Assembling a Theory of Dark Matter

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What is Dark Matter?

“Cold Dark Matter: An Exploded View” by Cornelia Parker
The Dark Matter Questionnaire

- Mass
- Spin
- Stable?
  - Yes
  - No

Couplings:
- Gravity
- Weak Interaction?
- Higgs?
- Quarks / Gluons?
- Leptons?

Thermal Relic?
- Yes
- No
Ultimately, we need to fill out the questionnaire experimentally. But as we try to relate the results of experiments to one another and unravel the deeper theoretical underpinning, we need at least some kind of theoretical framework in which to cast our progress.

What could the theory be? No lack of possibilities...
Theories of Dark Matter

- mSUGRA
- R-parity Conserving
- pMSSM
- R-parity Violating
- Gravitino DM
- NMSSM
- Extra Dimensions
- UED DM
- Warped Extra Dimensions
- Little Higgs
- Self-Interacting DM
- Dirac DM
- Q-balls
- RS DM
- Soliton DM
- WIMPless DM
- Hidden Sector DM
- Warm DM
- Asymmetric DM
- Axion DM
- Axion-like Particles
- QCD Axions
- Sterile Neutrinos
- Light Force Carriers
- Dark Photon
- T-diff DM
- Quark Nuggets
- Techni-baryons
- Soliton DM
- T-diff DM
- Quark Nuggets
- Techni-baryons
- Littlest Higgs
- WIMPless DM
- Self-Interacting DM
- Q-balls
- Soliton DM
The Most Complete Theory

- On the “complete” end of the spectrum is our favorite theory: the MSSM.
- Reasonable phenomenological models have ~20 parameters, leading to rich and varied visions for dark matter.
- This plot shows a scan of the `pMSSM’ parameter space in the plane of the WIMP mass versus the SI cross section.
- The colors indicate which (near) future experiments can detect this model: LHC only, Xenon 1ton only, CTA only, both Xenon and CTA, or can’t be discovered.
- It is clear that just based on which experiments see a signal, and which don’t, that there could be (potentially soon) suggestions of favored parameter space(s) from data.
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Moving away from complete theories, we come to simplified models. These contain the dark matter, and some of the particles which allow it to talk to the SM, but are not meant to be complete pictures.

As a simple example, we can look at a theory where the dark matter is a Dirac fermion which interacts with a quark and a (colored) scalar mediating particle.

There are three parameters: the DM mass, the mediator mass, and the coupling g. These are like the particles of the MSSM, but with subtle differences in their properties and more freedom in their interactions.

Just like the MSSM was one example of a complete theory, this is only one example of a “partially complete” one.

Limit on $g_{\text{DM}} - u_R$ Model

DiFranzo, Nagao, TMPT
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The new XENON100 data provide the most stringent limit for spin-independent WIMP-nucleon scatterings. The expected sensitivity of this run is shown by the green/yellow band (1σ) preferred by CRESST-II. The observed limit is shown in Fig. 3. Combined region using C. Strege et al., JCAP 1206, 030 (2012); A. Fowlie et al. (2012), arXiv:1206.0264.

- Z. Ahmed et al. (CDMS), Science 327, 045802 (2010).
- E. Armengaud et al., JCAP 1209, 002 (2012); E. Armengaud et al., JCAP 1210, 018 (2012).
- M. M. Szydagis et al., JINST 7, P01002 (2012).
Contact Interactions

- In the limit where the mediating particles are heavy compared to all energies of interest, we are left with a theory containing the SM, the dark matter, and nothing else.

- The residual effects of the mediators are left behind as what look like non-renormalizable interactions between DM and the SM.

- These are the simplest and least complete description of dark matter we can imagine.

- For any particular choice of interaction type, there are two parameters: the DM mass and the strength of that interaction.

![Diagram showing the discovery potential and current bounds for several near-term dark matter searches that are sensitive to interactions with quarks and gluons, or leptons. It is clear that the searches are complementary to each other in terms of being sensitive to interactions with different standard model particles. These results also illustrate that within a given interaction type, the reach of different search strategies depends sensitively on the dark matter mass. For example, direct searches for dark matter are very powerful for masses around 100 GeV, but have difficulty at very low masses, where the dark matter particles carry too little momentum to noticeably affect heavy nuclei. This region of low mass is precisely where collider production of dark matter is easiest, since high energy collisions readily produce light dark matter particles with large momenta.](1305.1605)
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since high energy collisions readily produce light dark matter particles with large momenta. Heavy nuclei. This region of low mass is precisely where collider production of dark matter is easiest, at very low masses, where the dark matter particles carry too little momentum to noticeably affect the reach of direct searches. Consequently, point to other dark matter species still waiting to be discovered. Which, however, could not account for all of the dark matter (within this model framework), and so we need to consider other channels still waiting to be observed. Finally, if an experiment were to observe a cross section only with that standard model particle and nothing else, that experiment will be able to discover thermal relic dark matter that interacts with respect to one of the interaction types. Reaching cross sections below the value, but the plots in Fig. 2 are still meaningful. For non-thermal WIMPs, e.g., asymmetric DM, the annihilation cross-section does not have a naturally preferred value, but the plots in Fig. 2 are still meaningful. In Fig. 2, we assemble the discovery potential and current bounds for several near-term dark matter search strategies. Each class of dark matter search outlined in Sec. III 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 quarks, gluons, and leptons, and the production rate of dark matter at colliders. Rate of both spin-dependent and spin-independent direct scattering, the annihilation cross section needs to be normalized to the value required for a thermal WIMP to account for all of the dark matter in the Universe. If the discovery potential for an experiment with observed dark matter density. This connection can be seen in the plots in Fig. 2, which show the reach of any experiment is thus equivalent to a fraction of the dark matter relic density, the reach of any experiment is thus equivalent to a fraction of the dark matter relic density.
A Possible Timeline

- Mass
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- Stable?
- Couplings:
  - Gravity
  - Weak Interaction?
  - Higgs?
  - Quarks / Gluons?
  - Leptons?
  - Thermal Relic?
A Possible Timeline

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.
A Possible Timeline

2013

2014
LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

2015

2016

2017

2018

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

- Mass: $150 \pm 15$ GeV
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- 2014
- 2015

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**2014**

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**2015**

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**2016**

- Neutrinos are seen coming from the Sun by IceCube.

- No jets + MET

- Mass: 150 +/- 15 GeV
- Spin: > 0
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- Couplings:
  - Gravity
  - Weak Interaction?
  - Higgs?
  - Quarks / Gluons
  - Leptons
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2016
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No jets + MET

2017
A positive signal of axion conversion is observed at an upgraded ADMX.

2018

- Mass: 150 +/- 15 GeV
- Spin: > 0
- Stable?
- Gravity
- Weak Interaction?
- Higgs?
- Quarks / Gluons
- Leptons
- Thermal Relic?

- Mass: 20 μeV
- Spin: 0
- Stable?
- Gravity
- Photon Interaction
- Higgs?
- Quarks / Gluons?
- Leptons?
- Thermal Relic?
A Possible Timeline

- 2013
  - Mass: 150 +/- 0.1 GeV
  - Spin: > 0
  - Stable?
  - Couplings:
    - Gravity
    - Weak Interaction?
    - Higgs?
    - Quarks / Gluons
    - Leptons
    - Thermal Relic

- 2014
  - Mass: 20 µeV
  - Spin: 0
  - Stable?
  - Couplings:
    - Gravity
    - Photon Interaction
    - Higgs?
    - Quarks / Gluons?
    - Leptons?
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- 2015
  - Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

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- 2018
  - Observation at a Higgs factory indicates that the interaction with leptons is too strong to saturate the relic density.
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A multi-pronged search strategy identifies a mixture of dark matter which is 50% classic WIMP and 50% axion.

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Outlook

• Putting together a detailed particle description of dark matter will necessarily involve many experimental measurements.

• Important details such as the mass and spin will hopefully come along as part of that program.

• The three traditional pillars of dark matter searches: direct, indirect, and collider, naturally probe different parts of the space of DM-SM couplings.

• They are highly complementary to one another in terms of discovery potential.

• Together they can probe a large fraction of the space of interesting WIMP models in the near future.

• Input from all of them is likely to be necessary to reconstruct enough of the couplings to be able to firmly understand the dark matter relic density.

“$\Omega h^2$ or bust!”