WIMPy Leptogenesis

With Absorptive Final State Interactions

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[arXiv:1309.1145]

Outline

We need *CP* violation

$$\mathcal{M}_{XX\to Y} = \mathcal{M}^{CP}_{XX\to Y} + \mathcal{M}^{CPV}_{XX\to Y}$$
$$\mathcal{M}_{XX\to \bar{Y}} = \pm\left(\mathcal{M}^{CP}_{XX\to Y} - \mathcal{M}^{CPV}_{XX\to Y}\right)$$

In order to generate a final state asymmetry, it is necessary that:

- There exist both *CP*-invariant and *CP*-violating contributions to the matrix element (inteference between tree and loop diagrams)
- The relative phase between the *CP*-invariant and *CP*-violating amplitudes differs from $\pm\pi/2$ (intermediate loop particles go on-shell)

$$\sigma_{XX\to Y} - \sigma_{XX\to \bar{Y}} \propto Re\left[\mathcal{M}^{CP}_{XX\to Y}(\mathcal{M}^{CPV}_{XX\to \bar{Y}})^*\right]$$

Sakharov Conditions

Given DM annihilations that violate *B* (or *L* before EWPT), *C* and *CP*, the WIMP framework provides a departure from thermal equilibrium

A UV Complete WIMPy Model

	X	$\bar{X}$	ψ	$\bar{\psi}$	S	n	SM
$\mathbb{Z}_4$	$+\imath$	$-\imath$	-1	-1	-1	-1	$+1$

Table: Field content for a typical WIMPy model described in [arXiv:1112.2704].

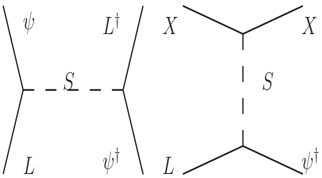


Figure: Washout diagrams.

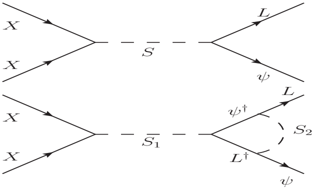


Figure: DM annihilation diagrams.

Notes

- Traditional *CP*-violating phase
- Dangerous washouts
- Mediator mass close to DM
- Large DM annihilation channel

WIMPy Phenomenology

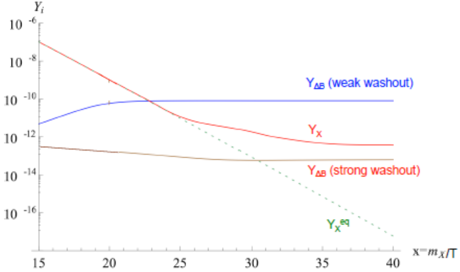


Figure: Solutions to Boltzmann equations yieldied by processes on previous slide given $\mathcal{O}(1)$ couplings. The mass parameters are $m_X = 3\,\mathrm{TeV}$ and $m_S = 5\,\mathrm{TeV}$. "Weak washout" corresponds to $m_\psi = 4\,\mathrm{TeV}$ and the "strong washout" has $m_\psi = 2\,\mathrm{TeV}$.

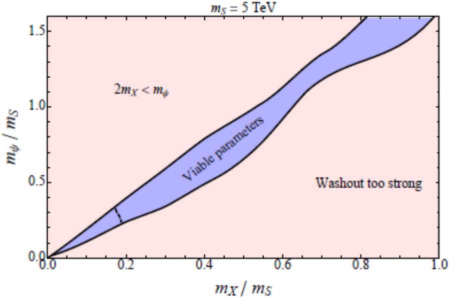
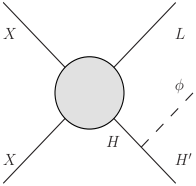


Figure: Parameter space of the model described in [arXiv:1112.2704] that yields the correct WIMP relic density as well as the observed baryon asymmetry with $\mathcal{O}(1)$ couplings. Below the dashed line, an asymmetry can't be shared between B and L due to the EWPT.

Field Content and EFT Operators

Fields	$SU(2)_L$	$Q_{U(1)_Y}$	$Q_{U(1)_L}$	$\mathbb{Z}_2$
X	1	0	0	-
$P_L L = l_L$	$\square$	-1/2	+1	+
H	1	0	0	+
$P_L L = \nu_L$	$\square$	-1/2	+1	+
H	1	0	0	+



$$\mathcal{O}_1 = \frac{\lambda_1}{2M_*^2}(\imath\bar{X}\gamma^5 X)(\bar{H}P_L L) + \frac{\lambda_1^*}{2M_*^2}(\imath\bar{X}\gamma^5 X)(\bar{L}P_R H)$$

$$\mathcal{O}_2 = \frac{\lambda_2}{2M_*^2}(\bar{X}\gamma_\mu\gamma^5 X)(\bar{H}\gamma^\mu P_L L) + \frac{\lambda_2^*}{2M_*^2}(\bar{X}\gamma_\mu\gamma^5 X)(\bar{L}\gamma^\mu P_L H)$$

$$\mathcal{O}_H = |g|(\phi^*\bar{H}' P_L H + \phi\bar{H}P_R H')$$

$$S(\not{p}) = \frac{\not{p}_H + (m_H - \imath\Gamma_H/2)}{p_H^2 - m_H^2 - \imath m_H\Gamma_H}$$

Asymmetry Calculation with an Absorbative Phase

In order to generate a final state asymmetry, it is necessary that:

- There exist both *CP*-invariant and *CP*-violating contributions to the matrix element (our asymmetry must be proportional to $Re(\lambda_1 \lambda_2^*)$)
- The relative phase between the *CP*-invariant and *CP*-violating amplitudes differs from $\pm\pi/2$ (asymmetry proportional to Γ_H)

$$(\sigma^{XX \to \phi^* \bar{H}' L} - \sigma^{XX \to \phi \bar{L} H'}) v \quad = \quad \Gamma_H \frac{Re(\lambda_1 \lambda_2^*) m_X}{4\pi M_*^4} \left[1 - \frac{m_H^2}{s} \right]^2$$

Result

CP asymmetry generated by the intereference between two **tree-level diagrams** with a relative phase from a **fully corrected propagator**

Lepton Injection

Definitions and Assumptions

- Write Boltzmann equations in terms of $x = m_X/T$ and $Y = n/s$
- H' and ϕ are in equilibrium. Track ΔL, but let $Y_L + Y_{\bar{L}} \simeq 2Y_{L_{eq}}$
- Get $3 \to 2$ rates by detailed balance and ignore off-shell processes

$$\frac{x^2 H(m_X)}{s(m_X)} \frac{dY_X}{dx} = -\langle \sigma_A v \rangle (Y_X^2 - Y_{X_{eq}}^2)$$

$$\begin{aligned} \frac{x^2 H(m_X)}{s(m_X)} \frac{dY_{\Delta L}^{inj}}{dx} = & \frac{1}{2}\left[\langle \sigma_{XX\to\phi^*\bar{H}'L} v \rangle\right] (Y_X^2 - Y_{X_{eq}}^2 Y_L / Y_{L_{eq}}) \\ & -\frac{1}{2}\left[\langle \sigma_{XX\to\phi\bar{L}H'} v \rangle\right] (Y_X^2 - Y_{X_{eq}}^2 Y_{\bar{L}} / Y_{\bar{L}_{eq}}) \\ & -\langle \sigma_{XL\to\phi X H'} v \rangle Y_X (Y_L - Y_{L_{eq}}) \\ & +\langle \sigma_{X\bar{L}\to\phi^* X\bar{H}'} v \rangle Y_X (Y_{\bar{L}} - Y_{\bar{L}_{eq}}) \end{aligned}$$

Sphaleron Effects

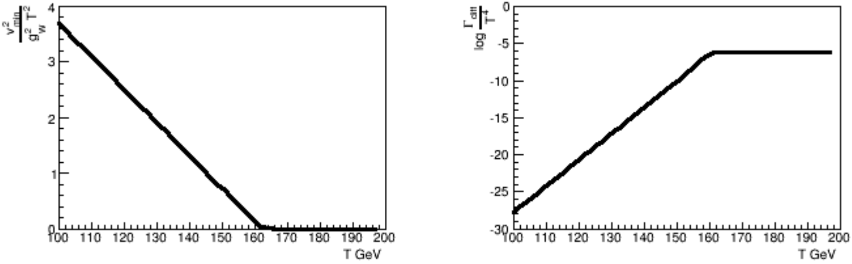


Figure: Extrapolated lattice calculation of the Higgs vev (left) and the Chern-Simons diffusion rate (right) through the EWPT [arXiv:1212.3206].

$$
\begin{aligned}
xH(T)\frac{dY_{\Delta B}}{dx} &= -\gamma(T)\left[Y_{\Delta B} + 3\eta(T)Y_{\Delta L}\right] \\
xH(T)\frac{dY_{\Delta L}}{dx} &= -\frac{1}{3}\gamma(T)\left[Y_{\Delta B} + \eta(T)Y_{\Delta L}\right] + xH(T)\frac{dY_{\Delta L}^{inj}}{dx}
\end{aligned}
$$

Boltzmann Equation Solutions

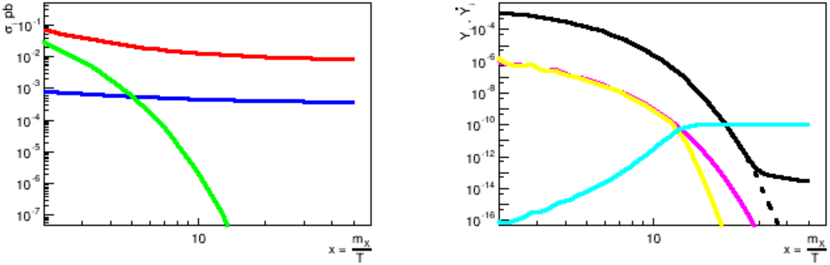


Figure: Thermally-averaged cross sections (left) for lepton injection equation rewritten below in terms of CP-odd terms generating the asymmetry and CP-even terms which wash it out. Corresponding rate contributions as well as Y_B (cyan), Y_X (black) and $Y_{X_{eq}}$ (black dashed). Note this is our "high-mass" benchmark.

$$\frac{dY^{inj}_{\Delta L}}{dx} \sim \langle \sigma^{CPV}_{XX} v \rangle (Y_X^2 - Y_{X_{eq}}^2) - \langle \sigma^{CP}_{XX} v \rangle Y^2_{X_{eq}} Y_{\Delta L}/Y_{L_{eq}} - \langle \sigma^{CP}_{XL} v \rangle Y_X Y_{\Delta L}$$

Interesting Cases

benchmark	m_X	m_H	Γ_H/m_H	$\lambda_1 = \lambda_2$	ϵ	δ
low-mass	1.5 TeV	2.2 TeV	0.10	1.0	0.045	0.002
high-mass	5.0 TeV	7.0 TeV	0.10	0.5	0.045	0.008
narrower-width	5.0 TeV	7.0 TeV	0.05	1.0	0.022	0.033

$$\epsilon \equiv \frac{\sigma^{XX\to\phi^*\bar{H}'L} - \sigma^{XX\to\phi\bar{L}H'}}{\sigma^{XX\to\phi^*\bar{H}'L} + \sigma^{XX\to\phi\bar{L}H'}}$$

$$\delta \equiv \langle\sigma_{XX\to\phi^*\bar{H}'L}v\rangle/\langle\sigma_A v\rangle$$

Note phenomenology contours similar to parameter scans in [arXiv:1210.0094].

Remarks

- Sphalerons cause a sharp freeze out of baryon number in low-mass case
- Narrow washouts freeze out later
- Narrow width approximation valid
- Can generate BAU with low ϵ while independently setting $M_* = 10\,\mathrm{TeV}$
- Lepton injection decoupled from primary DM annihilation channels

Summary and Outlook

- *CP*-violation from tree-level diagrams and an absorbative final state interaction, thus sequestering one-loop suppression of the asymmetry
- Eliminates dangerous tree-level washout processes which are not Boltzmann suppressed
- Inclusion of nonperturbative sphaleron effects through the electroweak crossover
- Decouple new weak scale physics from UV and baryons

- Broad H resonance?
- Possible UV completions
- Indirect detection signatures
- H decays back into SM
- Direct baryogenesis would avoid sphaleron shutoff, but H would be constrained by colliders
- Eliminate dangerous washout terms in more traditional baryogenesis scenarios
- Manifest calculation of lepton asymmetry in CTP formalism

Thank you!

Figure: "I will gladly pay you Tuesday for a hamburger today." - J.W. Wimpy

Observational Evidence for DM and BAU

Figure: Compostie image of the bullet cluster. X-ray emission due to baryonic interactions (red) and the total mass distribution inferred from lensing (blue).

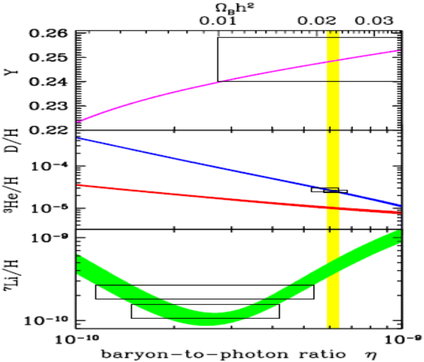


Fig. 1. Primordial abundances versus η, courtesy of R. Cyburt

Figure: Observed light element abundances (boxes) and corresponding BBN predictions (horizontal bands) [arXiv:hep-ph/0609145].

What is the universe made of?

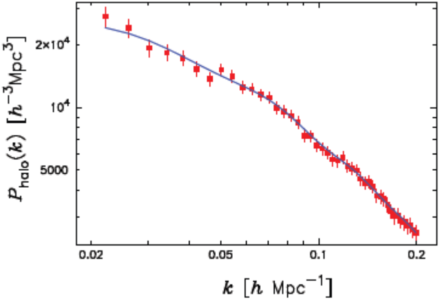


Figure: Observed halo power spectrum and corresponding prediction by Planck for best-fit ΛCDM parameters [arXiv:1303.5076].

Dark Matter

Density perturbations needed to seed stucture formation in ΛCDM

Baryonic Matter

Needed to suppress power at small scales and match observation

Planck Predictions

$$\Omega_b h^2 \sim 0.022$$

$$\Omega_{DM} h^2 \sim 0.12$$

WIMP Dark Matter

Boltzmann Equation

$$\frac{dn}{dt} = -3Hn - \langle\sigma_A v\rangle(n^2 - n_{equi}^2)$$

- Dilution of number density due to Hubble expansion
- Dilution arising from the dark matter annihilation rate
- Creation of dark matter from other processes

Given a weak scale mass and $\langle\sigma_A v\rangle \sim 1pb$, a WIMP will yield the correct reilc density!

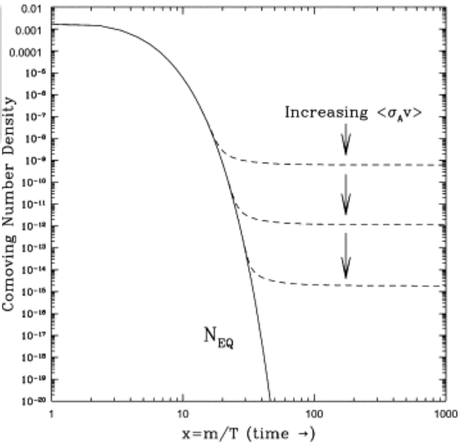


Figure: Solutions to the Boltzmann equation for dark matter annihilation.

Sakharov Conditions for Baryogenesis

Baryon Number Violation

- Or lepton number violation before the EWPT
- Instantons violate $B + L$ nonperturbatively in the SM
- GUTs manifestly violate B when broken to the SM

C Violation

- Take process $X \to Y + B$, for nonbaryonic inital state, X, and final state, Y
- Rates for $X \to Y + B$ and $\bar{X} \to \bar{Y} + \bar{B}$ must differ

CP Violation

- Take processes $X \to q_L q_L$ and $X \to q_R q_R$, for nonbaryonic inital state, X and final state quark pairs
- Need different rates for $X \to q_L q_L$ ($X \to q_R q_R$) and $\bar{X} \to \bar{q}_R \bar{q}_R$ ($\bar{X} \to \bar{q}_L \bar{q}_L$)

Departure from Equilibrium

- Rates for $X \to Y + B$ and $X \leftarrow Y + B$ must differ
- Thermal relic DM?