WIMP dark matter
and Baryogenesis

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Facts

• Baryon Asymmetry of the Universe (BAU)
  \[ Y_B \equiv \frac{n_B}{s} \approx 8.5 \times 10^{-11} \]

• Baryonic matter abundance (post Planck)
  \[ \Omega_{Bh^2} = 0.02214 \pm 0.00024 \]

• Dark matter (DM) abundance (post Planck)
  \[ \Omega_{DWh^2} = 0.1187 \pm 0.0017 \]
Coincidences?

\[ \frac{\Omega_{DM}}{\Omega_B} \sim 5 \rightarrow \text{Asymmetric Dark Matter} \]

WIMP miracle \[ \rightarrow \Omega_{DM} h^2 = 0.1 \]
Coincidences?

\[ \Omega_{DM} / \Omega_B \sim 5 \rightarrow \text{Asymmetric Dark Matter} \]

\[ \text{WIMP miracle} \rightarrow \Omega_{DM} h^2 = 0.1 \]
Keep the WIMP miracle and ask the question: can we have a framework where the baryon asymmetry can be related to the thermal WIMP relic abundance?
Two miracles in one framework!

1. WIMP miracle
   weak-scale DM, thermal relic abundance

2. WIMPy baryogenesis miracle
   DM annihilation generates the baryon asymmetry
Two miracles in one framework!

1. WIMP miracle
   weak-scale DM, thermal relic abundance

2. WIMPpy baryogenesis miracle
   DM annihilation generates the baryon asymmetry
Prediction for $\Omega_B / \Omega_{DM}$?

$$10^{-6} < \frac{\Omega_B}{\Omega_{DM}} < 10$$

This is no prediction, but the observed value 0.2 is easily accommodated in such a range.
The idea

Figure 1: Schematic diagrams showing the evolution of the asymmetry created by dark matter annihilation.

(left) Model where asymmetry created in exotic antibaryons is sequestered in a sterile sector through baryon-number-conserving decays.

(right) Model where asymmetry created in exotic antibaryons is converted into a Standard Model baryon asymmetry through baryon-number-violating decays.

We present models that satisfy all three Sakharov conditions, and that simultaneously generate the observed baryon asymmetry and WIMP relic density. In particular, we find successful models of WIMPy baryogenesis with $O(1)$ couplings and CP phases, and weak-scale masses for all new fields. This is the "WIMPy baryogenesis miracle."
The model

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A set of minimal ingredients for WIMPy baryogenesis

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Table 1. Particle content of the model. $\bar{u}$ and $\bar{d}$ are the right-handed up and down quarks of the SM. The rest of the SM quarks also have charge 1, while all the leptons are neutral under the $\mathbb{Z}_4$ symmetry. The reason for these charge assignments are explained in Appendix D. Other non-abelian discrete groups work for the WIMPy baryogenesis mechanism, although we have not investigated such a possibility.

In order to study the phenomenological implications of this model, we write down an effective Lagrangian that includes all the dimension six operators (four-fermion operators) consistent with the quantum numbers in Table 1.

The list of 20 (plus Hermitian conjugates) operators $O_i$ is given in Appendix B, using two-component spinor notation $[\psi \bar{\psi}]$.

The EFT approach is valid only as long as the biggest momenta, $k_{\text{max}}$, involved in the processes we are considering, is such that $k_{\text{max}} < 1$. In our study, $k_{\text{max}}$ is given by some temperature, $T$, before the DM freezes out. As we will explain in more detail in the next subsection, the baryon asymmetry builds up between the time the washout processes freeze out, $x = x_{WO}$, and the time of DM annihilation freeze-out, $x = x_{FO}$, where $x = m_X/T$. $x_{FO} \ll 25$, as in usual WIMP scenarios. We find that typical values for $x_{WO}$ are around 10. Given that we scan over a DM range up to 1 TeV, with $x_{WO} = 10$ as the value of reference for the highest temperature, we have $k_{\text{max}} \ll m_X/x_{WO} \ll 100$ GeV. Then the condition for the validity of the EFT approach translates into a bound for the couplings, $\sqrt{i} \ll (100 \text{ GeV})^{-1}$. For the purpose of the numerical analysis in the following sections of the paper we choose to fix $\sqrt{i} = 10$ TeV, that translates into $\sqrt{i} \ll 100$. To keep the number of parameters in the numerical analysis manageable, we set some equalities among the relevant couplings and we relabel them for the ease of the rest of the text.

This last bound can lead to some confusion, thus a comment is in due order. In our parametrization of the lagrangian (2.1), the couplings $\sqrt{i}$ can be thought of as dimensionless Yukawa's. In a UV completion of our theory, they would be subject to the usual perturbative bound, $\sqrt{i} \ll 4\pi$, which seems to be in conflict with our $\sqrt{i} \ll 100$. The point is that the only sensible condition for our EFT is expressed as $\sqrt{i} \ll (100 \text{ GeV})^{-1}$. In other words, one could always keep $\sqrt{i}$ below $4\pi$ by lowering the scale $\sqrt{i}$. Thus, $\sqrt{i} \ll 100$ is an artifact, it is a consequence of our choice of fixing $\sqrt{i}$ to 10 TeV. In our context, values of $\sqrt{i}$ bigger than $4\pi$ can just be thought of as lowering the scale $\sqrt{i}$ below 10 TeV.
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**Dark matter**

**Exotic heavy quark**

**Sterile majorana fermion**
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All the SM quarks have charge -1, while the leptons and the Higgs are neutral under the $Z_{4}$
**DM annihilation**

\[
\begin{align*}
X & \rightarrow \lambda_s^2 \bar{u} \\
X & \rightarrow \psi \\
X & \rightarrow \lambda_{WO}^2 \\
X & \rightarrow \bar{u}
\end{align*}
\]

**kinematics imply** \(2m_X > m_\psi\)

**Asymmetry**

\[
\epsilon = \frac{\sigma(XX \rightarrow \psi \bar{u}) + \sigma(\bar{X} X \rightarrow \psi \bar{u}) - \sigma(XX \rightarrow \psi^\dagger \bar{u}^\dagger) - \sigma(\bar{X} X \rightarrow \psi^\dagger \bar{u}^\dagger)}{\sigma(XX \rightarrow \psi \bar{u}) + \sigma(\bar{X} X \rightarrow \psi \bar{u}) + \sigma(XX \rightarrow \psi^\dagger \bar{u}^\dagger) + \sigma(\bar{X} X \rightarrow \psi^\dagger \bar{u}^\dagger)}
\]

\[
\epsilon \propto \frac{\text{Im}(\lambda_{WO}^2)}{\Lambda^2} \frac{(s - m_\psi^2)^2}{16\pi s} \quad \Lambda \sim 1 - 10 \text{ TeV}
\]
Decay of the exotic heavy quark

\[ \psi \rightarrow \bar{d} \bar{d} n \]

- The decay violates baryon number.
- The exotic quark has to decay in order to avoid overclosing the universe.
- The SM-singlet fermion n has to be very light. We take it to be massless.
- We require this decay to be fast enough so that \( \psi \) is in thermal equilibrium during DM annihilation. This simplifies the Boltzmann Equations.
Sakharov conditions

√ 1. B-number violation

√ 2. CP violation

√ 3. Out of thermal equilibrium
Washout processes

Where $x = \frac{m_y}{2m_c}$ and the CP phase has been assigned to the washout coupling:

$$l_{WO} = \frac{|l_{WO}| e^{i\phi}}$$

There are processes that can potentially wash out the asymmetry. They are shown schematically in figure 2. The processes $\bar{u} X \to \bar{u} X$ involving DM particles, are referred to as "mixed" washout. They are obtained from the DM annihilation diagrams by crossing symmetry, and so involve the same couplings $l_{s1,s2,t}$. The processes in the two lower diagrams, that involve only $\psi$ and $\bar{u}$, go under the name of "pure" washout. We will discuss further about these processes in the cosmology section.

A very important result, emphasized by the authors of [52], is that in order to produce a significant baryon asymmetry, washout processes must freeze out before WIMP freeze-out.

To achieve this early washout freeze-out, one needs either a $m_y$ heavier than the DM, $m_y > m_c$, so that the washout is Boltzmann suppressed while DM is still annihilating, or a small couplings, such that the washout cross section is small compared to the annihilation cross section.

Constraints from the LHC

One of the new particles that we need in our models, $\psi$, is colored, which makes it a good candidate to be discovered at the LHC. Alternatively, the LHC can put severe bounds on these models. $\psi$ can be pair-produced at the hadron
Central result

“If washout processes freeze out before WIMP freeze-out, then a large baryon asymmetry may accumulate, and its final value is proportional to the WIMP abundance at the time that washout becomes inefficient.”

One way to achieve this: $m_\psi > m_x$
LHC bounds

\[ m_{\psi} \gtrsim 800 \text{ GeV} \]

\[ \Rightarrow m_{x} \gtrsim 400 \text{ GeV} \]
Updated LHC bounds

See S. Caron talk

ATLAS-CONF-2012-109
13 August 2012

Squark-gluino-neutralino model, $m(\tilde{\chi}^0_1) = 0$ GeV

\[ \int L \, dt = 5.8 \, \text{fb}^{-1}, \sqrt{s}=8 \text{ TeV} \]

0-lepton combined

- Observed limit ($\pm 1\sigma_{\text{SUSY}}^{\text{theory}}$)
- Expected limit ($\pm 1\sigma_{\text{SUSY}}^{\text{theory}}$)
- Observed limit ($4.7 \, \text{fb}^{-1}, 7 \text{ TeV}$)

ATLAS Preliminary
Contour levels for the modulus of the coupling $\lambda_{WO}$ needed for generating the measured BAU, in the $m_y/m_c$ plane. We display the pseudoscalar (upper left pane), $t$-channel (upper right pane) and scalar (lower pane) cases. The white lower left part corresponds to $m_y \leq 800$ GeV, which is excluded by the LHC.

The operators in eq. (12) are also responsible for DM annihilation into a quark plus an anti-quark. This annihilation channel, which does not contribute to the asymmetry, would be competing with the one into quark plus exotic anti-quark. We want the former to be suppressed with respect to the latter, in order to generate the correct BAU. Therefore, even strict bounds on the couplings $\lambda_7$ and $\lambda_8$ from direct detection, would not challenge these models. Considering the SI bounds from XENON100 [58], we find that the combination $\lambda_2^2\lambda_7\lambda_8$ has to be smaller than $\sim 10$.

If $\lambda_7 = \lambda_8$, there is no SI contribution, but the SD one is at its maximum. The SD limits are a few orders of magnitude weaker [59, 60] than SI limits, and are of no interest for the present study, given that they are weaker than the bound from the validity of the EFT approach, $\lambda_i < 100$.

Constraints on the couplings $\lambda_s$, $\lambda_p$ and $\lambda_t$ would be more interesting, because they play a crucial role in the generation of the baryon asymmetry and the determination of the DM relic abundance. The lowest order contribution to the direct detection involving these couplings is naively expected to be at one loop. Let us take a closer look at this statement and let us consider first the situation where only the $s$-channel is turned on ($\lambda_t = 0$). There are two one-loop diagrams, as shown in Figure 5. It is easy to see that, in the limit of zero external momenta, appropriate for direct detection, the contributions are:

$$L \supset \frac{\lambda_s^2}{\Lambda^2} (XX)(\psi \bar{u}) + \frac{\lambda_t^2}{\Lambda^2} (\bar{X}^\dagger \psi^\dagger) (X \bar{u}) + \frac{\lambda_{WO}^2}{\Lambda^2} (\psi \bar{u})(\psi \bar{u})$$

Fixed:

$$\Lambda = 10 \text{ TeV}$$

$$\delta = \frac{\pi}{4}$$

Re$(\lambda_{WO}) = \text{Im}(\lambda_{WO})$

Large CP phase!
Take home message

Two conceptually different approaches when trying to explain baryogenesis and DM in a unified framework:

• Asymmetric Dark Matter, based on the $\Omega_{\text{DM}} / \Omega_{\text{B}} \sim 5$ coincidence;

• WIMPy baryogenesis, based on the WIMP miracle.

WIMPy models, after experimental constraints are taken into account, work in a good portion of the parameter space. They provide a viable mechanism for low energy thermal baryogenesis.
Thank you
Direct detection bounds

\[ \frac{1}{\Lambda^2} (\lambda_7^2 (X \bar{u})(X^\dagger \bar{u}^\dagger) + \lambda_8^2 (\bar{X} u)(\bar{X}^\dagger u^\dagger) + \text{h.c.}) \]

Translated into 4-component-spinor notation

\[ \frac{\lambda_8^2 - \lambda_7^2}{4\Lambda^2} (\bar{X} \gamma^\mu \gamma \bar{U} \gamma_\mu U + \bar{X} \gamma^\mu \gamma \bar{U} \gamma_\mu \gamma_5 U) + \frac{\lambda_8^2 + \lambda_7^2}{4\Lambda^2} (\bar{X} \gamma^\mu \gamma_5 \gamma \bar{U} \gamma_\mu U + \bar{X} \gamma^\mu \gamma_5 \gamma \bar{U} \gamma_\mu \gamma_5 U) \]
Direct detection bounds

\[ \frac{1}{\Lambda^2} (\lambda_7^2 (X \bar{u})(X^\dagger \bar{u}^\dagger) + \lambda_8^2 (\bar{X} \bar{u})(\bar{X}^\dagger \bar{u}^\dagger) + \text{h.c.}) \]

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\[ \frac{\lambda_8^2 - \lambda_7^2}{4\Lambda^2} (\bar{X} \gamma^\mu \chi \bar{U} \gamma_\mu U + \bar{X} \gamma^\mu \chi \bar{U} \gamma_\mu \gamma_5 U) + \frac{\lambda_8^2 + \lambda_7^2}{4\Lambda^2} (\bar{X} \gamma^\mu \gamma_5 \chi \bar{U} \gamma_\mu U + \bar{X} \gamma^\mu \gamma_5 \chi \bar{U} \gamma_\mu \gamma_5 U) \]

Spin Independent  Spin Dependent
Direct detection bounds

\[
\frac{1}{\Lambda^2} \left( \lambda_7^2 (X \bar{u}) (X^\dagger \bar{u}^\dagger) + \lambda_8^2 (\bar{X} \bar{u}) (\bar{X}^\dagger \bar{u}^\dagger) + \text{h.c.} \right)
\]

Translated into 4-component-spinor notation

\[
\frac{\lambda_8^2 - \lambda_7^2}{4\Lambda^2} (\bar{\chi} \gamma^\mu \chi \bar{U} \gamma_\mu U + \bar{\chi} \gamma^\mu \chi \bar{U} \gamma_\mu \gamma_5 U) + \frac{\lambda_8^2 + \lambda_7^2}{4\Lambda^2} (\bar{\chi} \gamma^\mu \gamma_5 \chi \bar{U} \gamma_\mu U + \bar{\chi} \gamma^\mu \gamma_5 \chi \bar{U} \gamma_\mu \gamma_5 U)
\]

Spin Independent

Spin Dependent

Very mild constraints
Direct detection bounds

One-loop contribution

FIGURE 5. Diagrams for direct detection at one loop. In the limit of zero external momenta the sum of these two diagrams vanishes. This is understood just by looking at the fermionic propagator for $y$ in the loop, the direction of which in the second diagram is opposite to the one in the first, thus giving a relative minus sign. This is enough to conclude that the contribution to the cross section is not only loop suppressed but also velocity suppressed. As a consequence current direct detection experiments place virtually no limits on the coupling $l_{s}$. The exact same conclusion holds for the pseudoscalar coupling $l_{p}$.

For the $t$-channel ($l_{t} = 0, l_{s} = l_{p} = 0$), there is no analogous obvious cancellation at the level of one-loop Feynman diagrams, but it turns out that there is only a SD contribution, which is loop suppressed. Since, as we said, the SD limits are not even important for the tree-level couplings, we are definitely far from putting constraints on $l_{t}$ with direct detection.

CONCLUSIONS

In this work we have investigated whether a general class of WIMPy baryogenesis models is viable, after experimental constraints are taken into account. Our models are based on the same mechanism and on the same external particles as in Ref. [52]. However, by following an EFT approach and writing down a complete list of four-fermion operators, we extend and generalize their study, considering all the possible DM annihilation channels. The models considered here require the presence of a heavy fermion, $y$, which is crucial to the success of the whole mechanism. Because $y$ is colored, the LHC represents an excellent laboratory for testing these models. Although we have not yet studied in detail possible collider signals, current LHC searches already put a lower bound of 800 GeV on the mass of $y$, which in turn directly translates into a lower bound of 400 GeV on the DM mass. With the impressive pace at which the LHC and the ATLAS and CMS collaborations are operating, this bound can increase relatively quickly, pointing to even higher masses, or, in a better (luckier) scenario, a heavy colored fermion could be discovered soon, which would provide a hint that these models could be realized in nature indeed.

In this work we focused mainly on the cosmological aspects and we examined in some detail the constraints from the measured DM relic density and BAU. We considered three different channels for DM annihilation into a quark and an exotic antiquark: scalar and pseudoscalar $s$-channel, and $t$-channel. We found the pseudoscalar channel to be the most promising: it has the highest annihilation cross section, the lowest washout cross section and it generates a large asymmetry $e$. This combination results in lower values of the coupling $l_{p}$, compared to $l_{s}$ and $l_{t}$, and in the most efficient production of the BAU. In the spirit that lower rather than higher values of the couplings are generally preferred in the EFT, our analysis, in all cases, points toward a high DM mass, between 800 GeV and 1 TeV, and a small hierarchy between $y$ and $c$, $m_{y}$.

We also considered bounds from direct detection. These constrain only two operators that would be responsible for the annihilation of DM into a pair of quarks. Given that this channel does not contribute to the generation of the baryon asymmetry, we want it to be suppressed anyway. In this sense such bounds do not challenge these models at all. There are in principle one-loop diagrams, involving the couplings that also enter the generation of the asymmetry, that could contribute to the direct detection cross section. We showed that they are not only loop suppressed, but also velocity suppressed. Thus, this scenario is out of reach for current direct detection experiments.
Direct detection bounds

One-loop contribution

The 2 diagrams cancel!!
Direct detection bounds

One-loop contribution

The 2 diagrams cancel!!

Similar story for t-channel operators.
Direct detection bounds

One-loop contribution

The 2 diagrams cancel!!

Similar story for t-channel operators.

NO BOUNDS FROM DIRECT DETECTION