Panel Discussion: Are WIMPs dead?

Tim M.P. Tait
University of California, Irvine
My Old Living Room Window…
New Controversy:
Is the Lake rising or is Chicago sinking?!
So, WIMPs...
Physicists Look Beyond WIMPs For Dark Matter
After top dark matter candidate fizzles out, physicists look to more exotic realms.

Meetings: WIMP Alternatives Come Out of the Shadows
May 14, 2018 • Physics 11, 48
At an annual physics meeting in the Alps, WIMPs appeared to lose their foothold as the favored dark matter candidate, making room for a slew of new ideas.

The Rencontres de Moriond (Moriond Conferences) have been a fixture of European high-energy physics for over half a century. These meetings—typically held at an Alpine ski resort—have been the site of many big announcements, such as the first public talk on the top quark discovery in 1995 and important Higgs updates in 2013. One day, perhaps, a dark matter detection will headline at Moriond. For now, physicists wait. But they've gotten a bit anxious, as their shoo-in candidate, the WIMP, has yet to make an appearance—despite several ongoing searches. At this year's Moriond, held this past March in La Thuile, Italy, some of the limelight passed to other dark matter candidates, such as axions, black holes, superfluids, and more.

More Negative Results in Hunt for Dark Matter WIMPs
But the search continues 2,500 meters underground at China’s PandaX experiment.

In the Dark about Dark Matter
Recent disappointments have physicists looking beyond WIMPs for dark matter particles

Dark Matter Recipe Calls for One Part Superfluid
A different kind of dark matter could help to resolve an old celestial conundrum.
Fake News?
What is behind this Question?
Relic Density

- Most of the statements about WIMPs are correlating null results for searches with the relic density.

- This is clearly a very attractive target, but it is worth remembering that typically freeze-out occurs at $\sim m_{\text{DM}}/20$ or so.

- For most masses of interest, these are times where we have no direct cosmological probes.

- My attitude is that this kind of standard cosmology is something we want to establish, not assume.
WIMP Searches

Indirect Detection

Collider Searches

Direct Detection

Self-Interactions
Ceiling:
These limits become ineffective around $10^{-33}$ cm$^2$.
“Electroweak” Cross section
(excluded by CDMS ~2000 for a wide range of masses)
Now: ~1 GeV to ~$10^7$ GeV

Warning:
Lots of “back of the envelope” estimates in these slides
FIG. 1. Constraints on the DM annihilation cross section at 95% CL for the $b\bar{b}$ (left) and $\tau^+\tau^-$ (right) channels derived from a combined analysis of 15 dSphs. Bands for the expected sensitivity are calculated by repeating the same analysis on 300 randomly selected sets of high-Galactic-latitude blank fields in the LAT data. The dashed line shows the median expected sensitivity while the bands represent the 68% and 95% quantiles. For each set of random locations, nominal J-factors are randomized in accord with their measurement uncertainties. The solid blue curve shows the limits derived from a previous analysis of four years of Pass 7 Reprocessed data and the same sample of 15 dSphs [1]. The dashed gray curve in this and subsequent figures corresponds to the thermal relic cross section from Steigman et al. [5].

FIG. 2. Comparison of constraints on the DM annihilation cross section for the $b\bar{b}$ (left) and $\tau^+\tau^-$ (right) channels from this work with previously published constraints from LAT analysis of the Milky Way halo (3 limit) [34], 112 hours of observations of the Galactic Center with H.E.S.S. [35], and 157.9 hours of observations of Segue 1 with MAGIC [36]. Pure annihilation channel limits for the Galactic Center H.E.S.S. observations are taken from Abazajian and Harding [37] and assumed an $\epsilon$ in a static Milky Way density profile with $\rho = 0$.

FIG. 1: Planck CMB limits at 95% C.L. for DM annihilation 100% to individual channels: electrons (blue), muons (purple), taus (red), gluons (green), gamma rays (orange). Light quarks and $b$-quarks overlap with the gluon line, so are not shown for clarity. Thermal relic cross section is the black dashed line. 

IV. PLANCK CMB LIMITS

Anisotropies of the CMB provide powerful insight into physical processes present during the cosmic dark ages. Any injection of ionizing particles, including those from DM annihilation, modifies the ionization history of hydrogen and helium gas, perturbing CMB anisotropies. Measurements of these anisotropies therefore provide robust constraints on production of ionizing particles from DM annihilation products. The most sensitive measurements to date are by Planck, superseding earlier measurements by WMAP.

A. Energy Injection from Annihilating DM

The power deposited by DM annihilation, controlled by the parameter $p_{\text{ann}} = f_e \cdot h v_i / m$, determines the strength of the CMB limit. Here $h v_i$ is the thermally averaged DM annihilation cross section and $m$ is the DM mass. We calculate the weighted efficiency factor $f_e \cdot h v_i$ by integrating our electron/positron and photon energy spectra from Pythia over the $f_e \pm$ curves.

$\frac{dN}{dE_{\text{e}\pm}} f_e = \frac{1}{2} m Z m_0 \cdot f_e \cdot \frac{dN}{dE_{\text{e}\pm}} \cdot E_{\text{e}\pm}$. 

Following Ref. [77], we neglect the contribution to energy deposition from protons and antiprotons; generally only a small fraction of the total energy of the annihilation products goes into $p\bar{p}$ production, and protons and antiprotons also deposit energy less efficiently than electrons, positrons, and photons [78]. Including these contributions would slightly strengthen the constraints.

From Planck data, the 95% C.L. limit on $p_{\text{ann}}$ is $f_e \cdot h v_i m < 4 \times 10^{-28} \text{cm}^3/\text{s}/\text{GeV}$.

Figure 1 shows the single-channel limits on the cross section from the CMB. Below 5 GeV DM mass, as there is extra uncertainty in the Pythia spectra, we also present arguments for the thermal WIMP exclusion based on generic arguments about the efficiency and energy injection rate, as discussed below.

B. Energy Injection Fractions

Figure 2 shows the fraction of power proceeding into EM channels (electrons, positrons, and photons) is quite stable as a function of DM mass, and is 26% or higher for $m_\chi$. Leane et al 1805.10305 

"Electroweak" Cross section 

Leane et al 1805.10305
$\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow W^+ (\rightarrow l^+ \nu) \tilde{\chi}_1^0 \ W^- (\rightarrow l^- \bar{\nu}) \tilde{\chi}_1^0$

**ATLAS**

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

All limits at 95% CL

- **Expected Limit** ($\pm 1 \sigma_{\text{exp}}$)
- **Observed Limit** ($\pm 1 \sigma_{\text{theory}}$)

ATLAS 8 TeV, arXiv:1403.5294
So what does this mean for WIMPs?

It depends what you mean by WIMP.
Electroweakly Interacting Massive Particles
To be EW-charged, but avoid full strength Z interactions, DM could have $T_3=0$.

This happens for odd-dimensional representations (triplet, quintuplet, …)
It doesn’t work for doublets, quadruplets, etc..

Another way to say it: Dark Matter should not carry hypercharge ($Q=T_3+Y$).

This implies EW-charged dark matter comes with electrically charged EW siblings whose masses differ by $O(<H> \sim 100 \text{ GeV})$. 
Relativistic EFT

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<th>Name</th>
<th>Operator</th>
<th>Coefficient</th>
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<tr>
<td>D1</td>
<td>$\bar{\chi}\chi q\bar{q}$</td>
<td>$m_q/M_*^3$</td>
</tr>
<tr>
<td>D2</td>
<td>$\bar{\chi}\gamma^5\chi q\bar{q}$</td>
<td>$i m_q/M_*^3$</td>
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<td>D3</td>
<td>$\bar{\chi}\chi q\gamma^5 q$</td>
<td>$i m_q/M_*^3$</td>
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<td>D4</td>
<td>$\bar{\chi}\gamma^5\chi q\gamma^5 q$</td>
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<td>$\bar{\chi}\gamma^\mu\chi q\gamma^\mu q$</td>
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<td>D6</td>
<td>$\bar{\chi}\gamma^\mu\gamma^5\chi q\gamma^\mu q$</td>
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<td>$1/M_*^2$</td>
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<td>D9</td>
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<tr>
<td>D10</td>
<td>$\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi q\sigma_{\alpha\beta} q$</td>
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<td>$\bar{\chi}\chi G_{\mu\nu} G^{\mu\nu}$</td>
<td>$\alpha_s/4M_*^3$</td>
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<td>D12</td>
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<td>D13</td>
<td>$\bar{\chi}\chi G_{\mu\nu} \tilde{G}^{\mu\nu}$</td>
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<td>D14</td>
<td>$\bar{\chi}\gamma^5\chi G_{\mu\nu} \tilde{G}^{\mu\nu}$</td>
<td>$\alpha_s/4M_*^3$</td>
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Nonrelativistic EFT

1. P-even, $S_X$-independent
   \[ \mathcal{O}_1 = 1, \quad \mathcal{O}_2 = (v^+)^2, \quad \mathcal{O}_3 = i\vec{S}_N \cdot (\vec{q} \times \vec{v}^+) \]

2. P-even, $S_X$-dependent
   \[ \mathcal{O}_4 = \vec{S}_X \cdot \vec{S}_N, \quad \mathcal{O}_5 = i\vec{S}_X \cdot (\vec{q} \times \vec{v}^+), \quad \mathcal{O}_6 = (\vec{S}_X \cdot \vec{q})(\vec{S}_N \cdot \vec{q}) \]

3. P-odd, $S_X$-independent
   \[ \mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^+ \]

4. P-odd, $S_X$-dependent
   \[ \mathcal{O}_8 = \vec{S}_X \cdot \vec{v}^+, \quad \mathcal{O}_9 = i\vec{S}_X \cdot (\vec{S}_N \times \vec{q}) \]

5. P-odd, $S_X$-independent:
   \[ \mathcal{O}_{10} = i\vec{S}_N \cdot \vec{q} \]

6. P-odd, $S_X$-dependent:
   \[ \mathcal{O}_{11} = i\vec{S}_X \cdot \vec{q} \]

Fitzpatrick et al, 1203.3542

This description knows that physics respects special relativity.

Goodman et al, 1008.1783

This description is the natural language for the scattering problem.
The Z boson is a problem because it switches on relativistic operator D5 which maps to $O_1$ (SI).
Majorana DM

The vector interaction vanishes (identically) for a Majorana particle. That leaves behind spin-dependent (and $v$-suppressed) terms.

That suggests another strategy for EW-charged WIMPs: Majorana particles are less constrained than Dirac, even if they carry hypercharge.

...this is not really enough at this point...
But...at loop level, what was spin-dependent at tree level can turn out to be spin-independent.

At weakly coupled loop costs $\sim 10^{-3}$.

At maximum sensitivity, the Xe limits on SI scattering are something like $A^2 \sim 10^5$ better than SD.
Mixed DM

Another strategy is to construct a dark matter which is a mixed state of more than one EW-charged object.

There can be cancellations between the different contributions to the couple coupling (though this may not be generic).

I don’t know of any theory where this is the dominant scheme to avoid constraints, though the MSSM benefits from it to some degree. Mostly, the MSSM survives by having a large component without EW charge.

\[ \chi_1 = N_{11} S_1 + N_{12} S_2 + N_{13} S_3 + ... \]

\[ \chi_1 \] \[
\begin{array}{c}
\chi_f \\
Z
\end{array} \]

\[ N_{11} T_3^{(1)} + N_{12} T_3^{(2)} + N_{13} T_3^{(3)} + ... \]
Heavy EW WIMPs

Baumgart, Cohen, Moult, Rodd, Slatyer, Solon, Stewart, Vaidya. 1712.07656
Dirac EW-Charged WIMP Scorecard

- Really a WIMP?
- Unitarity Bound
- CMB
- Gamma Rays
- Nuclear Recoils

Energy Scale:
- 100 MeV
- 1 GeV
- 10 GeV
- 100 GeV
- 1 TeV
- 10 TeV
- 100 TeV
Majorana EW-Charged WIMP Scorecard

Really a WIMP?  
Unitarity Bound
“Kinda-weakly” Interacting Massive Particles
Non-EW Mediators

Without the weak interaction itself to provide a scale, focus shifts to the relic density through freeze-out.

Though the couplings are typically free parameters, a general issue remains. The constraints from direct detection are very strong. Unless something mitigates them, they often rule out the cross sections necessary for freeze-in.

Things become much more model-dependent. Let’s just consider a few strategies one can use to engineer viable models.
Unlike the weak bosons, the Higgs coupling to dark matter is not specified in terms of parameters we’ve already measured.

It is very unlikely that the Higgs is the source of mass for the dark matter in the same way that it is for the SM particles.

Classic Scalar DM
Higgs portal

Mixed fermions
(MSSM-like)

Mixed scalar
mediator

Vector dark matter,
radiative portal
Even without a tree level coupling to the Higgs, an EW-charged WIMP picks up a coupling at one loop.
Axial vector — SD at tree level.
Note the choice of DM and quark couplings — the plot is totally different for other choices.
A pseudo-scalar mediator leads to scattering which is both SD and $v$-suppressed, but annihilation is not suppressed.
Secluded Dark Matter

- If the dark matter annihilates primarily into an on-shell mediator which has tiny couplings to the SM, the annihilation rate may be effectively uncorrelated with the scattering with nuclei or production at atom smashers.

\[
\sigma_{\text{ann}} \propto g^2
\]

\[
\sigma_{\text{direct}} \propto \epsilon^2 g^2
\]
Outlook

• Are WIMPs dead?

  • The answer really depends on how you frame the question.

  • Some are…
    
    • Electroweakly charged particles are rather constrained.
    
    • Some options survive by making choices of EW representation / spin.

  • Others not so much.
    
    • Freeze-out relics can exist for a wide variety of masses.
    
    • Engineering may be required on the theory side, but this could just be how nature works.

• We have learned a lot about what WIMPs aren’t.

• Where do you put your effort?
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    • Engineering may be required on the theory side, but this could just be how nature works.
• We have learned a lot about what WIMPs aren’t.
• Where do you put your effort?
  Yes.
Bonus Material
What IS a WIMP?

Weakly-interacting

Massive

Anything cold?

Anything cold?

> 10 keV?

> 1 GeV?

~ 100 GeV

< 100 TeV?

Electroweak interaction

$SU(2) \times U(1)$

$Z, W, \, Higgs$?

$\alpha_{EM}, \sin \theta_W$?

Random “weak interaction?”

Symmetries?

Mediator particles?

$g < \text{around 1}$

Freeze-out relic?

Yes?

Fields? Fuzzy? Superfluid?!
Indirect Constraints

It isn’t enough to engineer away scattering with nuclei. There are also important constraints from indirect detection too.

![Graph showing indirect constraints](image)

The Majorana and $T3=0$ options work here as well, below the threshold for $ZZ$ and $WW$ annihilation. $Z$-exchange is suppressed by either the velocity or the mass of the final fermions.