Brussels 20/4/12

Relating the Baryon Asymmetry to "WIMP Miracle" Dark Matter

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+ PRD 83 (2011) 083509 (arXiv:1009.3227)

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The Baryon-to-Dark Matter Density Ratio

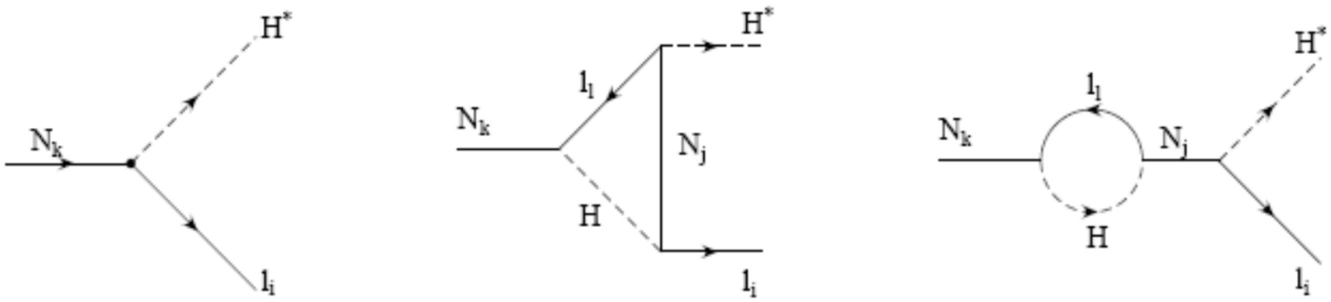
WMAP => $\Omega_B/\Omega_{DM} \approx 1/5$

In most models the physics of baryogenesis and of dark matter production are physically unrelated

Example of “conventional” baryogenesis: Leptogenesis

=> Out-of-equilibrium decay of RH neutrinos

Sakharov: Need, B, CP violation and thermal non-equilibrium



$$\epsilon_1 = \frac{\sum_\alpha \left[\Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})\right]}{\sum_\alpha \left[\Gamma(N_1 \to \ell_\alpha H) + \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})\right]} \simeq -\frac{3}{8\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_{i=2,3} \mathrm{Im}\left\{ (h_\nu h_\nu^\dagger)^2_{1i} \right\} \frac{M_1}{M_i}$$

$$Y_L \equiv \frac{n_L - \overline{n}_L}{s} = \kappa \frac{\epsilon_1}{g_*} \qquad g_* \simeq 106.75$$

Sphaleron
B+L violation
=> L → B

No relation to thermal WIMP dark matter density whatsoever!

$$\frac{n_{DM}}{s} \sim \frac{1}{m_{DM} M_{Pl} < \sigma v >} \quad , \quad < \sigma v > \sim \frac{g^4}{32\pi m_{DM}^2}$$

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

Either

Remarkable coincidence

or

Anthropic selection mechanism

or

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

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

=> New testable physics

Baryon-to-Dark Matter Ratio Models

Broadly two classes (up to now):

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

[Many models …] => Asymmetric DM in most models

No indirect detection signal via annihilation in galaxy

2. Indirect Mechanism:

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

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

eg Affleck-Dine leptogenesis/RH sneutrino DM (JMcD, JCAP 0701 (2007) 001, hep-ph/0609126)

But there are <u>TWO</u> 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?

It is quite possible to answer 1 without answering 2

(Most models do not address 2)

The 'WIMP Miracle'

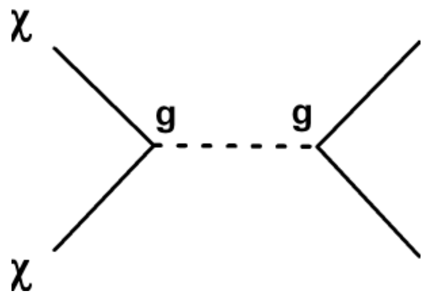
For the observed CDM density from thermal freeze-out, require :

Annihilation cross-section times relative velocity

$$<\sigma v_{rel}> \approx 10^{-9}\ \mathrm{GeV}^{-2}$$

DM annihilation amplitude^2

$$<\sigma v_{rel}>=\frac{|\mathcal{M}|^2}{32\pi m_{DM}^2}$$



$$|\mathcal{M}|^2 = g_{eff}^4$$

(Dimensionless)

$$<\sigma v_{rel}>=1.6\times 10^{-9}\left(\frac{g_{eff}}{0.2}\right)^4\left(\frac{100\ \mathrm{GeV}}{m_{DM}}\right)^2\ \mathrm{GeV}^{-2}$$

Therefore if m_{DM} ~ 100 GeV – 1 TeV and g_{eff} is not too much smaller than the weak interaction coupling (g ≈ 0.6), then we get the right amount of thermal relic dark matter

Widely viewed as most likely explanation for DM e.g. neutralinos

Why is it important to ask if a mechanistic explanation for a WIMP-Miracle-like baryon asymmetry is possible?

Because the answer is important <u>either</u> <u>way</u>

Possible answers [discounting coincidence] :

1. The WIMP miracle is the explanation for DM <u>and</u> it is possible to relate the baryon asymmetry to this via a particle physics mechanism
   => New TeV-scale physics

2. The WIMP miracle is the explanation for DM, but no plausible particle physics mechanism exists to relate this to the baryon asymmetry
   => Anthropic Selection determines Ω_B/Ω_{DM}

3. The WIMP-miracle is <u>not</u> the explanation for dark matter.
   The baryon and dark matter densities can be related directly
   [=> Asymmetric DM]   (or Anthropic Selection)

How might we relate the baryon asymmetry to a WIMP Miracle CDM Density?

Observed baryon density is determined by a process similar to thermal relic WIMP freeze-out

"BARYOMORPHOSIS" **JMcD, PRD 83 (2011) 083509 (1009.3227)**
PRD 84 (2011) 103514 (1108.4663)

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

Recently, a different approach proposed :

"WIMPy BARYOGENESIS" **Cui, Randall, Shuve 1112.2704**

≡ <u>Baryons and dark matter via weak-strength annihilation</u>

The Baryomorphosis mechanism/framework

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

Ingredients:

1. A baryon asymmetry in a heavy "progenitor" particle Σ, which decays at a low temperature < few x 100 GeV. (=> B-injection)

2. Pairs of new scalar particles, "Annihilons", to which Σ decays.

   Annihilons $\phi_B, \hat{\phi}_B$ have mass 100 GeV – few TeV. They have opposite gauge cnarge but not opposite baryon number.

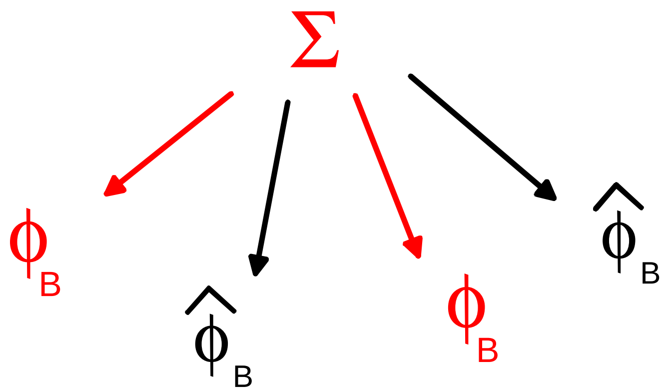
   They annihilate via a B-violating interaction which is of broadly weak interaction strength.

   [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_d < O(100) GeV

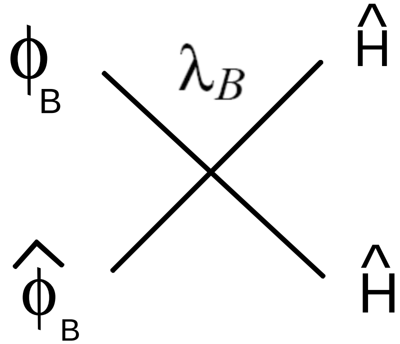


T_d < B-violating annihilation freeze-out temp, T_{ϕ_B}

$$T_{\phi_B} \approx m_{\phi_B}/25$$

2. Annihilons annihilate via B-violating interaction

B-violating annihilations via quartic scalar interaction



=> Quasi-thermal relic WIMP-like 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

Simple Model: Annihilation to complex bosons [JMcD 1108.4653]

$$\mathcal{L}_{\Sigma\, decay} = \frac{1}{M_*}\Sigma\phi_B^2\hat{\phi}_B^2 \quad + h.c.$$ (=> B-injection at low T_d)

$$M_* \sim 10^{11}(m_\Sigma/1\ \mathrm{TeV})^{3/2}(1\ \mathrm{GeV}/T_d)\ \mathrm{GeV}$$

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

Annihilation $\phi_B\hat{\phi}_B \to \hat{H}^\dagger\hat{H}$ => $\langle\sigma v\rangle = \frac{\lambda_B^2}{16\pi m_{\phi_B}^2}$

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

Annihilations ineffective

=>

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

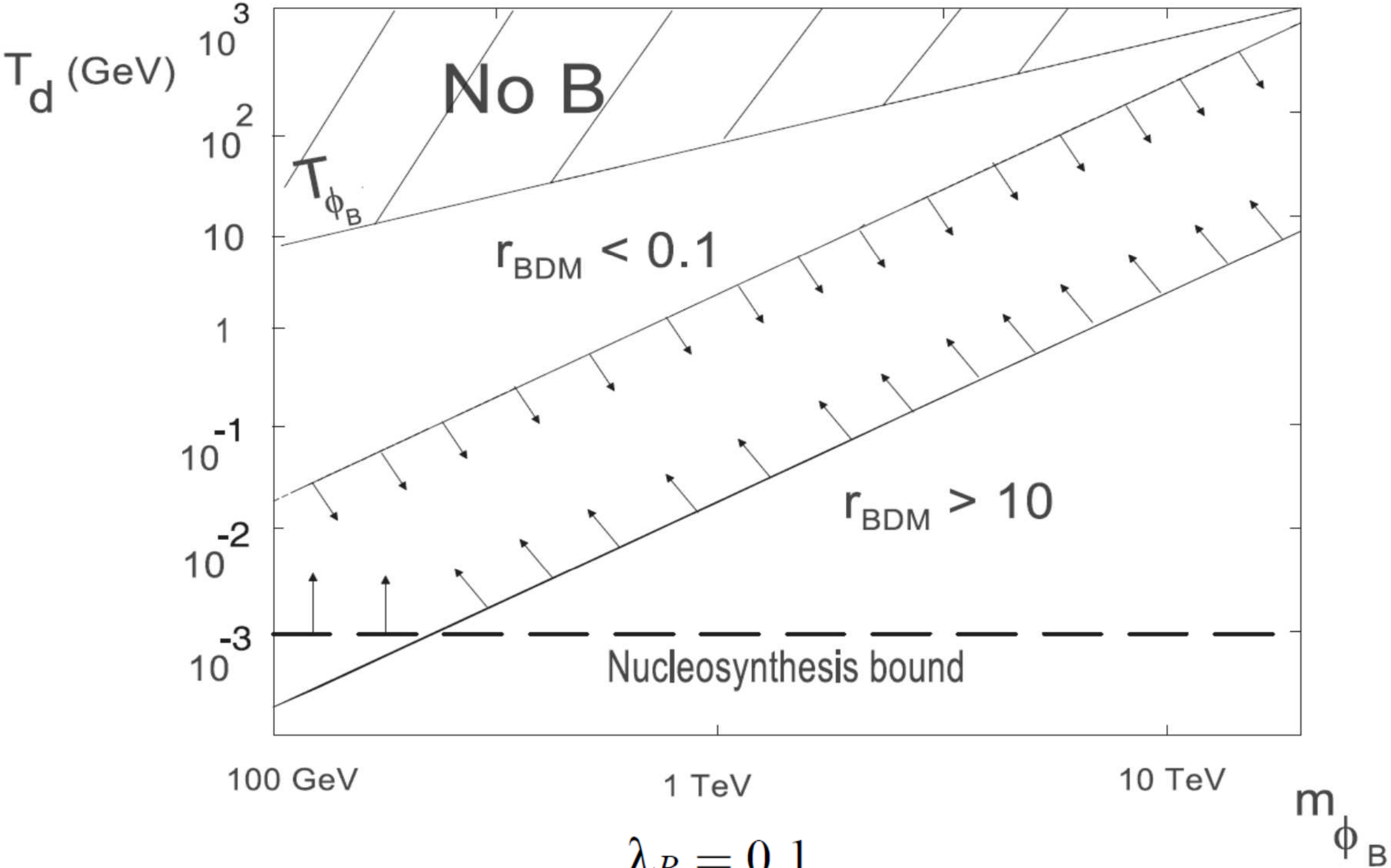
< 1 > 1

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

Typical thermal relic WIMP density

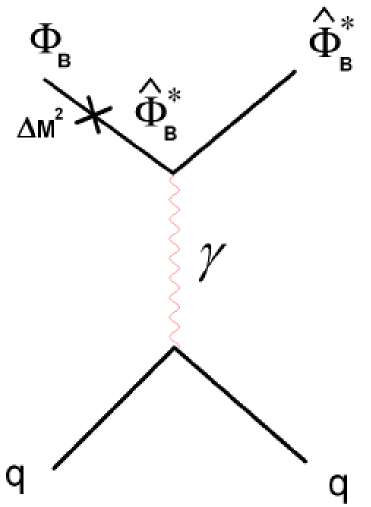
$r_{BDM} = \Omega_B/\Omega_{DM}$

B injection temp



$\lambda_B = 0.1$

Shortcomings of the simple model



1. No symmetry to prevent B-violating mass mixing terms

like $\phi_B \hat{\phi}_B$ and keep $\lambda_B \phi_B \hat{\phi}_B \hat{H}^\dagger \hat{H}$ => B-washout

=> $\Delta m \lesssim 0.1$ GeV

2. $\hat{H}$ cannot be the Higgs, since if <H> = v, $\lambda_B < H >^2 \phi_B \hat{\phi}_B$ => $\lambda_B \lesssim 3 \times 10^{-7}$

Therefore $\hat{H}$ must be a new scalar with no VEV.

3. No natural suppression of renormalizable couplings of ϕ_B to Standard Model fermions

=> ϕ_B decays too rapidly, before annihilating

4. No WIMP dark matter candidate specified
(The Standard Model needs a new particle)

∴ Need additional symmetries and particles (to prevent B-violating mixing) + a dark matter particle(s)

Improved Baryomorphosis Model

["Simultaneous generation of WIMP-like baryon and dark matter densities"]

(JMcD 1108.4653)

Combine baryomorphosis with scalar dark matter eg singlet or inert doublet

e.g. introduce a pair of real singlet scalars $\hat{s}$, s

plus a Z_2 discrete symmetry

$$Z_A : \;\; \phi_B \rightarrow \phi_B \; ; \;\; \hat{\phi}_B \rightarrow -\hat{\phi}_B \; ; \;\; s \rightarrow s \; ; \;\; \hat{s} \rightarrow -\hat{s}$$

This eliminates dangerous $\phi_B \hat{\phi}_B$ and $\phi_B \hat{\phi}_B H^{\dagger} H$ but allows

$$\mathcal{L}_{\phi_B \hat{\phi}_B \, ann} = \lambda_B \phi_B \hat{\phi}_B s \hat{s} \; + h.c.$$

=> Annihilation to a thermal WIMP-like baryon asymmetry

Also ϕ_B, $\hat{\phi}_B$ must carry gauge charge to prevent $\phi_B \phi_B$

Need a second discrete symmetry to stabilize dark matter

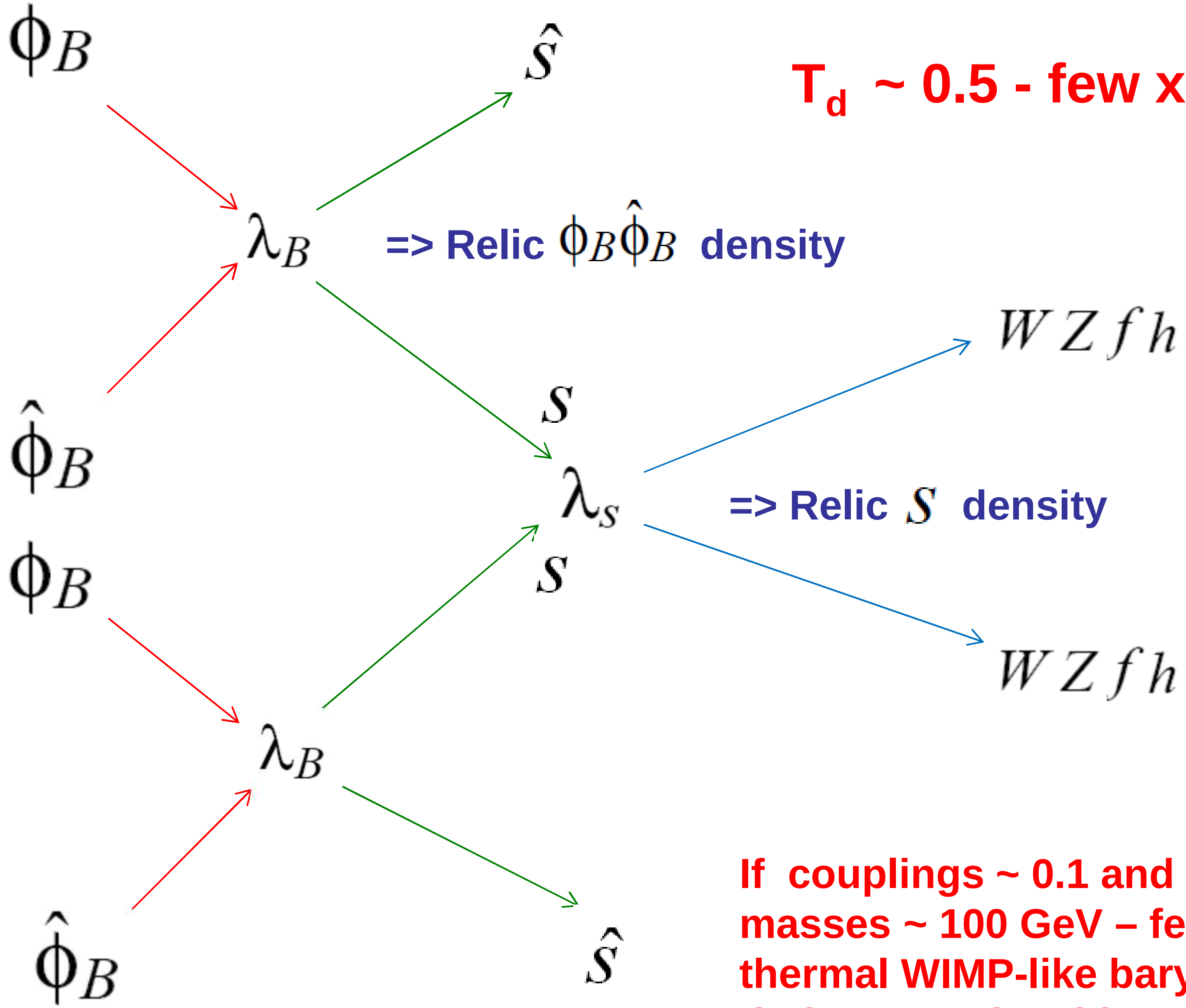
Z_S $$s \longrightarrow -s \; ; \quad \hat{s} \longrightarrow -\hat{s}$$

Z_A x Z_S allows coupling to the Standard Model Higgs

$$\frac{\lambda_s}{2} s s H^\dagger H + \frac{\lambda_{\hat{s}}}{2} \hat{s}\hat{s} H^\dagger H$$

=> Annihilation to thermal WIMP-like dark matter density

Schematic of annihilation process



T_d ~ 0.5 - few x 100 GeV

=> Relic $\phi_B \hat{\phi}_B$ density

=> Relic S density

If couplings ~ 0.1 and scalar masses ~ 100 GeV – few TeV, thermal WIMP-like baryon and dark matter densities remain

Annihilation to thermal WIMP-like baryon asymmetry

e.g. Coloured Annihilons: $\phi_B\ (\mathbf{3},\mathbf{1}) \quad \hat{\phi}_B\ (\overline{\mathbf{3}},\mathbf{1})$

$$< \sigma v >_{\phi_B} = \frac{\lambda_B^2}{32\pi m_{\phi_B}^2}\left(1 - \frac{m_s^2}{m_{\phi_B}^2}\right)^{1/2}$$

Broadly weak-interaction strength for λ_B ~ 0.1 and m_{ϕ_B} ~ 1 TeV

$$n_{\phi_B}(T_d) \approx \frac{H(T_d)}{< \sigma v >_{\phi_B}}$$

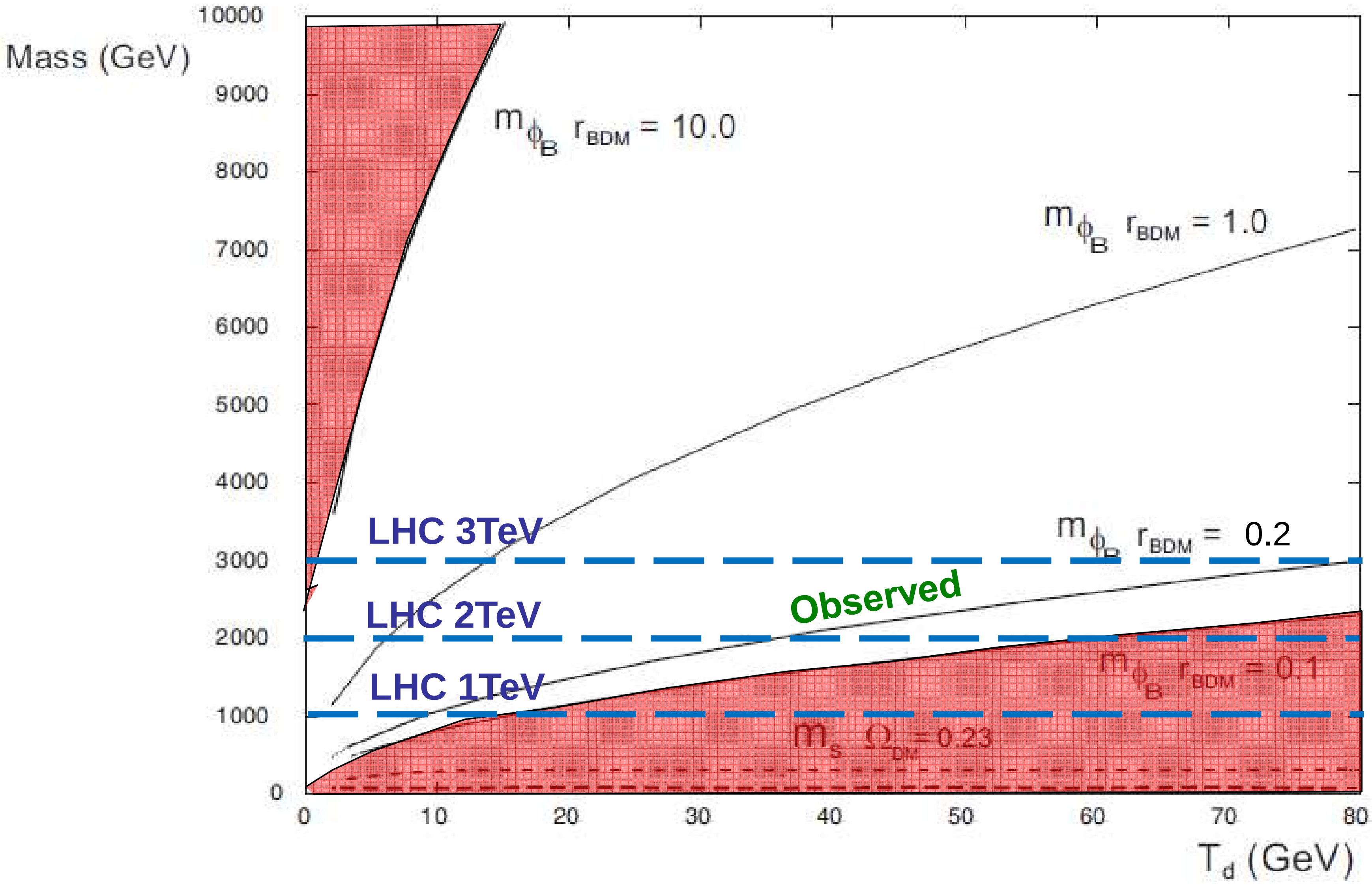
$$r_{BDM} \equiv \Omega_B / \Omega_{DM}$$

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

$\Omega_{DM} = 0.23$ **=>**

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

Annihilon mass vs. Injection Temp



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

$$\lambda_B = 0.1$$

Annihilation to thermal WIMP-like singlet scalar CDM density

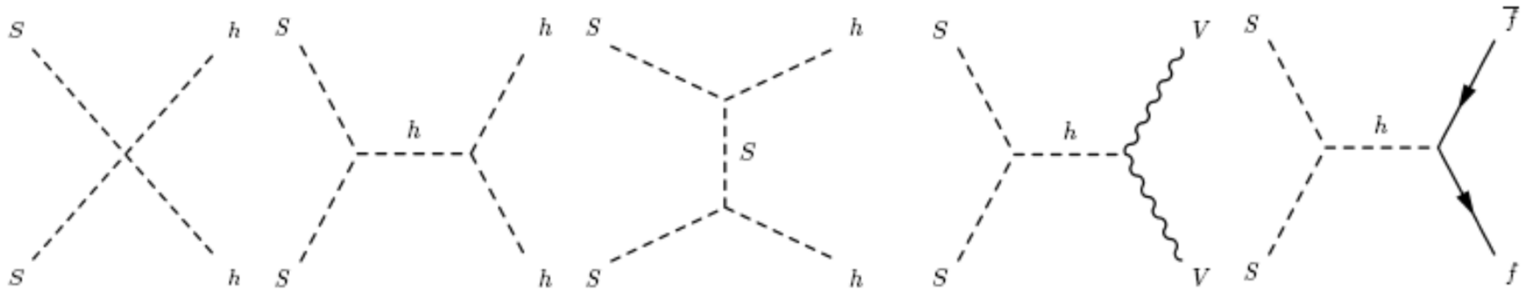
(Need to ensure that $m_{\phi_B} > m_s$ when $\Omega_{DM} = 0.23$)

Two cases:

[T_s = S annihilation freeze-out]

(i) $T_d < T_S$ **S density is non-thermal but thermal WIMP-like, with density enhanced by factor T_S / T_d** $(T_s \approx m_s/25)$

(ii) $T_d > T_S$ **S density is a thermal relic WIMP density**

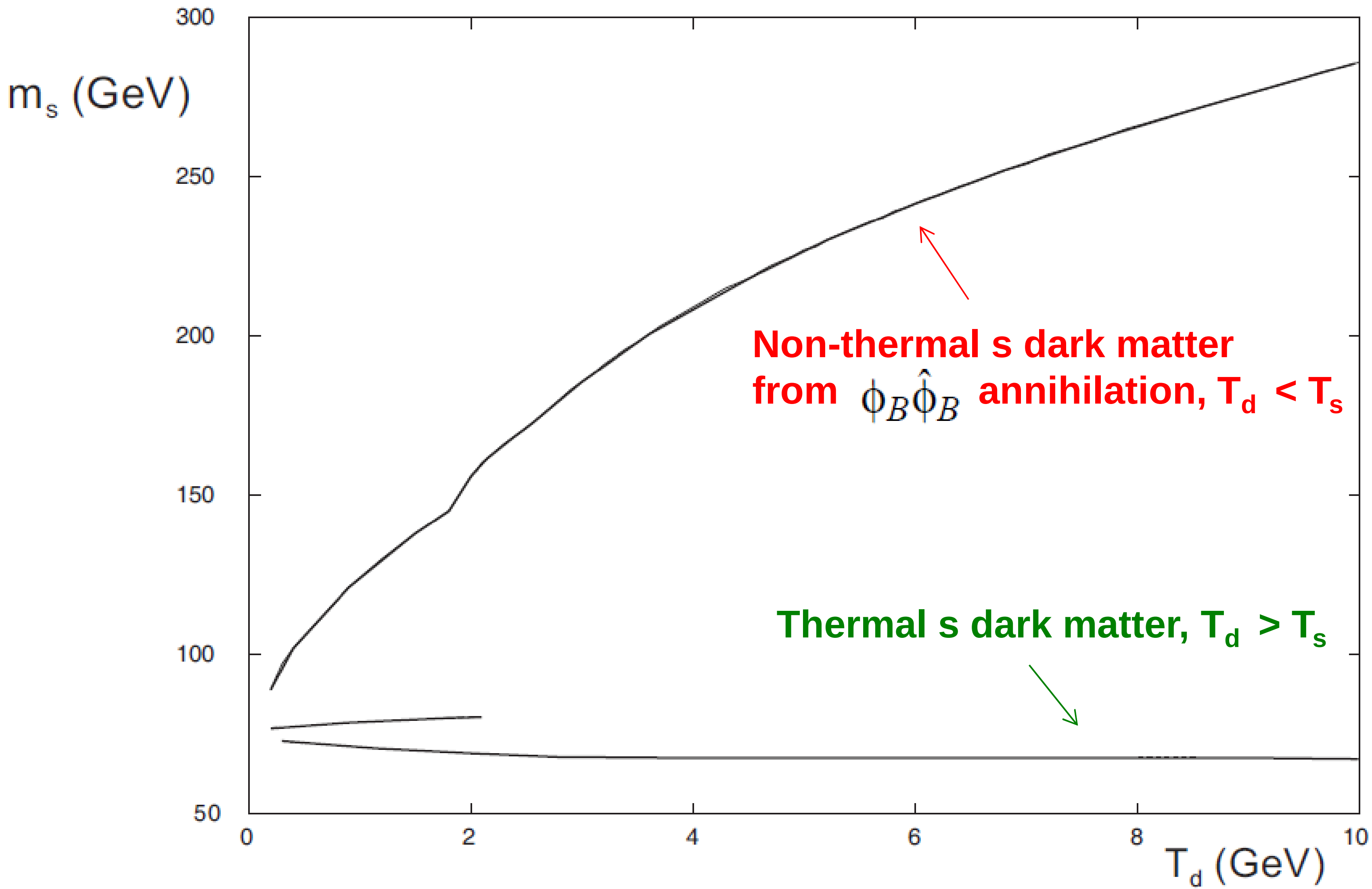


$$n_s(T_d) \approx \frac{H(T_d)}{< \sigma v >_s}$$

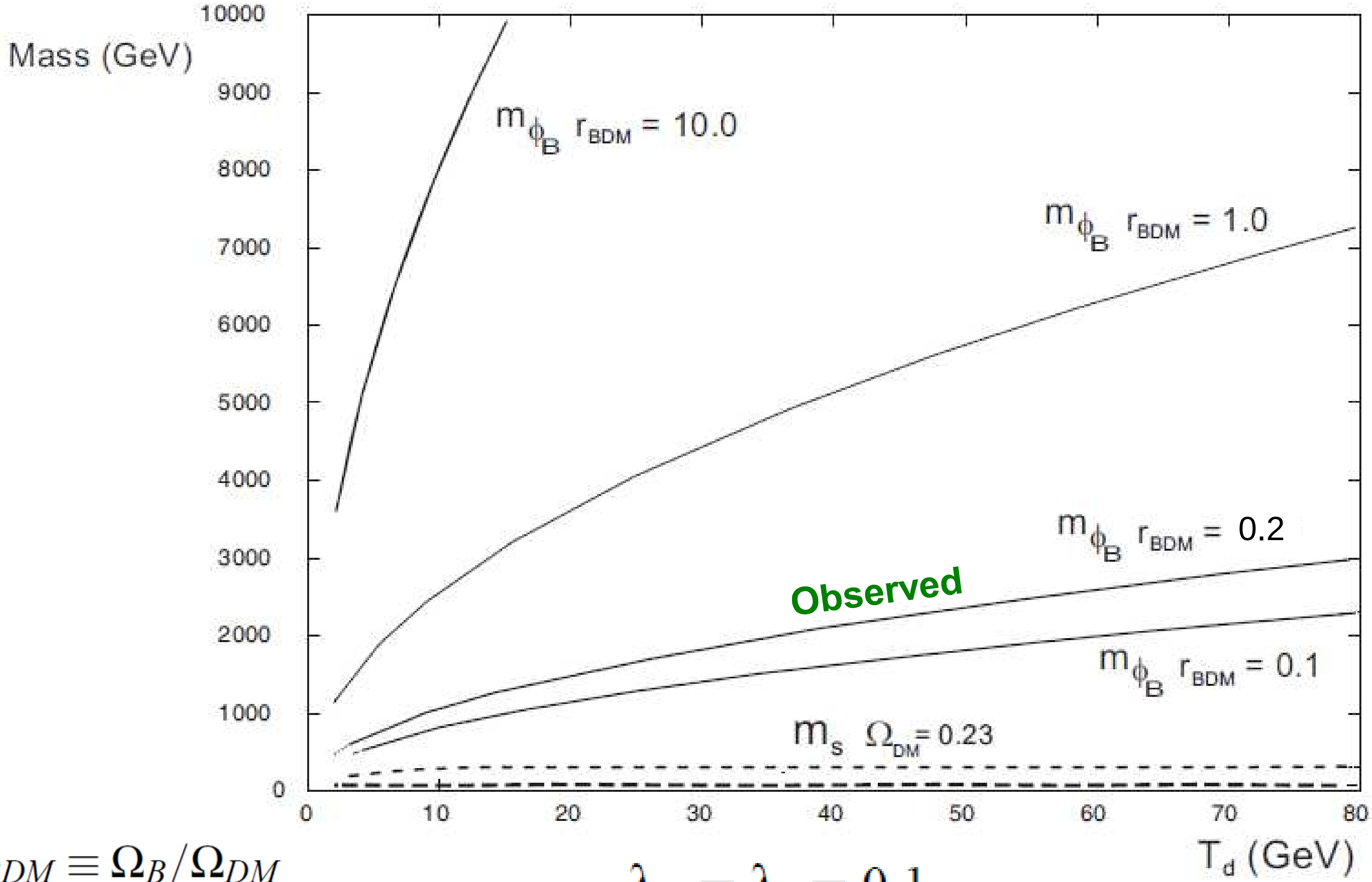
=>

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

($T_d > T_s$ => replace T_d by T_s)



$\Omega_{DM} = 0.23 \quad \lambda_s = 0.1 \quad m_h = 150$ GeV



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

$\lambda_B = \lambda_s = 0.1$

=> $m_s < m_{\phi_B}$ as required for consistency

Transfer of the B asymmetry to conventional baryons

After $\phi_B \hat{\phi}_B$ annihilation, a relic density of $\phi_B \hat{\phi}_B$ remains. This must decay to quarks at T_D after the $\phi_B \hat{\phi}_B$ annihilations freeze-out, $T_D < T_d$

=> Long-lived annihilons (=> Experimental Signature)

$$\text{BBN} \rightarrow \quad 1.5\,\mathrm{s} \gtrsim \tau \gtrsim 8 \times 10^{-11} \left(\frac{100\ \mathrm{GeV}}{T_d} \right)^2 s \quad \leftarrow T_D < T_d$$

Therefore require highly suppressed renormalizable couplings to SM fermions

$$\lambda \phi_B \overline{\psi} \psi \quad \Rightarrow \quad \lambda \lesssim 1.2 \times 10^{-10} \left(\frac{T_d}{1\ \mathrm{GeV}} \right) \left(\frac{1\ \mathrm{TeV}}{m_{\phi_B}} \right)^{1/2}$$

Unattractive !

Alternatively, can eliminate renorm. couplings to SM fermions if ϕ_B has a large hypercharge e.g. $Y(\phi_B) = 5/3$

e.g. $\phi_B\ (\mathbf{3},\mathbf{1},5/3) \qquad \hat{\phi}_B\ (\bar{\mathbf{3}},\mathbf{1},-5/3)$

ϕ_B , $\hat{\phi}_B$ decay via mass-suppressed non-renormalizable interactions eg

$$\frac{1}{M^3}\phi_B \overline{d^c_R} d_R \overline{L^c_L} L_L \quad \Rightarrow \quad B(\phi_B) = -2/3 \ , \ L(\phi_B) = 2$$

$$\frac{1}{M^3}\hat{\phi}_B \overline{d_R} e^c_R Q_L Q_L \quad \Rightarrow \quad B(\hat{\phi}_B) = -1/3 \ , \ L(\hat{\phi}_B) = -1$$

[slighly breaks Z_A]

$$M \sim 10^7 \left(\frac{1\ \mathrm{MeV}}{T_D}\right)^{1/3} \left(\frac{m_{\phi_B}}{1\ \mathrm{TeV}}\right)^{7/6} \mathrm{GeV} \quad \Rightarrow \quad M \sim 10^5 - 10^7\ \mathrm{GeV}$$

The <u>effective</u> baryon number of ϕ_B and $\hat{\phi}_B$ is determined by the leading decay operator.

But other decay modes can exist => B, L-violating ϕ_B , $\hat{\phi}_B$ decay modes eg

$$\frac{1}{M^3}\phi_B \left(\overline{e_R} Q_L \overline{e_R} L_L\right)^\dagger \quad \Rightarrow \quad B = 1/3 \ , \ L = 1 \quad \text{final state}$$

Experimental Signatures?

The key feature of the model for experiments are the annihilons ϕ_B $\hat{\phi}_B$

(ϕ_B and $\hat{\phi}_B$ could have different masses)

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

=> Can possibly produce at colliders

Annihilons have a long lifetime and decay to different B and L number

Possibly with B, L violating decays

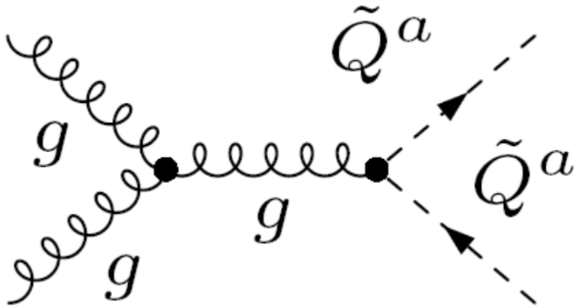
Long lifetime suggests large hypercharge $|Y| \geq 5/3$

Best Case: Coloured Annihilons

Can pair produce at LHC via gluon fusion up to ~ 2-3 TeV mass

Production of coloured annihilons at LHC similar to squarks

Gluon fusion



LHC reach squarks/gluinos:

Integrated luminosity

1 fb^{-1} => 1 TeV
10 fb^{-1} => 2 TeV
300 fb^{-1} => 2.5-3 TeV

After production, annihilons will form into long-lived R-hadron-like states.
(Squark/gluino R-hadrons are short-lived)

e.g. $d\,\hat{\phi}_B$ => B = 0, L = -1, Q = -2

$d^c\phi_B$ => B = -1, L = 2, Q = 2

(ϕ_B $\hat{\phi}_B$ can have different masses)

[Example of a MMCP = Massive Metastable Charged/coloured Particle]

Other examples of MMCPs: long-lived gluinos form Split SUSY, NLSPs in Gauge-mediated SUSY breaking, R-parity violating LSP decays

Searches already underway:

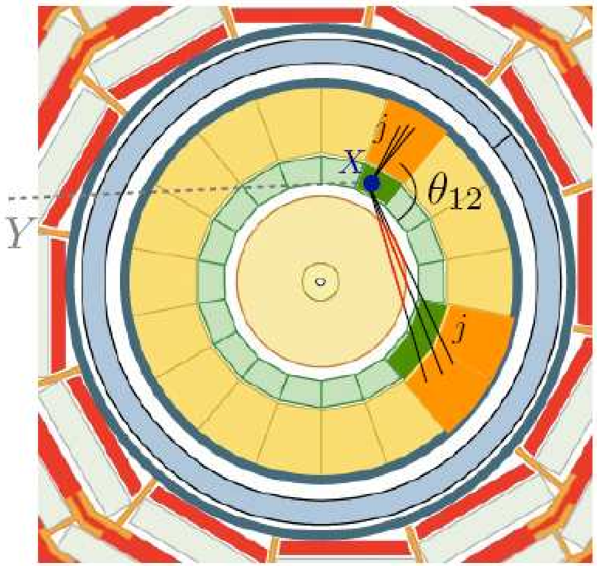
"Search for heavy long-lived charged particles"

CMS: 1101.1645 ATLAS: 1106.4495

Gluino R-hadrons > 530 GeV, ATLAS

Stopping in detectors:

If TeV-scale metastable particles are charged or coloured, a fraction will stop in detectors and produce out-of-time decays



"Stopping Gluinos" Arvanitaki et al hep-ph/0506242

"New Measurements with Stopped Particles at the LHC" Graham et al 1111.4176

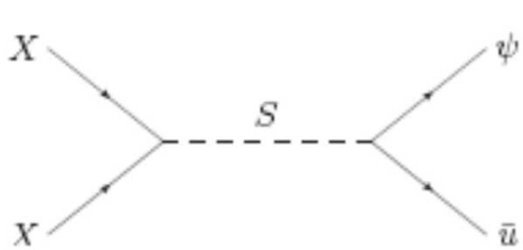
$\Rightarrow$ can determine mass, charge, spin and final state particles

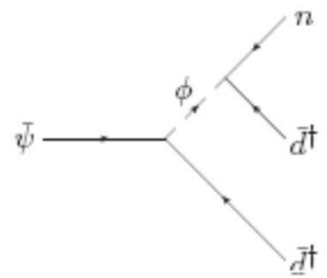
Other ways to relate the baryon density to the WIMP miracle?

WIMPy Baryogenesis

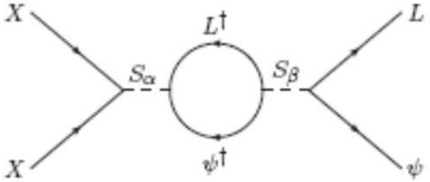
Cui, Randall, Shuve 1112.2704

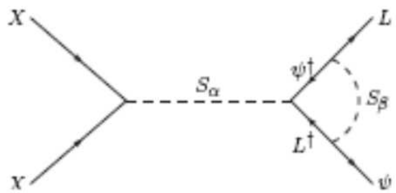
Baryon number is generated via thermal dark matter annihilation and freeze-out





=> ψ asymmetry





B-violating
ψ decay

$$\bar{\psi}\bar{d}\bar{d}n/\Lambda^2$$

The predictions of baryomorphosis and WIMPy baryogenesis are quite different

No long-lived particles in WIMPy baryogenesis

Conclusions

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

Requires additional particles and discrete symmetries
=> can naturally combine with a WIMP dark matter candidate
(eg gauge singlet scalars, inert doublets)

In addition, a particular sequence of events is also necessary:

B-injection at T_d < few x 100 GeV, after freeze-out of B-violating decays at T_{Φ_B}

Annihilon decay to quarks at $T_D < T_d$

1 MeV < T_D < O(100)GeV
=> long-lived annihilons

Generically requires pairs of new particles (annihilons) with masses ~ 100 GeV – few TeV => Could be produced at LHC!

- Two types of annihilon with opposite gauge charge but not opposite B
- Long lifetime, decay to different baryon number => MMCP; stop and decay
- Possibly large hypercharge and B-violating decays
- Distinct predictions from alternative model(s)

The WIMP miracle can account for DM without requiring coincidence or anthropic selection to explain $\Omega_B/\Omega_{DM} = 1/5$

End

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

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

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

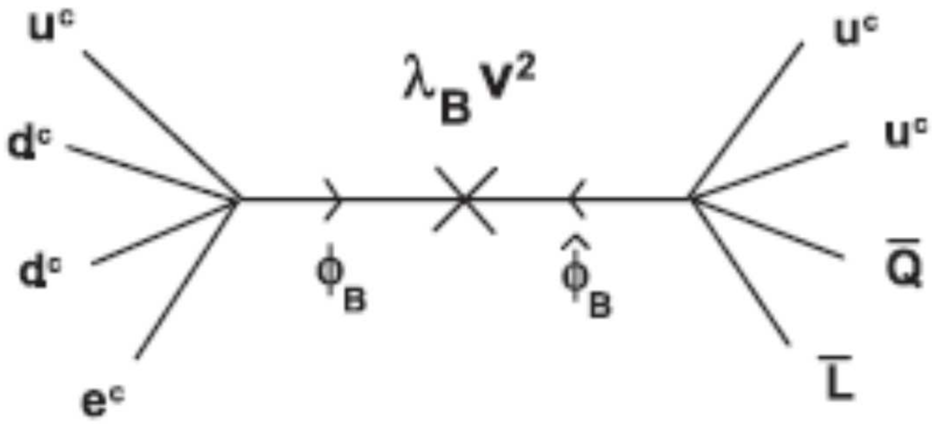
M_* from low T_d

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

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

=> 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