A WIMPy Leptogenesis Miracle
Baryogenesis via WIMP freeze-out

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Outline

- Motivation
- Overview of WIMPy baryogenesis
- Toy model of WIMPy leptogenesis
- Detection possibilities
Motivation

- There is a remarkable coincidence between the dark matter and baryon densities

\[ \Omega_{DM} \approx 5 \Omega_{\text{baryon}} \]

- Traditional models of WIMP dark matter do not address this coincidence
  - Dark matter is a thermal relic
  - Relic density set by annihilation cross section: WIMP miracle

\[ \frac{n_{DM}}{s} \propto \frac{1}{\sigma_{\text{ann}}} \]
Motivation

- Nearly all models explaining the DM-baryon ratio use asymmetric dark matter
- Compelling scenario with many possible mechanisms and models
  - Transfer of the $B$ asymmetry to dark matter
  - Transfer of a dark matter asymmetry to $B$
  - Co–generation of the asymmetries
- New work: transfer by mass mixing (see arXiv:1106.4834 and Yanou’s talk)
Motivation

- Nearly all models explaining the DM-baryon ratio use **asymmetric dark matter**
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(For more info, see SPIRES: “find t asymmetric dark matter” and references cited therein)
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However, asymmetric dark matter models give up the WIMP miracle.
WIMPy baryogenesis

We present a model of symmetric DM that preserves the WIMP miracle and gives a connection between the DM and baryon densities.

WIMPy baryogenesis:
- WIMP dark matter annihilates through baryon-violating couplings
- Physical $CP$ phases in annihilation operators
- Out-of-equilibrium condition satisfied by WIMP freeze-out

*WIMP freeze-out can generate a baryon asymmetry!*

Also, baryogenesis is around the weak scale $\Rightarrow$ new charged states and $CP$-phases

Asymmetry generation through annihilation first proposed by Gu and Sarkar, 2009
For another way of connecting the WIMP miracle and baryon density, see McDonald, 1009.3227 and 1108.4653
Overview of WIMPy baryogenesis

Baryon asymmetry comes from interference of tree-level and loop annihilation diagrams:

The baryon-violating coupling also leads to washout processes:
Overview of WIMPy baryogenesis: evolution

Consider dark matter particle $X$

Boltzmann equations:

In terms of $Y_i = n_i/s$ and $x = m_X/T$, the evolution is schematically:

$$\frac{dY_X}{dx} = -A \langle \sigma_{\text{ann}} v \rangle \left[ Y_X^2 - (Y_X^{\text{eq}})^2 \right] + \text{back reaction}$$

$$\frac{dY_{\Delta B}}{dx} = \epsilon A \langle \sigma_{\text{ann}} v \rangle \left[ Y_X^2 - (Y_X^{\text{eq}})^2 \right] - C \langle \sigma_{\text{washout}} v \rangle Y_{\Delta B} \prod_i Y_i^{\text{eq}}$$

- $\epsilon = $ fractional asymmetry produced per annihilation
- $A$ and $C$ are coefficient functions including factors of $s, H, \ldots$
- $Y_i$ are other baryon-number-carrying fields
Overview of WIMPy baryogenesis: asymmetry

In the limit where back-reaction on $X$ is small,

$$Y_{\Delta B}(x) \approx -\epsilon \int_0^x dx' \frac{dY_X(x')}{dx'} \exp \left[ - \int_{x'}^x dx'' C \langle \sigma_{\text{washout}} v \rangle \prod_i Y_{i}^{\text{eq}}(x'') \right]$$

Approximate $\exp(\cdots) \approx \theta(x - x_0)$, where $x_0$ is the time of washout freeze-out:

$$Y_{\Delta B}(x) \approx \epsilon [Y_X(x_0) - Y_X(x)] \theta(x - x_0)$$
Overview of WIMPy baryogenesis: asymmetry

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*Asymmetry proportional to change in $X$ density after washout processes freeze out*
Overview of WIMP$\gamma$ baryogenesis: asymmetry

\[ Y_{\Delta B}(x) \approx \epsilon \left[ Y_X(x_0) - Y_X(x) \right] \theta(x - x_0) \]

- Washout must freeze out before annihilations

\[ Y_{\Delta B} \sim 10^{-10} \text{ and } \epsilon < 1 \implies x_0 \lesssim 20 \]

Two possibilities for successful baryogenesis:
Overview of WIMPy baryogenesis: asymmetry

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1. \( \sigma_{\text{ann}} \gg \sigma_{\text{washout}} \)
Overview of WIMPy baryogenesis: asymmetry

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Two possibilities for successful baryogenesis:

1. \( \sigma_{\text{ann}} \gg \sigma_{\text{washout}} \)
2. Heavy baryon states so that washout rate is Boltzmann suppressed
Toy model: WIMPy leptogenesis

Toy model of annihilation to leptons:

- Vectorlike dark matter $X$, $\bar{X}$
- Heavy pseudoscalars $S_i$ (at least 2 needed for physical CP phase)
- Dark matter annihilates to Standard Model LH lepton doublet $L_j$
- Vectorlike exotic lepton doublet $\psi_j$, $\bar{\psi}_j$ (with lepton flavor charge)

$$\mathcal{L} \supset \mathcal{L}_{\text{mass}} - \frac{i}{2} (y_{Xi} X^2 + y'_{Xi} \bar{X}^2) S_i - i y_{Lij} S_i L_j \psi_j + \text{h.c.}$$

Lepton asymmetry converted to baryon asymmetry by sphalerons
Toy model: WIMPy leptogenesis

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Lepton asymmetry converted to baryon asymmetry by sphalerons

$$\sigma_{\text{ann}} \sim y_X^2 y_L^2 \quad \quad \sigma_{\text{washout}} \sim y_L^4$$
Toy model: WIMPy leptogenesis

\[ \mathcal{L} \supset \mathcal{L}_{\text{mass}} - \frac{i}{2} (y_{Xi} X^2 + y'_{Xi} \bar{X}^2) S_i - i y_{Lij} S_i L_j \psi_j + \text{h.c.} \]

- In this model, \( \psi \) carries generalized lepton number \(-1\)
- \( \psi \) decays to sterile sector with separately conserved global symmetry, asymmetry in sterile sector equal and opposite to SM lepton asymmetry
- ex. gauge singlet fermion \( n \)

\[ \mathcal{L} \supset y_n \psi H^\dagger n \]
Toy model: WIMPy leptogenesis

$Z_4$ symmetry:
- $X$ and $n$ stable
- Prevent $L - \bar{\psi}$ mixing

<table>
<thead>
<tr>
<th>Field</th>
<th>$Z_4$</th>
</tr>
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<tr>
<td>$X$</td>
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<tr>
<td>$\bar{X}$</td>
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<td>$S$</td>
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<td>$\psi$</td>
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<tr>
<td>$n$</td>
<td>$-1$</td>
</tr>
<tr>
<td>SM fields</td>
<td>$+1$</td>
</tr>
</tbody>
</table>
Toy model: asymmetry generation processes

Dark matter annihilations:

Decays and inverse decays:
Toy model: asymmetry generation processes

Dark matter annihilations:

Decays and inverse decays:

For weak scale masses and couplings, $\Gamma_S \gg H$ and asymmetry from decays is negligible
Toy model: washout processes

Washout processes:
Toy model: \( CP \)-violation

\( CP \)-violating factor:

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

There are many parameters! We make the assumptions

- Only one flavour of \( L \) relevant for WIMPy leptogenesis
- Annihilation through the lightest scalar \( S_1 \) is dominant

Treat \( y_L = y_{L1} \) and \( \epsilon \) as free parameters subject to the above conditions and perturbativity
Toy model: \( CP \)-violation

\( CP \)-violating factor:

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\[
\epsilon = \frac{1}{8\pi} \frac{\text{Im}(y_{L1}^2 y_{L2} ^*^2)}{|y_{L1}|^2} f \left( \frac{m_{S1}}{m_{S2}} \right)
\]

(\( f \) is a loop function)
Toy model: $CP$-violation

- Solve Boltzmann equations numerically:

$$\frac{dY_X}{dx} = -A \langle \sigma_{\text{ann}} \nu \rangle \left[ Y_X^2 - (Y_X^{eq})^2 \right] + B \langle \sigma_{\text{ann}} \nu \rangle Y_{\Delta L} (Y_X^{eq})^2$$

$$\frac{dY_{\Delta L}}{dx} = \epsilon A \langle \sigma_{\text{ann}} \nu \rangle \left[ Y_X^2 - (Y_X^{eq})^2 \right] - C \langle \sigma_{\text{washout}} \nu \rangle Y_{\Delta L} Y_L^{eq} Y_{\psi}^{eq}$$
Toy model: \( CP \)-violation

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\]

- Also include effects of other equilibrium interactions (sphalerons and Yukawas) by including a pre-factor in the \( Y_{\Delta L} \) equation
  - Some of the \( L \) asymmetry is converted to asymmetry in \( \bar{E}, \bar{Q}, \bar{d}, \bar{u} \)
  - Chemical potential relations come from sphalerons, Yukawas, conservation of gauge charges, conservation of \( U(1)_{B-L+n-\psi} \)
Toy model: Parameter scan

- 6 parameters: $m_X$, $m_\psi$, $m_S$, $y_X$, $y_L$, and $\epsilon$
- Show masses for which WIMPy leptogenesis gives correct relic density and asymmetry for which at least one set of perturbative couplings $y_L$, $y_X$, and $\epsilon$

- $X$ and $\psi$ mass typically constrained to lie within factor of a few
- Enhancement of $\sigma_{\text{ann}}$ around $m_X = m_S/2$ gives more parameter space there

- $m_S = 5$ TeV
- Asymmetry should be generated before sphalerons decouple $\Rightarrow m_X \gtrsim$ TeV
Toy model: Parameter scan

- How tuned do couplings have to be?
- Choose point in middle of parameter space
  - \( m_X = 3 \text{ TeV}, m_\psi = 4 \text{ TeV}, m_S = 5 \text{ TeV}, \epsilon = 0.1 \)

![Graph showing relic abundance and baryon asymmetry](image)

- Solid lines: \( X \) relic abundance
- Dotted lines: baryon asymmetry
  (from top, \( Y_{\Delta B} = 10^{-11}, 3 \times 10^{-11}, 8.85 \times 10^{-11}, 10^{-10} \))
- Observed values shown in red
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- Tuning of \( \sim 5\% \) to get observed values
- Tuning more severe for lighter \( m_\psi \), less severe for heavier \( m_\psi \)
- Less tuning for lighter \( m_X \) because \( Y_X \) is larger and washout is smaller due to large \( S \) width
Variations: annihilations to quarks

Dark matter can annihilate directly to quarks

- $\psi$ is now a colour triplet

$$W \supset y_{\bar{u}} S \psi \bar{u} + y_{\bar{\psi}} \bar{\psi} \bar{d} \bar{d}$$

- Asymmetry can be generated **after** sphalerons become inactive
- Collider constraint $m_\psi \gtrsim 500$ GeV
- $X$ can be as light as 250 GeV

Parameter space similar to that of toy model
Detection: electric dipole moments

Contributions to electric dipole moments ($e^-$ and neutron) are at two loops

\[ \frac{d}{e} \sim \sum_i \frac{\text{Im}(y_{L1i}^* y_{L21} y_{L1i} y_{L2i}^*)}{(16\pi^2)^2} \frac{m_e}{m_S^2} \]

- Constraints depend predominantly on coupling to first-generation quarks/leptons
- ex. need $y_{L1i} \lesssim 10^{-2} - 1$ for $m_S = 5$ TeV from neutron/electron EDM
- For couplings near the current constraints, could see in next generation experiments
Detection: colliders

New charged particles with TeV-scale mass
- Accessible at LHC?

Leptogenesis case

- Higgsino-like topology
- Signature is $2b\bar{b} + E_T$

- No explicit bound on direct Higgsino production
- In principle bounded by gluino searches
  - Better to add $b$-tags, $H$ mass reconstruction, etc.
- Also look for decay of charged $\psi$ through longitudinal $W$
  - 3-body decay to $b\bar{b}W$ and/or 2-body decay to $b\bar{c}$
Detection: colliders

Direct baryogenesis case

Gluino-like topology with different group theory factors

$4j + E_T$ final state

Current LHC bound excludes $m_\psi \lesssim 500 \text{ GeV}$

LHC should (hopefully) eventually test $m_\psi$ up to $\sim 3 \text{ TeV}$
Conclusions

- WIMPy baryogenesis: WIMP annihilations can generate a baryon asymmetry
- Generate baryon asymmetry at weak scale (directly or via leptogenesis)
- Predicts new TeV-scale gauge-charged particles
- Toy model representative of models of WIMPy baryogenesis
- Possible signals in EDM experiments and at the LHC
Back-up slides
\[
\begin{align*}
\frac{H(m_X)}{x} \frac{dY_X}{dx} &= -4s \langle \sigma_{XX} \rightarrow L_i \psi_i \nu \rangle [Y_X^2 - (Y_{X}^{eq})^2] - 2s \epsilon \frac{\xi Y_{\Delta Li}}{Y_{\gamma}} \langle \sigma_{XX} \rightarrow L_i \psi_i \nu \rangle (Y_{X}^{eq})^2 \\
&\quad - Br_{X}^2 \langle \Gamma_{S} \rangle Y_{S}^{eq} \left( \frac{Y_{X}}{Y_{X}^{eq}} \right)^2 + Br_{X} \langle \Gamma_{S} \rangle (Y_{S} - Br_{L} Y_{S}^{eq}) - \epsilon \frac{\xi Y_{\Delta Li}}{2Y_{\gamma}} Br_{X} Br_{L} \langle \Gamma_{S} \rangle Y_{S}^{eq}; \\
\frac{H(m_X)}{x} \frac{dY_{S}}{dx} &= -\langle \Gamma_{S} \rangle Y_{S} + \langle \Gamma_{S} \rangle Y_{S}^{eq} \left[ Br_{L} + Br_{X} \left( \frac{Y_{X}}{Y_{X}^{eq}} \right)^2 \right]; \\
\frac{H(m_X)}{x} \frac{dY_{\Delta Li}}{dx} &= \frac{\epsilon}{2} Br_{L} \langle \Gamma_{S} \rangle \left[ Y_{S} + Y_{S}^{eq} \left( 1 - 2Br_{L} - Br_{X} \left[ 1 + \frac{Y_{X}^2}{(Y_{X}^{eq})^2} \right] \right) \right] + 2s \epsilon \langle \sigma_{XX} \leftrightarrow L_i \psi_i \nu \rangle \left[ Y_{X}^2 - (Y_{X}^{eq})^2 \right] \\
&\quad - \frac{\xi Y_{\Delta Li}}{Y_{\gamma}} \left[ s \langle \sigma_{XX} \leftrightarrow L_i \psi_i \nu \rangle (Y_{X}^{eq})^2 + 2s \langle \sigma_{L_i \psi_i \leftrightarrow L_j^{\dagger} \psi_i^{\dagger} \nu} \rangle + \langle \sigma_{(j \neq i)} \rangle_{L_i \psi_i \leftrightarrow L_j^{\dagger} \psi_j^{\dagger} \nu} \rangle Y_{S}^{eq} \right] Y_{X}^{eq} \\
&\quad - \frac{2\xi Y_{\Delta Li}}{Y_{\gamma}} s \langle \sigma_{L_i \psi_i \leftrightarrow L_j^{\dagger} \psi_i^{\dagger} \nu} \rangle Y_{L}^{eq} Y_{\psi}^{eq} \\
&\quad - \frac{\xi Y_{\Delta Li}}{Y_{\gamma}} \left[ s \langle \sigma_{X \psi_i \leftrightarrow XL_i^{\dagger} \psi_i \nu} \rangle Y_{X}^{eq} + 2s \langle \sigma_{\psi_i \psi_i \leftrightarrow L_i^{\dagger} L_i^{\dagger} \psi_i^{\dagger} \nu} \rangle (Y_{\psi}^{eq})^2 + 2s \langle \sigma_{(j \neq i)} \rangle_{\psi_i \psi_j \leftrightarrow L_i^{\dagger} L_j^{\dagger} \nu} \rangle (Y_{\psi}^{eq})^2 \right] \\
&\quad + \frac{\epsilon^2 \xi Y_{\Delta Li}}{4Y_{\gamma}} Br_{L}^2 \langle \Gamma_{S} \rangle Y_{S}^{eq}.
\end{align*}
\]
The ψ mass: $\mu_\psi = -\mu_\bar{\psi}$.

The SU(2) sphalerons: $3\mu_Q + \mu_L = 0$.

The up quark Yukawa: $\mu_Q + \mu_H - \mu_u = 0$.

The down quark Yukawa: $\mu_Q - \mu_H - \mu_d = 0$.

The lepton Yukawa: $\mu_L - \mu_H - \mu_E = 0$.

The ψ Yukawa: $\mu_\psi - \mu_H + \mu_\chi = 0$.

Hypercharge conservation:

$\mu_Q + 2\mu_u - \mu_d - \mu_L - \mu_E + (\mu_\psi - \mu_\bar{\psi}) \times (n_{\psi}^{eq}/n_{\gamma}^{eq}) + 2\mu_H/3 = 0$.

Conservation of generalized $B + \psi - L - \chi$ symmetry:

$2\mu_Q + \mu_u + \mu_d - 2\mu_L - \mu_E - \mu_\chi + 2(\mu_\psi - \mu_\bar{\psi}) \times (n_{\psi}^{eq}/n_{\gamma}^{eq}) = 0$. 

Back-up slides: chemical potential solutions

\[ \mu_Q = -\frac{1}{3} \mu_L, \]
\[ \mu_u = \frac{5 - 19r}{21 + 84r} \mu_L, \]
\[ \mu_d = -\frac{19 + 37r}{21 + 84r} \mu_L, \]
\[ \mu_E = \frac{3 + 25r}{7 + 28r} \mu_L, \]
\[ \mu_H = \frac{4 + 3r}{7 + 28r} \mu_L, \]
\[ \mu_\chi = -\frac{79 - 9r}{21 + 84r} \mu_L \]
\[ \mu_\psi = \frac{13}{3 + 12r} \mu_L, \]
Variations: new annihilation channels

What happens if we move beyond the minimal model?

- May generically expect additional annihilation channels

\[
\begin{align*}
X^\dagger & \rightarrow Z' \\
Z' & \rightarrow L^\dagger \\
L & \rightarrow X \\
X & \rightarrow L^\dagger
\end{align*}
\]

- DM relic density constraints mean that lepton violating coupling is smaller \(\Rightarrow\) less washout
- If \(\sigma_{\text{ann}} \rightarrow \alpha \sigma_{\text{ann}}\), then \(Y_{\Delta L} \rightarrow Y_{\Delta L}/\alpha\)

Does smaller \(y_L\) compensate for smaller \(Y_{\Delta L}\)?
Variations: new annihilation channels

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\[ X^\dagger \rightarrow L \]

- DM relic density constraints mean that lepton violating coupling is smaller $\Rightarrow$ less washout
- If $\sigma_{\text{ann}} \rightarrow \alpha \sigma_{\text{ann}}$, then $Y_{\Delta L} \rightarrow Y_{\Delta L}/\alpha$

Does smaller $y_L$ compensate for smaller $Y_{\Delta L}$?

- Yes, if $m_\psi \ll m_X$
Variations: new annihilation channels

\( m_S = 5 \text{ TeV} \)

\[ \alpha = 1 \]

\[ \alpha = 10 \]

More parameter space open at low \( m_X, m_\psi \) 
More restricted at high \( m_X, m_\psi \)
Variations: new annihilation channels

\( m_S = 5 \text{ TeV} \)

- More parameter space open at low \( m_X, m_\psi \)
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