

Simultaneous Generation of WIMP Miracle-like Densities of Baryons and Dark Matter

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Abstract.

The observed density of dark matter is of the magnitude expected for a thermal relic weakly-interacting massive particle (WIMP). In addition, the observed baryon density is within an order of magnitude of the dark matter density. This suggests that the baryon density is physically related to a typical thermal relic WIMP dark matter density. We present a model which simultaneously generates thermal relic WIMP-like densities for both baryons and dark matter by modifying a large initial baryon asymmetry. Production of unstable scalars carrying baryon number at the LHC would be a clear signature of the model.

The ratio of the mass density of baryons to that of dark matter (the BDM ratio) is observed to be $\Omega_B/\Omega_{DM} \approx 1/5$. However, in most models the physics of baryogenesis and of dark matter production is physically unrelated. Why then is the density in baryons within an order of magnitude of that in dark matter? Either:

- A remarkable coincidence
- An anthropic selection mechanism
- The physics of the observed baryon asymmetry and dark matter densities is in some way related.

Therefore the BDM ratio may be a powerful clue to the correct particle physics theory.

Up to now there have been broadly two classes of model:

1). Direct mechanism: The dark matter particle and baryon number densities are directly related by a conserved charge,

$$\Rightarrow Q_{tot} = Q_B + Q_X \Rightarrow n_{cdm} \sim n_B \Rightarrow M_{DM} \sim m_n n_B / n_{cdm} \sim 1 - 10 \text{ GeV}$$

There are many models in this category, which typically predict asymmetric dark matter [1, 2, 3, 4, 5, 6, 7, 8]. Models also exist which break the simple mass relation $M_{DM} \sim 1 - 10 \text{ GeV}$, see [9, 10, 11, 12, 13, 14]. (In [15] a new idea is discussed where the correct dark matter density is generated via its interaction with the baryon asymmetry.)

2). Indirect mechanism: The dark matter and baryon densities are related by *similar* but *separate* physical mechanisms for their origin \Rightarrow Less rigid relation between n_B and n_{cdm} ; can have $n_B \gg n_{cdm} \Rightarrow$ larger M_{DM} . An example based on $d = 4$ Affleck-Dine leptogenesis is given in [16], where dark matter is due to a condensate of right-handed sneutrinos ¹

¹ The author is not aware of other examples in this class and would be interested to know if other models exist.

However, there are in fact *two* separate coincidences. 1). Why are the baryon and dark matter densities similar to each other? 2). Why are they both similar to the "WIMP Miracle" density? (Most models do not address 2.)

The "WIMP Miracle" refers to the natural similarity of the observed dark matter density and the thermal relic density of particles with weak-scale masses and interactions. This is widely interpreted as a strong indication that dark matter is due to thermal relic WIMPs. For dark matter with constant $\langle \sigma v_{rel} \rangle$, where σ is the non-relativistic annihilation cross-section, the observed dark matter density requires

$$\langle \sigma v_{rel} \rangle \approx 10^{-9} \text{ GeV}^{-2}$$

The DM annihilation cross-section may be expressed in terms of the annihilation matrix element \mathcal{M} as

$$\langle \sigma v_{rel} \rangle = \frac{|\mathcal{M}|^2}{32\pi m_{DM}^2}. \quad (1)$$

The matrix element is dimensionless and typically has the form $|\mathcal{M}|^2 = g_{eff}^4$. where g_{eff} is an effective coupling constant. Therefore

$$\langle \sigma v_{rel} \rangle = 1.6 \times 10^{-9} \left(\frac{g_{eff}}{0.2} \right)^4 \left(\frac{100 \text{ GeV}}{m_{DM}} \right)^2 \text{ GeV}^{-2}. \quad (2)$$

Therefore if M_{DM} is in the range 100 GeV – 1 TeV and if g_{eff} is not too much smaller than the weak interaction coupling $g \approx 0.65$ (which is natural as g_{eff} can have additional factors from mixing angles, mass ratios etc), then we get the right amount of thermal relic dark matter.

If the WIMP miracle does explain dark matter, and if we discount coincidence and antropic selection, then we need to explain why the baryon asymmetry is also similar to the WIMP miracle density. The similarity to the dark matter density then *follows* from this i.e. the observed baryon to dark matter ratio is actually due to a more fundamental relation between each of the densities and the WIMP miracle density.

In [17] and [18] we presented one approach to making this connection, based on a mechanism we call *baryomorphosis*. [Recently an alternative approach to achieving a WIMP-like baryon asymmetry, *WIMPy baryogenesis*, has been proposed in [19].]

This idea of baryomorphosis that the *observed* baryon density is determined by a process similar to thermal relic WIMP freeze-out. The model does not explain the baryon asymmetry, but modifies a large initial baryon asymmetry into a final thermal WIMP-like baryon asymmetry; hence "baryomorphosis" rather than "baryogenesis".

The ingredients of the baryomorphosis mechanism are:

- An initial baryon asymmetry, for example in a heavy particle Σ which is out of thermal equilibrium, which decays at a low temperature $T_d \lesssim O(100) \text{ GeV}$.
- Pairs of new scalar particles, ϕ_B and $\hat{\phi}_B$, called "annihilons", to which Σ decays. The annihilons have opposite Standard Model (SM) charges but, crucially, do not have opposite baryon numbers. ϕ_B and $\hat{\phi}_B$ are distinct particles which can have different masses, although for simplicity we will consider their masses to be equal in the following.
- A B-violating interaction which is broadly of weak interaction strength, via which ϕ_B and $\hat{\phi}_B$ annihilate, leaving a thermal WIMP-like baryon number density.
- A mechanism to transfer the baryon asymmetry from annihilons to conventional quarks.

This is illustrated schematically in Figure 1.

In [17] a simple model implementing the baryomorphosis mechanism was presented. In this model the annihilons annihilate to a complex boson \hat{H} via a renormalizable B-violating interaction of the form

$$\mathcal{L}_{\phi_B \hat{\phi}_B ann} = \lambda_B \phi_B \hat{\phi}_B \hat{H}^\dagger \hat{H} + h. c. . \quad (3)$$

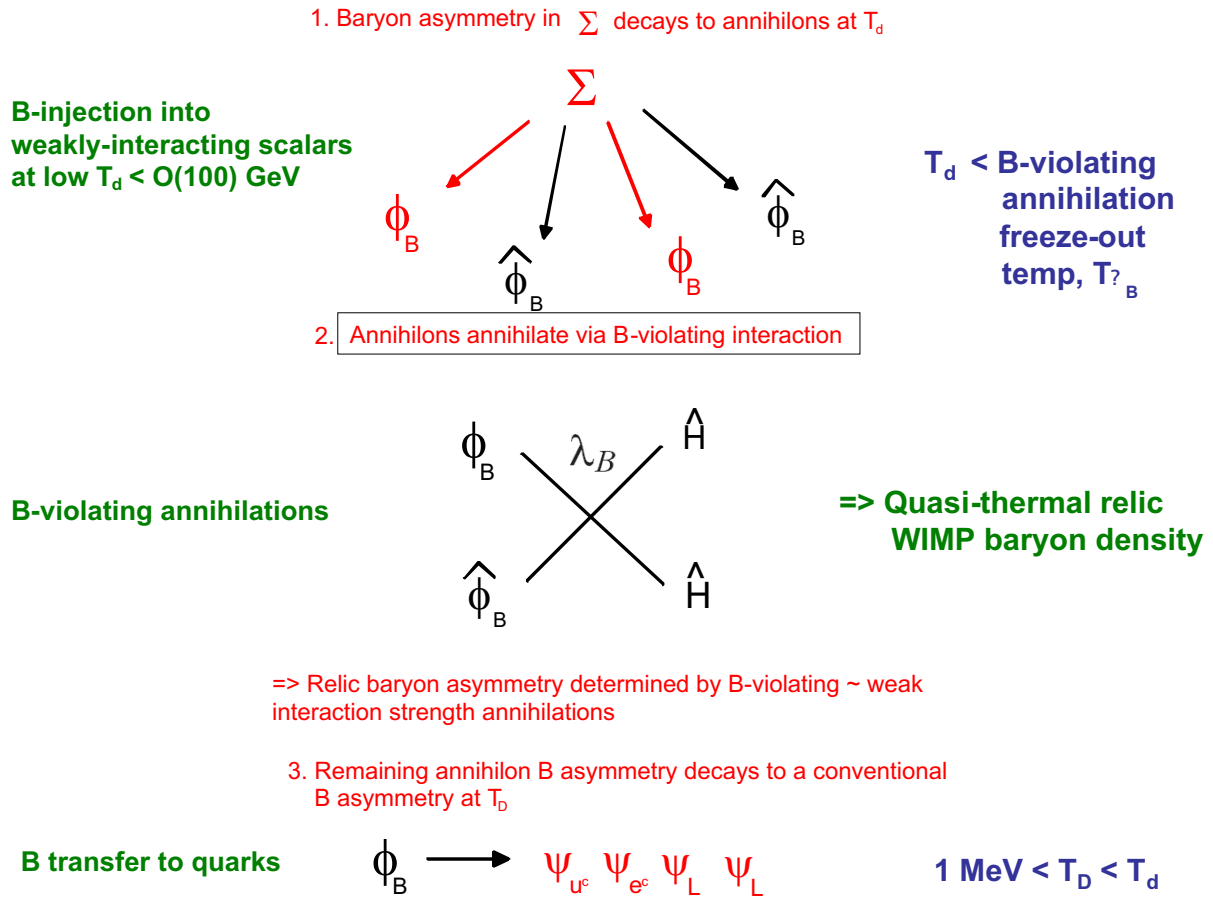


Figure 1.

Note that the \hat{H} cannot be the Higgs boson, since the $\phi_B, \hat{\phi}_B$ will mix once the Higgs VEV is introduced, resulting in a B-violating mass insertion which will wash out the annihilon asymmetry via scattering from thermal background quarks. Therefore the final state in the B-violating annihilation must have no VEV.

However, the original model in [17] has some features which do not have a symmetry explanation and must therefore simply be imposed:

- There is no symmetry to prevent B-violating mass mixing terms like $\phi_B \hat{\phi}_B$ (\Rightarrow B washout).
- There is no suppression of renormalizable couplings of ϕ_B to SM fermions ($\Rightarrow \phi_B$ decay too rapidly, before annihilating).

In addition, although it is not really problem, no WIMP dark matter candidate is specified.

In order to address these issues, in [18] a model was presented which uses a simple discrete symmetry to ensure no $\phi_B \hat{\phi}_B$ mixing terms leading to baryon washout. Since additional discrete symmetries are necessary to evade B washout, and since additional symmetries are also necessary to stabilize dark matter, it is natural to identify as dark matter particles the additional fields necessary as final states in the $\phi_B \hat{\phi}_B$ annihilation process. The model can be naturally combined with gauge singlet (or inert doublet [20]) dark matter to provide a unified model of baryomorphosis and scalar WIMP dark matter.

We introduce a pair of real singlet scalars $s \hat{s}$ plus a Z_2 discrete symmetry of the annihilons, Z_A ,

$$Z_A : \phi_B \rightarrow \phi_B ; \hat{\phi}_B \rightarrow -\hat{\phi}_B ; s \rightarrow s ; \hat{s} \rightarrow -\hat{s} , \quad (4)$$

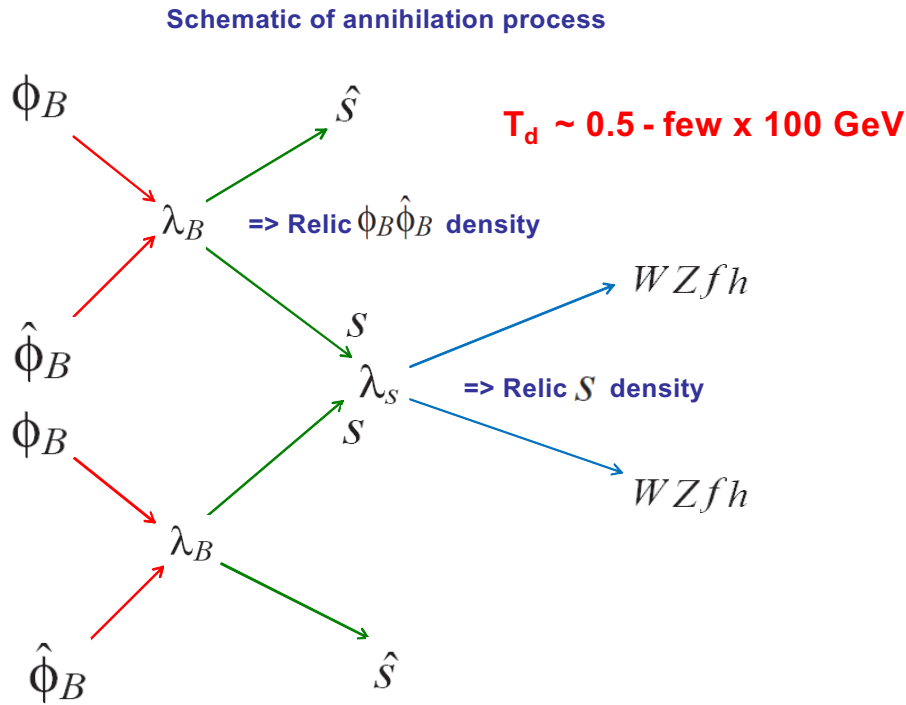


Figure 2.

with all SM fields invariant under Z_A . This eliminates the dangerous B-violating mass mixing terms $\phi_B \hat{\phi}_B$ and $\phi_B \hat{\phi}_B H^\dagger H$ but allows the B-violating annihilation process

$$\mathcal{L}_{\phi_B \hat{\phi}_B \text{ ann}} = \lambda_B \phi_B \hat{\phi}_B s \hat{s} + h. c. . \quad (5)$$

Note that ϕ_B and $\hat{\phi}_B$ must carry gauge charges to prevent the dangerous terms $\phi_B \phi_B$ and $\hat{\phi}_B \hat{\phi}_B$, which are allowed under Z_A .

We need a second discrete symmetry to stabilize the dark matter, Z_S ,

$$Z_S : s \rightarrow -s ; \hat{s} \rightarrow -\hat{s} . \quad (6)$$

The $Z_A \times Z_S$ symmetry then allows the coupling to the SM:

$$\frac{\lambda_s}{2} s s H^\dagger H + \frac{\lambda_{\hat{s}}}{2} \hat{s} \hat{s} H^\dagger H . \quad (7)$$

This allows the s and \hat{s} to annihilate down to a thermal WIMP-like dark matter density.

The formation of the final baryon asymmetry and dark matter density in this model is shown schematically in Figure 2. As before, the initial annihilon asymmetry is injected at a low temperature $T_d \sim 0.1 - 100 \text{ GeV}$. The s and \hat{s} subsequently annihilate down to thermal WIMP-like density if $T_d < T_s$, or to a standard thermal WIMP density if $T_d > T_s$, where $T_s \approx m_s/25$ is the freeze-out temperature of the s and \hat{s} dark matter.

The annihilation cross-section for $\phi_B \hat{\phi}_B \rightarrow s \hat{s}$ is

$$\langle \sigma v \rangle_{\phi_B} = \frac{\lambda_B^2}{32\pi m_{\phi_B}^2} \left(1 - \frac{m_s^2}{m_{\phi_B}^2} \right)^{1/2} . \quad (8)$$

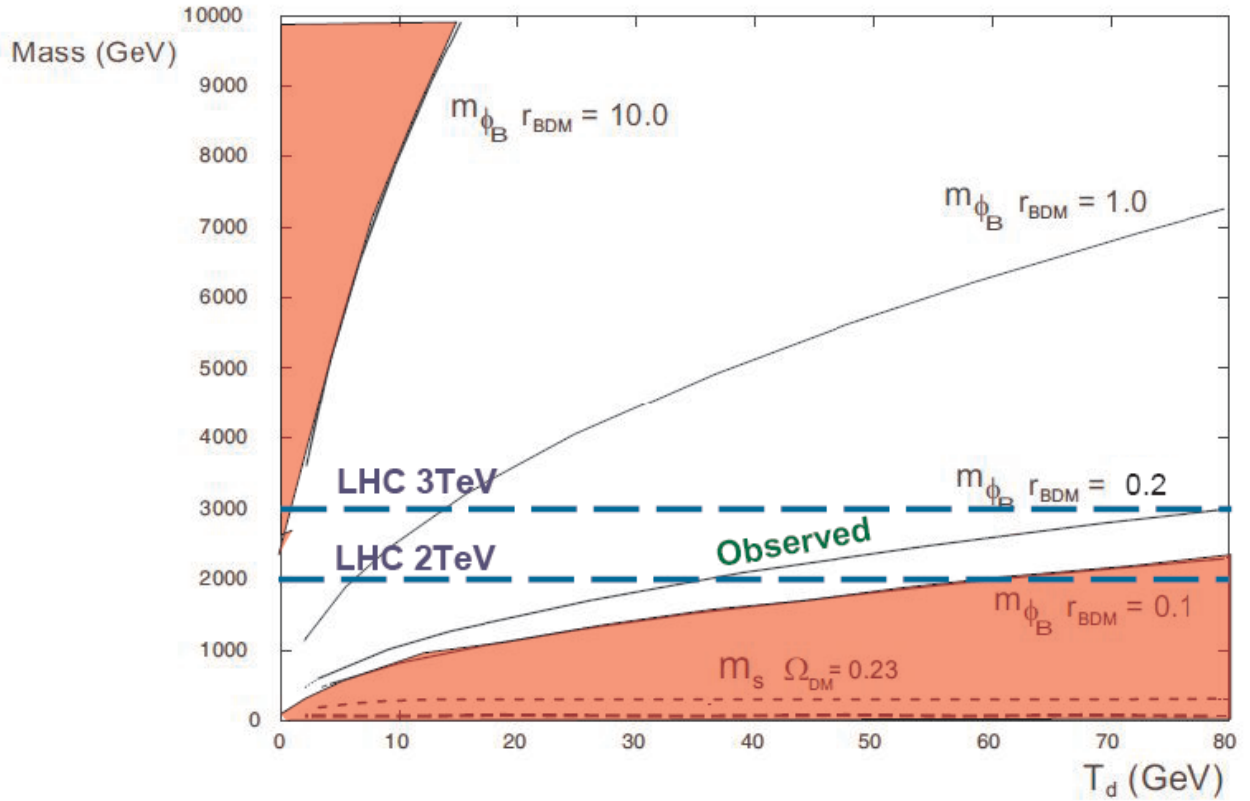


Figure 3.

The freeze-out number density at T_d is then

$$n_{\phi_B}(T_d) \approx \frac{H(T_d)}{\langle \sigma v \rangle_{\phi_B}} . \quad (9)$$

(The $\hat{\phi}_B$ number density is the same when $m_{\phi_B} = m_{\hat{\phi}_B}$.) If ϕ_B later decays to baryon number $B(\phi_B)$ and $\hat{\phi}_B$ to $B(\hat{\phi}_B)$, the baryon asymmetry to dark matter ratio at present, $r_{BDM} \equiv \Omega_B/\Omega_{DM}$, is given by

$$r_{BDM} = 3(B(\phi_B) + B(\hat{\phi}_B)) \frac{m_n}{\Omega_{DM}} \frac{g(T_\gamma)}{g(T_d)^{1/2}} \left(\frac{4\pi^3}{45M_{Pl}^2} \right)^{1/2} \frac{T_\gamma^3}{\rho_c} \frac{1}{T_d} \frac{1}{\langle \sigma v \rangle_{\phi_B}} . \quad (10)$$

Here $g(T)$ is the effective number of relativistic degrees of freedom, m_n is the nucleon mass, ρ_c the critical density, T_γ is the present photon temperature and $M_{Pl} = 1.22 \times 10^{19}$ GeV. The prefactor 3 accounts for the three colours of ϕ_B . Requiring that $\Omega_{DM} = 0.23$ then determines the annihilon mass

$$m_{\phi_B} = 2.81 \text{ TeV} \times g(T_d)^{1/4} r_{BDM}^{1/2} (B(\phi_B) + B(\hat{\phi}_B))^{-1/2} \left(\frac{T_d}{1 \text{ GeV}} \right)^{1/2} \lambda_B \left(1 - \frac{m_S^2}{m_{\phi_B}^2} \right)^{1/4} . \quad (11)$$

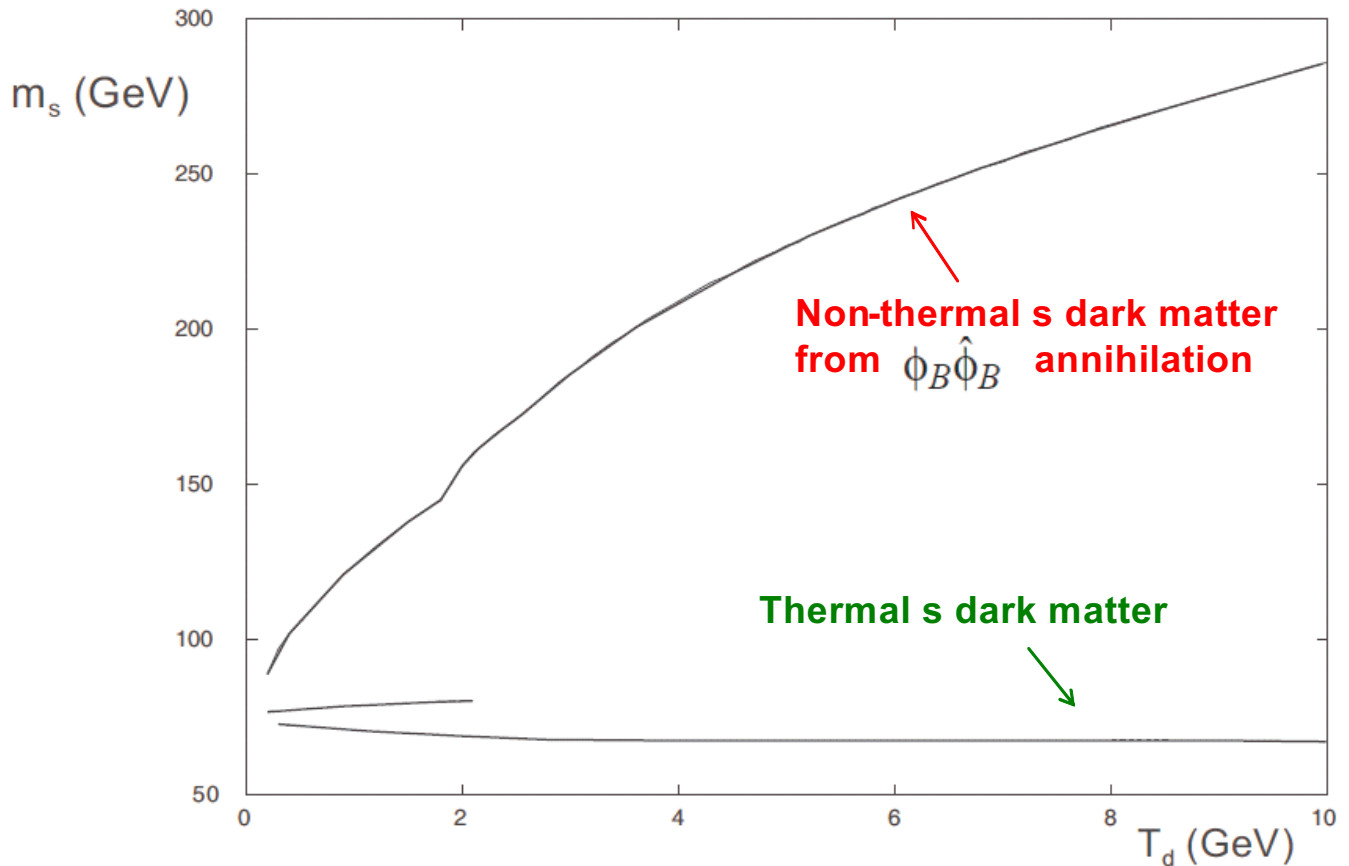


Figure 4.

In this we have assumed that ϕ_B and $\hat{\phi}_B$ are non-relativistic when the B-violating annihilation occurs. This is generally true for gauge-charged ϕ_B and $\hat{\phi}_B$, as discussed in [18]. It is also true in s and \hat{s} annihilation provided $T_d \gtrsim 0.4$ GeV [18].

In Figure 3 we show the annihilation mass as a function of the B injection temperature T_d for different values of the baryon-to-dark matter ratio r_{BDM} . We have set $\lambda_B = \lambda_s = 0.1$, which are dimensionally natural values in particle physics models. Since the mystery of the baryon-to-dark matter ratio may be considered why they are within an order of magnitude of each other, we have shown r_{BDM} in the range 0.1 to 10. We see that a wide range of annihilation masses in the 100 GeV to 10 TeV range is compatible with r_{BDM} in the range 0.1 to 10 when T_d is in the range 0.1 GeV to 100 GeV. There is also an upper bound on T_d from the requirement that $T_d < T_{\phi_B}$, where T_{ϕ_B} is the freeze-out temperature of the B-violating annihilation process, $T_{\phi_B} \approx m_{\phi_B}/20$. T_{ϕ_B} equals a few hundred GeV for the range of m_{ϕ_B} considered in Figure 4.

Therefore we see that for a wide range of T_d , $O(0.1)$ GeV to $O(100)$ GeV, the baryon density is naturally within an order of magnitude of the dark matter density. (Note that a low T_d is essential for a baryon asymmetry to exist at all.)

In Figure 3 we have also shown lines for m_{ϕ_B} equal to 2 TeV and 3 TeV, corresponding to bounds that may be achievable for coloured scalars at the LHC. The observed $r_{BDM} = 0.2$ favours annihilation masses less than ~ 3 TeV over the range of T_d from 0.1 to 100 GeV. Therefore, should the annihilons be coloured, there is a good prospect of producing them at the LHC.

In the case where s and \hat{s} are degenerate in mass, both scalars are stable and contribute to dark matter.

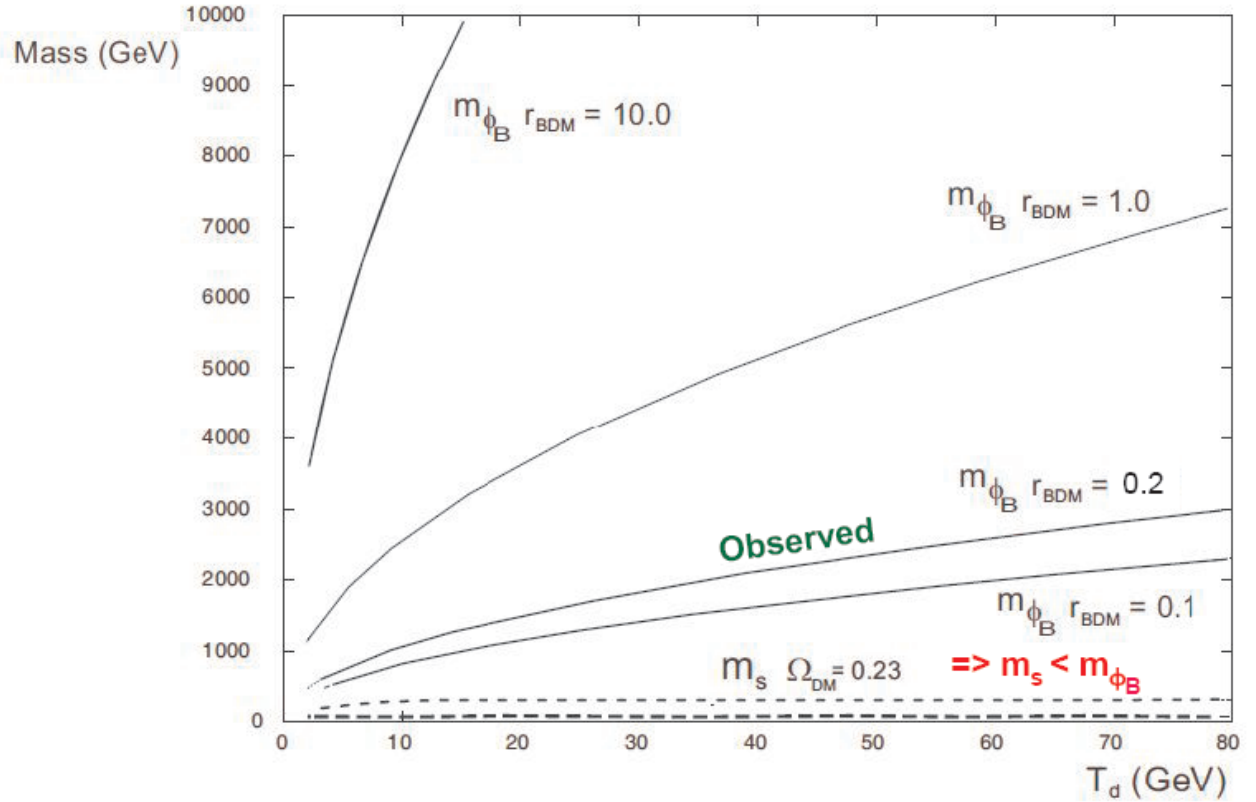


Figure 5.

A key requirement is that $m_s < m_{\phi_B}$, so that the $\phi_B \hat{\phi}_B$ annihilation process is kinematically allowed. If $T_d < T_s$, then the s and \hat{s} dark matter density is non-thermal, coming from the s and \hat{s} produced as final state particles in $\phi_B \hat{\phi}_B$ annihilation. This gives an enhancement of the density by T_s/T_d relative to the thermal relic s density,

$$\Omega_{DM} = \frac{2m_s}{\rho_c} \frac{g(T_\gamma)}{g(T_d)^{1/2}} \left(\frac{4\pi^3}{45M_{Pl}^2} \right)^{1/2} \frac{T_\gamma^3}{T_d} \frac{1}{\langle \sigma v \rangle_s}. \quad (12)$$

If $T_d > T_s$ then the dark matter is purely thermal relic in nature. In this case we can approximately replace T_d by T_s in Eq. (12). The resulting m_s is shown in Figure 4 for Higgs mass $m_h = 150$ GeV, $\lambda_s = 0.1$ and $\Omega_{DM} = 0.23$. In Figure 5 we show m_s together with m_{ϕ_B} . For all T_d the s mass is much less than the ϕ_B mass, as required for consistency of the model. In addition, for most T_d the s freeze-out temperature is less than T_d , so that s dark matter is in fact thermal relic in nature. Non-thermal s dark matter is found only at $T_d \lesssim 10$ GeV.

We conclude that a consistent baryomorphosis model can be constructed using only a simple $Z_2 \times Z_2$ symmetry.

So far we have produced a thermal WIMP-like baryon asymmetry in ϕ_B and $\hat{\phi}_B$ particles. This must still be transferred to conventional quarks. We will focus on the example of coloured annihilons, which have the best prospect of being produced at the LHC. We assume the annihilons transform under $SU(3)_c \times SU(2)_L$ as $\phi_B(\mathbf{3}, \mathbf{1})$ and $\hat{\phi}_B(\bar{\mathbf{3}}, \mathbf{1})$. In order to produce a thermal WIMP-like baryon asymmetry,

the decay of $\phi_B, \hat{\phi}_B$ must occur after the baryon asymmetry has frozen out, at $T_D < T_d$. This means that ϕ_B and $\hat{\phi}_B$ must be *very long-lived* particles:

$$1.5 \text{ s} \gtrsim \tau \gtrsim 8 \times 10^{-11} \left(\frac{100 \text{ GeV}}{T_d} \right)^2 \text{ s}, \quad (13)$$

where the upper bound is from nucleosynthesis. This provides a key experimental signature of annihilons. The long annihilon life-time requires either an extremely small renormalizable Yukawa coupling $\lambda \phi_B \bar{\psi} \psi$ to SM fermions ψ with

$$\lambda \lesssim 1.2 \times 10^{-10} \left(\frac{T_d}{1 \text{ GeV}} \right) \left(\frac{1 \text{ TeV}}{m_{\phi_B}} \right)^{1/2}, \quad (14)$$

or a non-renormalizable coupling suppressed by a sufficiently large mass scale. The former possibility seems overtly unnatural, so we will consider the latter. However, in this case we need to explain why there are no renormalizable couplings leading to rapid ϕ_B decay.

The simplest way to achieve this is if ϕ_B has a large hypercharge e.g. $Y(\phi_B) = 5/3$. In this case ϕ_B and $\hat{\phi}_B$ can decay only via mass-suppressed non-renormalizable interactions. For example, for the case $\phi_B(\mathbf{3}, \mathbf{1}, 5/3)$ and $\hat{\phi}_B(\bar{\mathbf{3}}, \mathbf{1}, -5/3)$, we can form

$$\frac{1}{M^3} \phi_B \bar{d}_R^c d_R \bar{L}_L^c L_L \quad (15)$$

and

$$\frac{1}{M^3} \hat{\phi}_B \bar{d}_R^c e_R^c Q_L Q_L. \quad (16)$$

The mass M should then be in the range $10^6 - 10^8$ GeV to account for the low decay temperature T_D [17].

Note that for $\hat{\phi}_B$ to decay, we must assume that Z_A is slightly broken by the non-renormalizable operators. However, since these operators are suppressed by a large mass scale, this small breaking of Z_A will not introduce any dangerous mass mixing between ϕ_B and $\hat{\phi}_B$. If baryon number is conserved, then from Eq. (15) and Eq. (16) the baryon numbers² of ϕ_B and $\hat{\phi}_B$ would be $B(\phi_B) = -2/3$ and $B(\hat{\phi}_B) = -1/3$.

However, if we do not assume baryon number conservation, then there are other possible operators, for example

$$\frac{1}{M^3} \phi_B (\bar{e}_R Q_L \bar{e}_R L_L)^\dagger, \quad (17)$$

which allows ϕ_B to decay to a final state with $B = 1/3$. In this case the effective baryon number of ϕ_B and $\hat{\phi}_B$ will be determined by their dominant decay modes.

Observation of such unstable particles might be achieved via the decay of particles which are stopped in detectors (see e.g. [21]).

In summary, the key experimental feature of the baryomorphosis model are the annihilons $\phi_B, \hat{\phi}_B$:

- Their mass must be 100 GeV - few TeV to produce weak-strength annihilations \Rightarrow good prospect of producing at colliders.
- They have a long lifetime and decay to net B number.
- They may have B-violating decays.
- Their long lifetime suggests large hypercharge $|Y| \geq 5/3$.
- The best case is that of coloured annihilons: Can pair produce at LHC up to 2-3 TeV. (Similar to squark production.)

² ϕ_B and $\hat{\phi}_B$ also carry lepton number, $L(\phi_B) = -2$ and $L(\hat{\phi}_B) = 1$.

Conclusions

- It is possible to *modify* a large initial baryon asymmetry to be similar to a thermal relic WIMP mass density \Rightarrow *Baryomorphosis*.
- Requires additional particles and discrete symmetries \Rightarrow Can naturally combine with a WIMP dark matter candidate (gauge singlet scalars, inert doublets) \Rightarrow Simultaneous generation of thermal WIMP-like baryon and dark matter densities.
- Therefore can understand both of the puzzles of the baryon density: why it is similar to the dark matter density and why it is similar to the "WIMP miracle" density.
- Need a low B-injection temperature, $T_d < \text{few} \times 100 \text{ GeV}$.
- Generically requires pairs of new particles ("annihilons") with gauge interactions and with mass $\sim 100 \text{ GeV} - \text{few TeV} \Rightarrow$ Could be produced at the LHC.
- Two types of annihilon are necessary, with opposite gauge charge but different B.
- Annihilons have long lifetime and decay to baryon number, with possibly large hypercharge and B-violating decay modes.

To sum up, the WIMP miracle *can* account for DM without requiring either coincidence or anthropic selection to explain $\Omega_B/\Omega_{DM} = 1/5$.

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References

- [1] S.M.Barr, R.S.Chivukula and E.Fahri, *Phys. Lett.* **B241** (1990) 387; S.M.Barr, *Phys. Rev. D* **D44** (1991) 3062; D.B.Kaplan, *Phys. Rev. Lett.* **68** (1992) 741.
- [2] N.Cosme, L.Lopez Honorez and M.H.G.Tytgat, *Phys. Rev. D* **D72** (2005) 043505; R. Kitano and I. Low, *Phys. Rev. D* **71**, 023510 (2005) [arXiv:hep-ph/0411133]. K. Agashe and G. Servant, *JCAP* **0502**, 002 (2005) [arXiv:hep-ph/0411254]; D. Hooper, J. March-Russell and S. M. West, *Phys. Lett. B* **605** (2005) 228 [arXiv:hep-ph/0410114]; M. Y. Khlopov, *Pisma Zh. Eksp. Teor. Fiz.* **83**, 3 (2006) [*JETP Lett.* **83**, 1 (2006)] [arXiv:astro-ph/0511796]. G. R. Farrar and G. Zaharijas, *Phys. Rev. Lett.* **96**, 041302 (2006) [arXiv:hep-ph/0510079]; S. Abel and V. Page, *JHEP* **0605**, 024 (2006) [arXiv:hep-ph/0601149]. H. An, S. L. Chen, R. N. Mohapatra and Y. Zhang, *JHEP* **1003**, 124 (2010) [arXiv:0911.4463 [hep-ph]].
- [3] S.D.Thomas, *Phys. Lett.* **B356** (1995) 256.
- [4] K.Enqvist and J.McDonald, *Nucl. Phys.* **B538** (1999) 321; K. Enqvist and J. McDonald, *Phys. Lett. B* **440**, 59 (1998) [arXiv:hep-ph/9807269]. L. Roszkowski and O. Seto, *Phys. Rev. Lett.* **98**, 161304 (2007) [arXiv:hep-ph/0608013]; O. Seto and M. Yamaguchi, *Phys. Rev. D* **75**, 123506 (2007) [arXiv:0704.0510 [hep-ph]]; F. Deldato and J. McDonald, *JCAP* **1106**, 008 (2011) [arXiv:1101.5328 [hep-ph]]; F. Deldato and J. McDonald, arXiv:1111.2305 [hep-ph].
- [5] T. Cohen, D. J. Phalen, A. Pierce and K. M. Zurek, *Phys. Rev. D* **82**, 056001 (2010) [arXiv:1005.1655 [hep-ph]]; H. Davoudiasl, D. E. Morrissey, K. Sigurdson and S. Tulin, *Phys. Rev. Lett.* **105**, 211304 (2010) [arXiv:1008.2399 [hep-ph]]. J. Shelton and K. M. Zurek, *Phys. Rev. D* **82** (2010) 123512 [arXiv:1008.1997 [hep-ph]]. M. Blennow, B. Dasgupta, E. Fernandez-Martinez and N. Rius, *JHEP* **1103**, 014 (2011) [arXiv:1009.3159 [hep-ph]].
- [6] T. Cohen and K. M. Zurek, *Phys. Rev. Lett.* **104**, 101301 (2010) [arXiv:0909.2035 [hep-ph]]; L. J. Hall, J. March-Russell and S. M. West, arXiv:1010.0245 [hep-ph]; B. Dutta and J. Kumar, *Phys. Lett. B* **699**, 364 (2011) [arXiv:1012.1341 [hep-ph]]; J. J. Heckman, S. -J. Rey, *JHEP* **1106** (2011) 120. [arXiv:1102.5346 [hep-th]]. M. L. Graesser, I. M. Shoemaker and L. Vecchi, arXiv:1103.2771 [hep-ph]; M. T. Frandsen, S. Sarkar and K. Schmidt-Hoberg, arXiv:1103.4350 [hep-ph]. S. D. McDermott, H. B. Yu and K. M. Zurek, arXiv:1103.5472 [hep-ph]; C. Kouvaris, P. Tinyakov, *Phys. Rev. Lett.* **107** (2011) 091301. [arXiv:1104.0382 [astro-ph.CO]]. C. Cheung, K. M. Zurek, [arXiv:1105.4612 [hep-ph]]; J. March-Russell, M. McCullough, [arXiv:1106.4319 [hep-ph]]; H. Davoudiasl, D. E. Morrissey, K. Sigurdson and S. Tulin, arXiv:1106.4320 [hep-ph]; C. Arina and N. Sahu, arXiv:1108.3967 [hep-ph]; K. Petraki, M. Trodden and R. R. Volkas, arXiv:1111.4786 [hep-ph].
- [7] N. F. Bell, K. Petraki, I. M. Shoemaker and R. R. Volkas, arXiv:1105.3730 [hep-ph];
- [8] B. von Harling, K. Petraki and R. R. Volkas, arXiv:1201.2200 [hep-ph].
- [9] Y. Cai, M. A. Luty and D. E. Kaplan, arXiv:0909.5499 [hep-ph].

- [10] M. R. Buckley and L. Randall, arXiv:1009.0270 [hep-ph].
- [11] P. H. Gu, M. Lindner, U. Sarkar and X. Zhang, arXiv:1009.2690 [hep-ph].
- [12] Y. Cui, L. Randall and B. Shuve, arXiv:1106.4834 [hep-ph].
- [13] A. Falkowski, J. T. Ruderman and T. Volansky, JHEP **1105**, 106 (2011) [arXiv:1101.4936 [hep-ph]].
- [14] R. Allahverdi, B. Dutta and K. Sinha, Phys. Rev. D **83**, 083502 (2011) [arXiv:1011.1286 [hep-ph]].
- [15] F. D'Eramo, L. Fei and J. Thaler, arXiv:1111.5615 [hep-ph].
- [16] J. McDonald, JCAP **0701**, 001 (2007) [arXiv:hep-ph/0609126].
- [17] J. McDonald, Phys. Rev. D **83**, 083509 (2011) arXiv:1009.3227 [hep-ph].
- [18] J. McDonald, arXiv:1108.4653 [hep-ph].
- [19] Y. Cui, L. Randall and B. Shuve, arXiv:1112.2704 [hep-ph].
- [20] L. Lopez Honorez, E. Nezri, J. F. Oliver and M. H. G. Tytgat, JCAP **0702**, 028 (2007) [arXiv:hep-ph/0612275].
- [21] P. W. Graham, K. Howe, S. Rajendran and D. Stolarski, arXiv:1111.4176 [hep-ph].