} \quad \rho_{\text{DM}} = 0.3 \text{ GeV cm}^{-3} \]

<table>
<thead>
<tr>
<th>Label</th>
<th>Reference</th>
<th>Description</th>
<th>Sampling</th>
<th>( \rho_{\text{dm}} ) [M(_{\odot}) pc(^{-3})]</th>
<th>( \rho_{\text{dm}} ) [GeV cm(^{-3})]</th>
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<tr>
<td>a) Local measures (( \rho_{\text{dm}} ))</td>
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<td>Kapteyn</td>
<td>Kapteyn (1922)</td>
<td>–</td>
<td>–</td>
<td>0.0076</td>
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<td>Jeans</td>
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<td>Oort</td>
<td>Oort (1932)</td>
<td>–</td>
<td>–</td>
<td>0.0006 ± 0.0184</td>
<td>0.0225 ± 0.69</td>
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<tr>
<td>Hill</td>
<td>Hill (1960)</td>
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<td>-0.0054</td>
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<td>Oort</td>
<td>Oort (1960)</td>
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<td>0.0586 ± 0.015</td>
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<td>Bahcall (1984a)</td>
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<td>–</td>
<td>0.033 ± 0.025</td>
<td>1.24 ± 0.94</td>
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<tr>
<td>Bienaymé(^f)</td>
<td>Bienaymé et al. (1987)</td>
<td>–</td>
<td>–</td>
<td>0.006 ± 0.005</td>
<td>0.22 ± 0.187</td>
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<tr>
<td>KG(^f)</td>
<td>Kuijken &amp; Gilmore (1991)</td>
<td>–</td>
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<td>0.0072 ± 0.0027</td>
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<td>Bahcall</td>
<td>Bahcall et al. (1992)</td>
<td>–</td>
<td>–</td>
<td>0.033 ± 0.025</td>
<td>1.24 ± 0.94</td>
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<td>Creze</td>
<td>Creze et al. (1998)</td>
<td>–</td>
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<td>-0.015 ± 0.015</td>
<td>-0.58 ± 0.56</td>
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<td>HF(^f)</td>
<td>Holmberg &amp; Flynn (2000b)</td>
<td>–</td>
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<td>0.011 ± 0.01</td>
<td>0.4 ± 0.375</td>
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<tr>
<td>HF(^f)</td>
<td>Holmberg &amp; Flynn (2004)</td>
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<td>0.0086 ± 0.0027</td>
<td>0.324 ± 0.1</td>
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<td>Bienaymé</td>
<td>Bienaymé et al. (2006)</td>
<td>–</td>
<td>–</td>
<td>0.0059 ± 0.005</td>
<td>0.51 ± 0.56</td>
</tr>
</tbody>
</table>

| Latest measurements | | | | | |
| MB12 | Moni Bidin et al. (2012) | CSF | 412 | 0.00062 ± 0.001 | 0.023 ± 0.042 |
| [0 ± 0.001] | [0 ± 0.042] |
| BT12 | Bovy & Tremaine (2012) | CSF | 412 | 0.008 ± 0.003 | 0.3 ± 0.11 |
| G12 | Garbari et al. (2012) | VC | \( 2 \times 10^3 \) | 0.022\(^{+0.015}_{-0.023}\) | 0.85\(^{+0.57}_{-0.3}\) |
| G12* | Garbari et al. (2012) | VC + \( \Sigma_b \) | \( 2 \times 10^3 \) | 0.0087\(^{+0.007}_{-0.002}\) | 0.33\(^{+0.26}_{-0.075}\) |
| S12 | Smith et al. (2012) | CSF | \( 10^4 \) | 0.005 [no error] | 0.19 |
| [0.015] | [0.57] |
| Z13 | Zhang et al. (2013) | CSF | \( 10^4 \) | 0.0065 ± 0.0023 | 0.25 ± 0.09 |
| BR13 | Bovy & Rix (2013) | CSF + MAP | \( 10^4 \) | 0.006 ± 0.0018 | 0.22 ± 0.07 |
| [0.008 ± 0.0025] | [0.3 ± 0.094] |

Read: 1404.1938

Christopher McCabe  IPPP - Durham University
Astrophysical parameters

- Velocity parameters of Sun (v0) also has some influence
- Shifts the limit horizontally at low mass
Response of the detector

- Detector effects important near threshold
  eg light response of XENON100 (now understood better)
Nuclear physics

- Issue for SD: Spin structure functions not known well
Mini summary

• How robust are these limits?

• About a 30-50% uncertainty at 30 GeV and above

• Can be larger at low mass (near threshold)
Application to simple models

• Consider vector mediators

\[ \mathcal{L} = \bar{\chi} \gamma^\mu (a + b \gamma^5) \chi Z'_\mu + \bar{q} \gamma^\mu (c + d \gamma^5) q Z'_\mu \]

\[ \sum_q \frac{ac}{M^2_{Z'}} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma^\mu q \quad \text{N.R.} \quad \text{Spin-independent (SI)} \]

\[ \sum_q \frac{bd}{M^2_{Z'}} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma^\mu \gamma^5 q \quad \text{N.R.} \quad \text{Spin-dependent (SD)} \]

\[ \sum_q \frac{bc}{M^2_{Z'}} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma^\mu q \quad \text{N.R.} \quad \text{Suppressed by} \quad v^2_{DM} \sim 10^{-6} \]

\[ \sum_q \frac{ad}{M^2_{Z'}} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma^\mu \gamma^5 q \quad \text{N.R.} \quad \text{Suppressed by} \quad v^2_{DM} \sim 10^{-6} \]

• If vector (SI) interaction is present, it will dominate
  – forbidden for Majorana fermions
Vector interaction (SI)

- The nucleon cross-section is \( \sigma_n = \frac{f^2 \mu^2}{\pi} \)

  - For protons: \( f_p = \frac{(2g_u + g_d)g_{DM}}{M_Z^2} \)

  - For neutrons: \( f_n = \frac{(g_u + 2g_d)g_{DM}}{M_Z^2} \)

- Only \( u, d \) coupling contributes

- Interactions with proton and neutron generally different

- Simplify problem by assuming all \( g_q \) equal
Vector interaction (SI) – some intuition

For
\[ g_q \sim g_{DM} \sim 1 \]
\[ M_{Z'} \sim 100 \text{ GeV} \]
\[ \sigma_n \approx 10^{-36} \text{ cm}^2 \]
Vector interaction (SI)

Vector: 90% CL limits

$g_q = g_{DM} = 1$

LUX

$M_{med} [\text{GeV}]$

$m_{DM} [\text{GeV}]$
Vector interaction (SI)

$g_q = g_{DM} = 1$

- LUX
- LHC8: 20 fb$^{-1}$

$m_{DM} \text{ [GeV]}$ vs $M_{med} \text{ [GeV]}$
Axial-Vector interaction (SD)

- The nucleon cross-section is \( \sigma_n = \frac{3f^2\mu^2}{\pi} \)

- For protons: \( f_p = \frac{g_{DM}}{M_{Z'}^2} \sum_{q=u,d,s} g_q \Delta^p_q \)

- For neutrons: \( f_n = \frac{g_{DM}}{M_{Z'}^2} \sum_{q=u,d,s} g_q \Delta^n_q \)

- Only u, d, s coupling contributes
- Interactions with proton and neutron generally different

- Simplify problem by assuming all \( g_q \) equal

\[ \Delta^p_u = \Delta^n_u \approx 0.842 \]
\[ \Delta^p_d = \Delta^n_u \approx -0.427 \]
\[ \Delta^p_s \approx \Delta^n_s \approx -0.085 \]
Axial-Vector interaction (SD) – some intuition

For
\[ g_q \sim g_{\mathrm{DM}} \sim 1 \]
\[ M_{Z'} \sim 100 \ \text{GeV} \]
\[ \sigma_n \approx 10^{-36} \ \text{cm}^2 \]
Axial-Vector interaction (SD)

- Searches have comparable sensitivity and are complementary
Axial-Vector interaction (SD)

- Searches have comparable sensitivity and are complementary
Problems with EFT approach

- Limit on \( \Lambda \) in the EFT approach for

- Are these limits useful?
Problems with EFT approach: Example

- Find limit in simplified model and map back onto direct detection plane:

  - EFT limit gives misleading results

\[ g_q = g_{DM} = 1 \]

- CMS: EFT

\[ \sigma_n \leq 10^{-39} \, \text{cm}^2 \]

\[ M_{DM} \leq 10^{-38} \, \text{GeV} \]

\[ M_{med} \geq 10^{3} \, \text{GeV} \]

\[ m_{DM} \geq 10^{3} \, \text{GeV} \]

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Summary

• Important to interpret dark matter searches in the right framework

• Direct detection experiments constrain the ‘WIMP-nucleon cross section’
  – Very useful: constrains a large number of theories
  – Straightforward to map limits into other forms

• LHC monojet searches have been interpreted in an EFT framework
  – Limited use: gives wrong constraints when applied to simple models
  – Comparison with direct detection limits is misleading