How Dark is Dark Matter

Itay Yavin
McMaster University
Perimeter Institute

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Road Map

1. How dark are Majorana fermions? (Effective field theory).

2. New charged states (UV completion).

3. The only 5-sigma so far . . . (What does DAMA really tell us).
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1. How dark are Majorana fermions? 
   *(Effective field theory)*.

2. New charged states 
   *(UV completion)*.

3. The only 5-sigma so far . . .
   *(What does DAMA really tell us)*.
How Dark is Dark Matter?

From Effective Field Theory point of view, a natural reason why DM is dark is that its interactions with light are all coming through irrelevant operators. Weiner and IY arXiv:1206.2910

Magnetic (inelastic) Dark Matter

\[ \mathcal{L}_{\text{MiDM}} = \left( \frac{\mu_\chi}{2} \right) \bar{\chi}^* \sigma_{\mu\nu} B^{\mu\nu} \chi + c.c. \]
Phases of MiDM

The two Weyl states that comprise the dipole operator need not have the same mass. See Chang, Weiner, & IY, and also Tulin, Yu, & Zurek arXiv:1208.0009

\[ \mathcal{L}_{\text{MiDM}} = \left( \frac{\mu \chi}{2} \right) \bar{\chi} \sigma_{\mu \nu} B^{\mu \nu} \chi + \text{c.c.} \]

Dipole is strongly constrained by Direct Detection. Very difficult to see anywhere unless it is very light.

Excited state is never around. Phenomenology is similar to RayDM

Splitting is roughly equal to the kinetic energy in the halo. Interesting, can also explain DAMA.

Difficult to see in direct detection, but interesting for all other frontiers.

\[ m_\chi \approx m_{\chi^*} \]

\[ m_\chi - m_{\chi^*} \approx 100 \text{ keV} \]

\[ m_\chi - m_{\chi^*} \leq m_\chi / 20 \]

\[ m_\chi - m_{\chi^*} \geq m_\chi \]
Scaling Relations

For thermally produced MiDM, the direct and gamma-ray line indirect signatures are roughly independent of the size of the dipole.

See also Duda, Gelmini, & Gondolo arXiv:hep-ph/0102200

\[
\rho_{\text{MiDM}} = \rho_0 \times \frac{\mu_{\text{thermal}}^2}{\mu_{\chi}^2}
\]

\[
R_{\text{DD}} \propto n_\chi \mu_{\chi}^2 = \frac{\rho_0}{m_\chi} \frac{\mu_{\text{thermal}}^2}{\mu_{\chi}^2} \times \mu_{\chi}^2
\]

\[
R_{\gamma\gamma} \propto n_\chi^2 \mu_{\chi}^4 = \frac{\rho_0^2}{m_\chi^2} \frac{\mu_{\text{thermal}}^4}{\mu_{\chi}^4} \times \mu_{\chi}^4
\]
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Magnetic (inelastic) Dark Matter

\[ \mathcal{L}_{\text{MiDM}} = \left( \frac{\mu}{2} \right) \bar{\chi} \sigma_{\mu\nu} B^{\mu\nu} \chi + \text{c.c.} \]

If excited state is heavy then should integrated it out to get,

Rayleigh Dark Matter

\[ \mathcal{L}_{\text{RayDM}} = \frac{1}{4\Lambda^3_R} \bar{\chi} \chi \left( \cos \theta_{\chi} B_{\mu\nu} B^{\mu\nu} + \sin \theta_{\chi} \text{Tr} W_{\mu\nu} W^{\mu\nu} \right) \]

\[ + \frac{i}{4\Lambda^3_R} \bar{\chi} \gamma_5 \chi \left( \cos \theta_{\chi} B_{\mu\nu} \tilde{B}^{\mu\nu} + \sin \theta_{\chi} \text{Tr} W_{\mu\nu} \tilde{W}^{\mu\nu} \right) \]

See also Pospelov & ter Veldhuis arXiv:hep-ph/0003010
Other Searches
Is there any testable phenomenology? More in the next section, but

**MiDM (one-photon vertex)**

Excited state will decay.
Look for lines in DD.

Very ruled out if splitting is large.
Production at LHC, monophoton from FSR.

**RayDM (two-photon vertex)**

Seems hopeless, but forced us to find new ways to calculate these effects.

Motivates mono-W searches
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New Charged States

The MiDM and RayDM operators arise from integrating out charged matter that couples to the WIMP. Charged matter at the electroweak scale seems necessary (See also Fan & Reece arXiv:1301.2597)

New charged scalar

\[ WIMP \rightarrow \lambda \]

New charged fermion

Magnetic (inelastic) Dark Matter

Rayleigh Dark Matter

\[ p_1 \rightarrow q, \mu \]

\[ p_2 \rightarrow q, \mu \]

\[ (a) \]

\[ (b) \]

\[ (c) \]

\[ (d) \]
The relic abundance is determined by the annihilation of DM into charged pairs through the dipole operator.

Annihilation today is dominated by the Rayleigh operator. (no excessive continuum - See Cohen et al arXiv:1207.0800)

Now at 2-loop, Tamarit & IY arXiv:hope.soon
LHC Searches

While search for the WIMP itself is challenging, the new charged states are easier to looks for (Liu, Shuve, Weiner, IY).

The production cross-section for the fermionic states is a lot larger.

These cross-sections are now being probed at the LHC.

The discovery prospects really depend on how they decay.

Charged states decay through off-shell W.

Tough, similar to AMSB.

Charged states mix with SM.

Already strongly constrained, unless decay into taus.
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DAMA

One Year

2-4 keV

DAMA/LIBRA = 250 kg (0.87 ion\textperday)

Residuals (cpd/kg/keV)

Time (day)

One Year

Dark Matter Observed?
Other Experiments

Other experiments looking for this signal have not seen it.
Models

But, there has been no repetition of the DAMA experiment and these exclusions depend on a specific model for the interactions of DM. Here are some models that try to explain DAMA while avoiding the exclusions coming from other experiments:

2) LDM (Feldstein, Graham, & Rajendran 2010)
3) Light DM (Bottino, Donato, Fornengo, and Scopel, 2008, and others)
4) Channeling (Bozorgnia, Gelmini, and Gondolo 2010 and others)
5) RDM (Bai, Fox, 2009)
6) Leptonic DM (Bernabei 2008 and others)
7) Neutrinos with new baryonic currents (Pospelov 2012)
8) Isospin violating (Chang, Liu, Pierce, Weiner, IY, 2010 and others)
9) . . .

Is there something further we can learn about the signal which is model independent?
Modulation Fraction

The modulation fraction expected in most models is no more than 10%. Is that compatible with the total number of events seen?
Unmodulated part of the signal

(Kudryavtsev, Robinson, Spooner, 2010)
(Pradler, Singh, IY, 2012)
A Simple(r) Fit to the Background

(Pradler, Singh, IY, 2012)
(Pradler, IY, 2012)
Full Fit - it only gets worse...
Remarks

1) The flat background is well motivated, it is the universal spectral-shape of *beta-decays* at low energies.

2) This analysis highlights the importance of understanding both the modulating as well as the unmodulating (mostly background) parts of the signal.

3) But, something is modulating in DAMA, what is it? Maybe DM, but higher modulation fraction, maybe something more exotic? Maybe something more mundane . . .

4) There does not seem much hope of getting more information from the DAMA collaboration. Many things are left unexplained. Maybe another experiment?
Unmeasured Nuclear Decay

One piece of nuclear physics that emerged out of it is the identification of an hitherto unmeasured special nuclear transition in potassium.
The Muon Hypothesis

It is well established that the flux of atmospheric muons modulate with the seasons,

So maybe what DAMA is seeing is just the result of muons from the atmosphere.

This has been discussed by several independent authors (Ralston 2010, Nygren 2011, Blum 2011).
Phaseogram

We can compare the two datasets in phase-period space using a generalization of the Lomb-Scargle periodogram (Chang, Pradler, IY, 2011)

$$P(\omega, t_0 \mid d) \propto \frac{\sigma^{1-N}}{\sqrt{p}} \left[1 + \text{Erf} \left( \frac{h}{\sqrt{2\sigma^2 p}} \right) \right]$$

$$\times \exp \left( \frac{h^2}{2\sigma^2 p} \right),$$

$$p = \sum_i \cos^2 \omega (t_i - t_0),$$

$$h = \sum_i d_i \cos \omega (t_i - t_0).$$

But, maybe this is just an artifact of forcing the data into a sinusoidal modulation?
Correlation Analysis

Without assuming any model, we can compute Pearson’s coefficient of correlation between the two datasets.

\[ r_{LVD-DAMA} = 0.44 \]

But, what we really want to test is whether there is causation.

We generated 10,000 mock datasets based on a simple stochastic model proposed by Blum and calculated the resulting Fisher Z transform.

\[ Z = \frac{1}{2} \log \left( \frac{1 + r}{1 - r} \right) \]
Conclusions

1. MiDM and RayDM provide a simple effective field theory in which the phenomenology of Majorana fermions as WIMPs can be studied.

2. Interestingly, these operators can now be probed in several frontiers. Direct detection experiments will continue to place bounds on the magnetic dipole, while indirect observation are more sensitive to the Rayleigh operator.

3. New charged states have to accompany these operators. They can be searched for at the LHC.

4. The modulations seen by DAMA are intriguing, but whatever explains it requires fairly large modulation fraction (unless it is just the background). It is difficult to know how seriously to consider these claims as many details are (still) not provided.
Thank You