Dark matter in the coming decade:  
Complementary paths to discovery and beyond  

(CliffsNotes version)

Snowmass 2013 Cosmic Frontier Working Group 4:  
Dark Matter Complementarity*

Cosmic Frontier Workshop, March 6, 2013

*Suggestions and corrections are most welcome and should be directed to one or more of the following contributors: Jim Buckley, Jonathan Feng, Manoj Kaplinghat, Konstantin Matchev, Dan McKinsey, and Tim Tait
Intro: part I

• Dark matter is six times as prevalent as normal matter in the Universe, but its identity is unknown. Dark matter is a grand challenge for fundamental physics and astronomy. Its mere existence implies that our inventory of the basic building blocks of nature is incomplete, and uncertainty about its properties clouds all attempts to understand how the universe evolved to its present state and how it will evolve in the future. At the same time, the field of dark matter will be transformed in the coming decade. This prospect has drawn many new researchers to the field, which is now characterized by an extraordinary diversity of approaches unified by the common goal of discovering the identity of dark matter.
As we will discuss, a compelling solution to the dark matter problem requires synergistic progress along many lines of inquiry. Our primary conclusion is that the diversity of possible dark matter candidates requires a balanced program based on four pillars: direct detection experiments that look for dark matter interacting in the lab, indirect detection experiments that connect lab signals to dark matter in the galactic halos, collider experiments that elucidate the particle properties of dark matter, and astrophysical probes that determine how dark matter has shaped the evolution of large-scale structures in the Universe.
In this Report we summarize the many dark matter searches currently being pursued in each of these four approaches. The essential features of broad classes of experiments are described, each with their own strengths and weaknesses. The goal of this Report is not to prioritize individual experiments, but rather to highlight the complementarity of the four general approaches that are required to sustain a vital dark matter research program. Complementarity also exists on many other levels, of course; in particular, complementarity *within* each approach is also important, but will be addressed by the Snowmass Cosmic Frontier subgroups that focus on each approach.
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What is dark matter?

• Overwhelming observational evidence for it
  – 6 times as prevalent as normal matter
• We are completely ignorant about its properties
  – mass, spin, lifetime, gauge quantum numbers
  – there could even be several DM species
• It could couple to any of the SM particles
  – including hidden sector particles
• There are many possibilities, including:
  – WIMPs (studied by CF1, CF2)
  – Asymmetric DM (CF1)
  – Axions (CF3)
  – Sterile neutrinos (CF3)
  – Hidden sector DM (CF4)
DM interactions vs. DM probes

• For the purposes of this report, DM candidates are categorized according to their basic interactions.
Concrete illustration of complementarity

- Different experimental probes fall in different regions
  - detailed explanation of these plots will follow shortly
Appendices: lists of experiments

### DIRECT DETECTION

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<tr>
<th>Status</th>
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TO BE CONTINUED
How to illustrate complementarity?

- Qualitatively: the presence of a signal in:
  - Colliders
  - Direct detection
  - Indirect detection

The point being this:
How to illustrate complementarity?

- Quantitatively: compare rates for the three probes
  - Problem: different quantities are being reported

How can we uniquely correlate those results?
I. Specific theory models

• Choose a complete new physics model with a dark matter candidate
  – See tomorrow afternoon’s CF4 sessions for talks on
    • MSSM (Baer)
    • MSUGRA (Sanford)
    • NMSSM (McCaskey)
    • UED (Kong)
    • Hidden charged DM (Yu)

• Compute the three types of signals as a function of the model parameters. Impose constraints.

• Problem: too many free input parameters
  – fewer parameters come at the cost of introducing model dependent assumptions
II. Model-independent approaches

• Alternatively, be agnostic about the underlying theory model

• Parameterize our ignorance about
  – the origin of SUSY breaking
    • pMSSM talks (Ismail, Cotta, Cahill-Rowley, Drlica-Wagner)
  – the type of DM-SM interactions and their mediators
    • effective operators (Shepherd)

• Effective Lagrangian considered in the complementarity document:

\[ \frac{1}{M_q^2} \bar{\chi} \gamma^\mu \gamma_5 \chi \sum_q \bar{q} \gamma_\mu \gamma_5 q + \frac{\alpha_S}{M_g^3} \bar{\chi} \chi G^{a\mu\nu} G_a^{\mu\nu} + \frac{1}{M_\ell^2} \bar{\chi} \gamma^\mu \chi \sum_\ell \bar{\ell} \gamma_\mu \ell \]
if dark matter annihilation is insignificant nowi for examplei as in the case of asymmetric dark matterl

Particle Colliders provide the opportunity to study dark matter in a highly controlled laboratory environmenti may be used to precisely constrain many dark matter particle propertiesi and are sensitive to the broad range of masses favored for WIMPsl Hadron colliders are relatively insensitive to dark matter that interacts only with leptonsi and colliders are unable to distinguish missing momentum signals produced by a particle with lifetime ∼10^{-7} s from one with lifetime >10^{-17} s as required for dark matterl

Astrophysical Probes are unique probes of the "warmth" of dark matter and hidden dark matter propertiesi such as its self-interaction strengthi and they directly measure the effects of dark matter properties on large-scale structure in the Universe. Astrophysical probes are typically unable to distinguish various forms of CDM from each other or make other precision measurements of the particle properties of dark matterl

B. Model-Independent Examples

The qualitative features outlined above may be illustrated in a simple and fairly model-independent setting by considering dark matter that interacts with standard model particles through four-particle contact interactionsi which represent the exchange of very heavy particlesl To do thisi we may choose representative couplings of a spin-dependent dark matter particle χ with quarks q, gluons g, and leptons ℓ given by

\[
\frac{1}{M_q^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \sum_q \bar{q} \gamma_\mu \gamma^5 q
\]

The interactions with quarks mediate spin-dependent direct signalsi whereas those with gluons mediate spin-independent direct signalsl The coefficients M_q, M_g, and M_ℓ characterize the strength of the interaction with the respective SM particlei and in this representative example should be chosen such that the annihilation cross section into all three channels provides the correct relic density of dark matterl The values of the three interaction strengths together with the mass of the dark matter particle m_χ completely defines this theory and allows one to predict the rate of both spin-dependent and spin-independent direct scatteringi the annihilation cross section into quarksi gluonsi and leptonsi and the production rate of dark matter at collidersl

Each class of dark matter search outlined in Sec. III is sensitive to some range of the interaction strengths for a given dark matter massl Thereforei they are all implicitly putting a bound on the annihilation cross section into a particular channell Since the annihilation cross section predicts the dark matter relic densityi the reach of any experiment is thus equivalent to a fraction of the observed dark matter densityl This connection can be seen in the plots in Fig. where the left vertical axis shows the annihilation cross section normalized to \(\sigma_{\text{th}}\)ethe relic density \(\Omega_{\chi}\) normalized to \(\Omega_{\text{DM}}\)fl If the discovery potential for an experiment with respect to one of the interaction types maps on to one times the observed dark matter density ethe horizontal dashed lines in Fig. that experiment will be able to discover dark matter which interacts only with that SM particlel If an experiment were to observe an interaction consistent with a DM fraction larger than one egreenshaded regions in Fig. it would have discovered dark matter but we would infer that there were still important annihilation channels still waiting to be observedl Finallyi if an experiment were to observe an interaction consistent with a fraction less than one egreenshaded regions in Fig. it would have discovered one species of dark matteri whichi howeveri could not account for all of the dark matteri and there are still important other DM species still waiting to be discoveredl
Complementarity parameter space

\[ \Omega_\chi \sim \frac{\sigma_{thermal}}{\sigma(\chi\bar{\chi} \rightarrow qq) + \sigma(\chi\bar{\chi} \rightarrow \text{other})} \]
DM coupling exclusively to quarks

- Flavor universal axial vector coupling (D8 operator)

\[ \frac{1}{M_q^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \sum_q \bar{q} \gamma_\mu \gamma^5 q \]

B. Model-Independent Examples

The qualitative features outlined above may be illustrated in a simple and fairly model-independent setting by considering dark matter that interacts with standard model particles through four-particle contact interactions, which represent the exchange of very heavy particles. To do this, we may choose representative couplings of a spin-dependent dark matter particle \( \chi \) with quarks \( q \), gluons \( g \), and leptons \( \ell \), given by

\[ o \quad M_{q_i}^2 \quad \bar{q} \chi \gamma^\mu \gamma_5 \chi \quad q \]

\[ o \quad M_{g}^i \quad \bar{g} \chi \chi \quad G_a \mu \nu \quad G_a \mu \nu \quad g \]

\[ o \quad M_{\ell}^i \quad \bar{\ell} \gamma^\mu \ell \quad \ell \]

The interactions with quarks mediate spin-dependent direct signals, whereas those with gluons mediate spin-independent direct signals. The coefficients \( M_{q_i}, M_g, M_{\ell} \) characterize the strength of the interaction with the respective SM particle and in this representative example should be chosen such that the annihilation cross section into all three channels provides the correct relic density of dark matter. The values of the three interaction strengths together with the mass of the dark matter particle \( m_\chi \) completely define this theory and allows one to predict the rate of both spin-dependent and spin-independent direct scattering, the annihilation cross section into quarks, gluons, and leptons, and the production rate of dark matter at colliders.

Each class of dark matter search outlined in Sec II is sensitive to some range of the interaction strengths for a given dark matter mass. Therefore, they are all implicitly putting a bound on the annihilation cross section into a particular channel. Since the annihilation cross section predicts the dark matter relic density, the reach of any experiment is thus equivalent to a fraction of the observed dark matter density. This connection can be seen in the plots in Fig. where the left vertical axis shows the annihilation cross section normalized to \( \sigma_{\text{th}} \), the relic density normalized to \( \Omega_{\text{DM}} \), and the right vertical axis shows the rate of production at colliders normalized to \( \sigma_{\text{th}} \).

1. If the discovery potential for an experiment with respect to one of the interaction types maps on to one times the observed dark matter density, the horizontal dashed lines in Fig. that experiment will be able to discover dark matter which interacts only with that SM particle. If an experiment were to observe an interaction consistent with a DM fraction larger than one, the yellow shaded regions in Fig., it would have discovered dark matter but we would infer that there were still important annihilation channels still waiting to be observed. Finally, if an experiment were to observe an interaction consistent with a fraction less than one, the green shaded regions in Fig., it would have discovered one species of dark matter, which however, could not account for all of the dark matter, and there are still important other DM species still waiting to be discovered.
DM coupling exclusively to leptons

- Flavor universal vector coupling (D5 operator)

\[
\frac{1}{M_L^2} \bar{\chi} \gamma^\mu \chi \sum_\ell \bar{\ell} \gamma^\mu \ell
\]

![Graph showing DM interacting with leptons](image)

- **Indirect**
- **Colliders**

\[
\frac{\sigma(x \chi \rightarrow \ell \nu)}{\sigma_{\text{th}}}
\]

\[
m_\chi (\text{GeV})
\]

\[
\frac{\text{weak coupling}}{U}
\]
DM coupling exclusively to gluons

• 4-point interaction (D11 operator)
Action items

• Collect feedback at the CF workshop
  – suggestions are already coming in
  – are there any major points missing?

• Finish writing
  – Write conclusions section
    • Venn diagram?
  – References: more or fewer?
  – Complete the tables with DM experiments
  – Authorship?

• Draft an executive summary document

• Anything else?