COSMO'10

Baryomorphosis :

A framework relating the Baryon Asymmetry to the “WIMP Miracle”

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Baryon-to-Dark Matter Ratio

WMAP 7-year Data => $\Omega_{DM}/\Omega_B = 5.89$

In most cases the physics of baryogenesis and of dark matter production is unrelated

Why is the density in baryons within an order of magnitude of that of dark matter?

Either

Remarkable coincidence or undefined anthropic selection mechanism

or

The physics of the observed baryon asymmetry and dark matter densities are related

The BDM ratio may be a powerful indicator of the correct particle physics theory

Baryon-to-Dark Matter Ratio Models [BDM models]

Broadly two classes:

1. Direct Mechanism:

The dark matter particle and baryon number are directly related by a conserved charge $Q_{tot} = Q_B + Q_X \Rightarrow n_{cdm} \sim n_B$

$\Rightarrow M_{cdm} \sim m_n n_B / n_{cdm} \sim$ 1-10 GeV

Variation: The dark matter and baryon density originate from a common asymmetry, but the ratio depends on the transfer mechanism to baryon number

$M_{cdm} >> 1$ GeV possible

2. Indirect Mechanism:

The dark matter and baryon density are related by similar but <u>separate</u> physical mechanisms for their origin

=> Less rigid relation between n_B and n_{cdm} [Can have $n_B >> n_{cdm}$]

Direct BDM Models:

Non-SUSY: (Conserved generalized baryon number)

Additional $SU(2)_L$ fermions + sphalerons Barr, Chivukula & Farhi, PLB241 (1990) 387

Additional anomalous U(1) + EW baryogenesis Kaplan PRL68 (1992) 741

B carrying DM with $\sigma_{\overline{X}}^{ann} \neq \sigma_{X}^{ann}$ Farrar & Zaharijas, PRL96 (2006) 041302

SUSY: (Conserved R-parity)

Scalar condensate asymmetry $\phi \rightarrow \tilde{u}dd$ Thomas, PLB356 (1995) 256

Q-Ball Decay $Q \rightarrow q + \chi$ Enqvist & JMcD, NPB538 (1999) 321

Implies $n_B = (1\text{-}3)\, n_{cdm}$ => $m_{cdm} \approx$ 2-6 GeV

Q-Ball Decay to axinos $Q \rightarrow q + \tilde{a}$ Roszkowski & Seto, hep-ph/0608013, Seto & Yamaguchi, hep-ph/0704.0510

$m_{\tilde{a}} \sim 2GeV$ => Can explain baryon-to-dark matter ratio

Indirect BDM Model: d=4 Affleck-Dine leptogenesis + RH sneutrino DM

(JMcD, JCAP 0701 (2007) 001, hep-ph/0609126)

Recent Examples (Asymmetric DM)

Direct:

“Darkogenesis”, Shelton & Zurek 1008.1997 (1-15 GeV)

“Aidnogenesis”, Blennow, Dasgupta, Fernandez-Martinez, Rius, 1009.3159 (1-10 GeV)

“Hylogenesis”, Davoudiasl, Morrissey,Sigurdson,Tulin, 1008.2399 (1-10 GeV)

Direct (with variation):

“Strongly interacting Asymmetric DM”, Cai, Luty, Kaplan, 0909.5499 (2 TeV)

“Xogenesis”, Buckley & Randall, 1009.0270 (10 GeV-10 TeV)

Gu, Lindner, Sarkar and Zhang, 1009.2690 (10 GeV-10 TeV)

But what about the “WIMP Miracle”?

The previous models can account for <u>baryogenesis</u>, dark matter and the ratio of the observed baryon and dark matter densities

But they give up on the other striking observation: the dark matter and baryon densities are similar to a typical thermal relic WIMP density (the “WIMP miracle”)

Ideally we would like to retain thermal relic WIMP dark matter

A key point is that we only need to understand the <u>final</u> baryon density, not the initial baryon asymmetry

=> BARYOMORPHOSIS

<u>Modification</u> of an initial large baryon asymmetry to a final thermal WIMP-like baryon density

The Baryomorphosis mechanism/framework

The key ingredients are:

1. A baryon asymmetry in a gauge singlet progenitor particle Σ, which decays at a low temperature < 10 GeV.

2. Pairs of new particles, “Annihilons”, to which Σ decays.

   Annihilons have mass 100 GeV – 1 TeV. They have opposite gauge charge but <u>not</u> opposite baryon number.

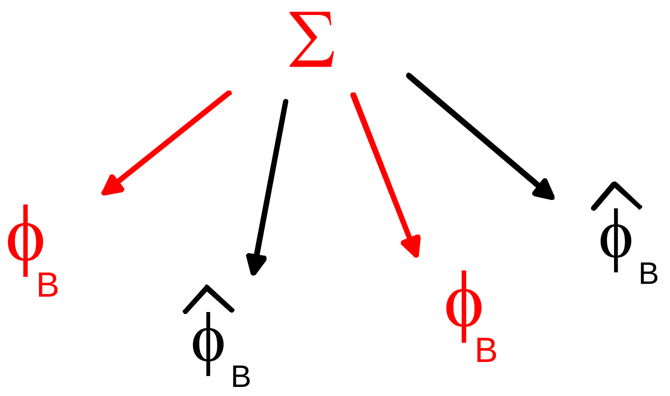
   They mediate a B-violating interaction which is of broadly weak interaction strength.

   The existence of Annihilon pairs is the main prediction of the model for collider experiments.

3. A way to transfer the baryon asymmetry from Annihilons to quarks.

1. Baryon asymmetry in Σ decays to annihilons at T_d

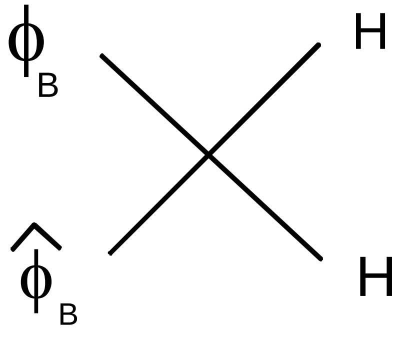
B-injection into weakly-interacting scalars at low T



T_d < B-violating annihilation freeze-out temp

2. Annihilons annihate via Higgs portal interaction

B-violating annihilations



=> Quasi-thermal relic WIMP baryon density

=> Relic baryon asymmetry determined by B-violating ~ weak interaction strength annihilations

3. Remaining annihilon B asymmetry decays to a conventional B asymmetry at T_D

B transfer to quarks $\phi_B \longrightarrow \psi_{u^c}\ \psi_{e^c}\ \psi_L\ \psi_L$ **1 MeV < T_D < T_d**

Example: Coloured Scalar Annihilons

$$\phi_B(3, 2/3), \ \hat{\phi}_B(\overline{3}, -2/3).$$

$$B(\phi_B) = 1/3, B(\hat{\phi}_B) = 2/3 \text{ and } B(\Sigma) = -2.$$

$$\mathcal{L}_{\Sigma\, decay} = \frac{1}{M_*}\Sigma\phi_B^2\hat{\phi}_B^2 \quad + h.c.$$

(B-injection)

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

(B-violating annihilation)

$$\phi_B\hat{\phi}_B \rightarrow H^\dagger H$$

=>

$$\langle\sigma v\rangle = \frac{\lambda_B^2}{16\pi m_{\phi_B}^2}$$

$$n_{\phi_B} < \sigma v > \ < \ H$$

=>

$$\Omega_B h^2 = \frac{m_n}{m_{\phi_B}}\frac{T_{\phi_B}}{T_d}\times\Omega_{\phi_B\, th}h^2$$

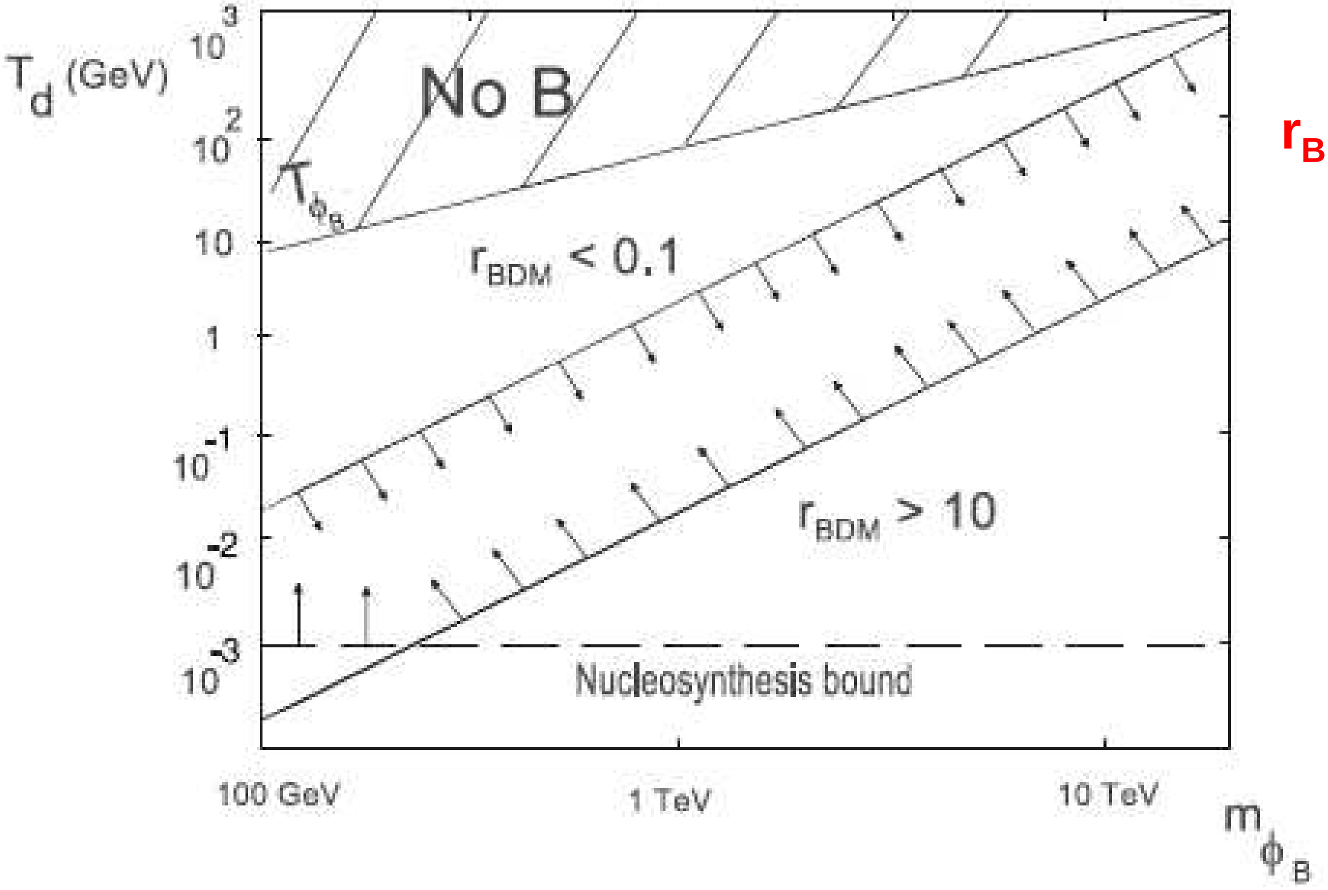
$$\Omega_{\phi_B\, th} = \frac{g(T_\gamma)}{g(T_{\phi_B})}\frac{k T_{\phi_B} T_\gamma^3}{x_{\phi_B}\langle\sigma v\rangle\rho_c M_{Pl}},$$

< 1

> 1

Typical thermal relic WIMP density

Σ decay temp



$r_{BDM} = \Omega_B/\Omega_{DM}$

FIG. 1: Region of T_d, m_{ϕ_B} parameter space for where Ω_B is within an order of magnitude of Ω_{DM}, for the case $\lambda_B = 0.1$. The "No B" region corresponds to $T_d > T_{\phi_B}$, where $\phi_B - \hat{\phi}_B$ annihilations are in equilibrium and erase the B asymmetry.

The B asymmetry is in the relic annihilons => must transfer this to a conventional quark baryon asymmetry

$$\mathcal{L}_{\phi_B\, decay} = \frac{1}{M_D^3}\phi_B \psi_{u^c}\psi_{e^c}\psi_L\psi_L \quad + h.c.$$

$$\mathcal{L}_{\hat{\phi}_B\, decay} = \frac{1}{M_D^3}\hat{\phi}_B \psi_{u^c}\psi_{d^c}\overline{\psi}_L\overline{\psi}_L \quad + h.c..$$

=> Annihilon decay at T_D

$$\Gamma_{\phi_B} \approx k_p \frac{m_{\phi_B}^7}{M_D^6} \, ,$$

=> $m_D \approx 5\times 10^7 \text{ GeV} \left(\frac{k_p}{k_T}\right)^{1/6}\left(\frac{1\text{ MeV}}{T_D}\right)^{1/3}\left(\frac{m_{\phi_B}}{1\text{ TeV}}\right)^{7/6}$

Also determines the baryon number and Standard Model charges

$$\phi_B(\mathbf{3}, 2/3), \;\; \hat{\phi}_B(\overline{\mathbf{3}}, -2/3).$$

$$B(\phi_B) = 1/3, B(\hat{\phi}_B) = 2/3 \text{ and } B(\Sigma) = -2.$$

Experimental Signatures?

The key feature of the models for experiments are the <u>annihilons</u>

Mass must be 100 GeV- 1 TeV to produce weak-strength annihilations

=> Can produce at colliders

Best Case: Coloured Annihilons

Can pair produce at LHC via gluon fusion up to ~ 1 TeV mass

Annihilons generally have a long lifetime and decay to net B number

$1 \text{ MeV} < T_D < T_d$ =>

$$1.5\, s \gtrsim \tau \gtrsim 8 \times 10^{-9} \left(\frac{10 \text{ GeV}}{T_d} \right)^2 s\ .$$

Coloured annihilons can be pair produced and form exotic heavy hadrons by combining with quarks

e.g. $d\,\hat{\phi}_B$, which has $B = 1$ and $Q = -1$.

Mass = 100 -1000 GeV, long-lived

$\Rightarrow$ Might be able to decay/stop in a detector and observe long lifetime and decay to baryons

Two different annihilons exist and are pair produced => different types of heavy hadrons

Update: Due to the B-violating interaction, the scalar annihilons mix

$$\lambda_B < H^\dagger H > \phi_B \hat{\phi}_B$$

=> Mass eigenstates have B-violating decays!

e.g. B = 1 and B = 0 final states in above example

Consistency Conditions

1. ‘Progenitor’ Σ asymmetry is not erased by B-violating interactions
2. Proton is sufficiently stable

1. The annihilons are in thermal equilibrium at high T => B-violating interactions could thermalize and erase Σ asymmetry

Doesn’t happen because of the weakness of the coupling of Σ to the annihilons which is necessary to have a low Σ decay temperature T_d [Encouraging!]

e.g. coherently oscillating Σ condensate

$$\mathcal{L}_{\Sigma\, decay} = \frac{1}{M_*}\Sigma\phi_B^2\hat{\phi}_B^2 \quad + h.c.$$

$$M_* \qquad = 5.5 \times 10^{13}\ \mathrm{GeV}\left(\frac{k_p}{kT_d}\right)^{1/2}\left(\frac{m_\Sigma}{1\ \mathrm{TeV}}\right)^{3/2}\left(\frac{1\ \mathrm{GeV}}{T_d}\right)$$

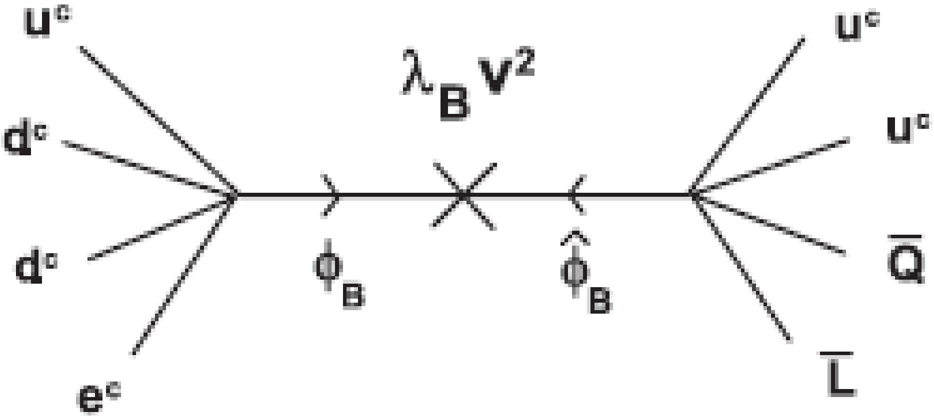
M_* from low T_d

$$\Gamma_{sc} \approx n_{\phi_B}(T)\sigma \approx \frac{k_1 T^3}{\pi^2 M_*^2}$$

=> $T_R \lesssim 5 \times 10^8\ \mathrm{GeV}\left(\frac{m_\Sigma}{1\ \mathrm{TeV}}\right)^3\left(\frac{1\ \mathrm{GeV}}{T_d}\right)^2$

=> No thermalization of Σ condensate

2. Proton decay could occur via annihilon exchange and the B-violating portal interaction



$$\Gamma_{proton} \approx k_{\Gamma} \left| \frac{\lambda_B v^2}{m_D^6 m_{\phi_B}^4} \right| M^{17}$$

$$\tau \approx 10^{75} yrs \times \frac{1}{k_{\Gamma} \lambda_B^2} \left(\frac{k_p}{k_{T_D}} \right)^2 \left(\frac{m_{\phi_B}}{1 \text{ TeV}} \right)^{22} \left(\frac{1 \text{ MeV}}{T_D} \right)^4$$

(Dimensional underestimate!)

No problem with proton decay

Conclusions

It is possible to modify a large initial baryon asymmetry to be similar to a thermal relic WIMP mass density => Baryomorphosis

⇒ Can understand both the puzzles of the baryon density:
i.e. that it is similar to the dark matter density and why it is similar to the “WIMP miracle” density. [Something like this might just be right!]

The baryomorphosis framework has generic features:

A ‘progenitor’ B asymmetry which decays at low temperature (< 100 GeV) to pairs of annihilons.

Annihilon pairs subsquently annihilate down to a thermal relic WIMP-like density

Finally annihilons decay, transferring the B asymmetry to quarks

Could test by producing annihilons at colliders and observing their long lifetime and decay to baryon number B-violating decays in the scalar model!

Should be able to build more realistic baryomorphosis models

SUSY; natural product of symmetries, ...