Dark Matter-Baryogenesis Connection

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7th Symposium on Large TPCs for low-energy rare event detection,
Paris, December 15 2014
Are the Dark Matter and baryon abundances related?

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

- Dark Matter: 26.8%
- Ordinary Matter: 4.9%
- Dark Energy: 68.3%

Particles:
- Atoms: 4.9%
- Photons: 0.0022%
- Neutrinos: 0.0016%
Matter Anti-matter asymmetry:

characterized in terms of the baryon to photon ratio

\[ \eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \equiv \eta_{10} \times 10^{-10} \]

5.1 < \eta_{10} < 6.5 (95% CL)

The great annihilation

10 000 000 001
Matter

10 000 000 000
Anti-matter

1 (us)
Matter Anti-matter asymmetry of the universe:

\[ \eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma} \approx 6 \times 10^{-10} \]

characterized in terms of the baryon to photon ratio

The great annihilation between nucleons & anti-nucleons

\[ n + \overline{n} \rightarrow \pi + \pi \rightarrow \gamma + \gamma + ... \]

occurs when \( \Gamma \sim (m_N T)^{3/2} e^{-m_N / T} / m_\pi^2 \sim H \sim \sqrt{g_* T^2 / m_{Pl}} \)

corresponding to a freeze-out temperature \( T_F \sim 20 \text{ MeV} \)

In absence of an asymmetry:

\[ \frac{n_N}{S} \approx 7 \times 10^{-20} \]

10^9 times smaller than observed, and there are no antibaryons

→ need to invoke an initial asymmetry

10 000 000 001 Matter

10 000 000 000 Anti-matter

1 (us)
The Baryon Asymmetry of the Universe (BAU) deduced from the Cosmic Microwave Background measurements is now more precise than the one deduced from Big Bang Nucleosynthesis (D/H abundance).
η remains unexplained within the Standard Model

double failure:

- lack of out-of-equilibrium condition

- so far, no baryogenesis mechanism that works with only SM CP violation (CKM phase)

proven for standard EW baryogenesis  
Gavela, P. Hernandez, Orloff, Pene ’94
Konstandin, Prokopec, Schmidt ’04

unconclusive attempts in cold EW baryogenesis  
Tranberg, A. Hernandez, Konstandin, Schmidt ’09
Brauner, Taanila, Tranberg, Vuorinen ’12
History of baryogenesis papers

- Number of papers with “leptogenesis” in the title
- Number of papers with “baryogenesis” or “baryon asymmetry” or “leptogenesis” in the title

(from Inspire)

- 1967: Sakharov
- 1980: Kuzmin
- 1994: LEP ends
- 2000: LHC
- 2010: Leptogenesis
Two leading candidates for baryogenesis:

--> Leptogenesis by out of equilibrium decays of RH neutrinos before the EW phase transition

--> Baryogenesis at a first-order EW phase transition
**Models of Baryogenesis**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Models</th>
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<tbody>
<tr>
<td>0</td>
<td>GUT baryogenesis</td>
</tr>
<tr>
<td></td>
<td>B washout unless B-L ≠ 0</td>
</tr>
<tr>
<td></td>
<td>requires SO(10)</td>
</tr>
<tr>
<td></td>
<td>requires too high reheat temperature to produce enough GUT particles</td>
</tr>
<tr>
<td>1</td>
<td>Thermal leptogenesis</td>
</tr>
<tr>
<td></td>
<td>hierarchy pb -&gt; embed in susy-&gt; gravitino pb (can be solved if M_gravitino&gt;100 TeV and DM is neutralino or gravitino is stable)</td>
</tr>
<tr>
<td></td>
<td>Affleck-Dine (moduli decay)</td>
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<tr>
<td>2</td>
<td>Non-thermal leptogenesis (via oscillations)</td>
</tr>
<tr>
<td>3</td>
<td>Asymmetric dark matter-cogenesis</td>
</tr>
<tr>
<td>4</td>
<td>EW breaking, sphalerons freese-out</td>
</tr>
<tr>
<td>5</td>
<td>EW (non-local) baryogenesis</td>
</tr>
<tr>
<td>6</td>
<td>EW cold (local) baryogenesis</td>
</tr>
</tbody>
</table>
Baryon asymmetry and the EW scale

1) nucleation and expansion of bubbles of broken phase

broken phase $\langle \Phi \rangle \neq 0$
Baryon number is frozen

2) CP violation at phase interface responsible for mechanism of charge separation

Chirality Flux in front of the wall

3) In symmetric phase, $\langle \Phi \rangle = 0$, very active sphalerons convert chiral asymmetry into baryon asymmetry

Electroweak baryogenesis mechanism relies on a first-order phase transition
In the SM, a 1rst-order phase transition can occur due to thermally generated cubic Higgs interactions:

\[
V(\phi, T) \approx \frac{1}{2}(-\mu_h^2 + cT^2)\phi^2 + \frac{\lambda}{4}\phi^4 - ET\phi^3
\]

\[
-ET\phi^3 \subset -\frac{T}{12\pi} \sum_i m_i^3(\phi)
\]

In the SM: \(\sum_i \not\approx \sum_{W,Z}\) not enough

for \(m_h > 72\text{ GeV}\), no 1st order phase transition

In the MSSM: new bosonic degrees of freedom with large coupling to the Higgs

Main effect due to the stop
The (fine-tuned) EW baryogenesis window in the Minimal Supersymmetric Standard Model: A Stop-split supersymmetry spectrum

excluded by recent higgs measurements and stop searches

The light stop scenario: testable at the LHC

bounds get relaxed when adding singlets or in BSSM
Very light stop searches at the LHC

The 2 decay channels that have been studied in most detail:

\[ \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 \]
\[ \tilde{t}_1 \rightarrow b\tilde{\chi}_1^+ \]

When stop is very light we have instead:

\[ \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0 W^+ \] \hspace{1cm} 3-body
\[ \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0 f\tilde{f}' \] \hspace{1cm} 4-body
\[ \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 \] \hspace{1cm} flavour-violating

branching ratios depend on flavour structure
Supersymmetry: 3rd generation

Direct stop production:

\[ m_{\text{stop}} > m_{\text{bottom}} + m_W + m_{\text{LSP}} \]

\[ m_{\text{stop}} > m_{\text{charm}} + m_{\text{LSP}} \]

\[ m_{\text{stop}} > m_{\text{charm}} + m_{\text{LSP}} \]

\[ m_{\text{stop}} > m_{\text{charm}} + m_{\text{LSP}} \]
and in addition... EDM constraints!

Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron

The ACME Collaboration*: J. Baron¹, W. C. Campbell², D. DeMille³, J. M. Doyle¹, G. Gabrielse¹, Y. V. Gurevich¹, P. W. Hess¹, N. R. Hutzler¹, E. Kirilov¹, It. Kozyryev¹, B. R. O'Leary³, C. D. Panda¹, M. F. Parsons³, E. S. Petrik¹, B. Spaun¹, A. C. Vutha¹, and A. D. West³

\[ |d_e| < 8.7 \times 10^{-29} \text{ e cm} \quad @ \ 90\% \text{ CL} \]
Three ways to obtain a strongly 1st order phase transition by inducing a barrier in the thermal effective potential

- **thermally driven**
  - (thermal loop of bosonic modes)
  - (example: stop loop in MSSM)

- **tree-level driven**
  - (competition between renormalizable operators)

- **tree-level driven**
  - (competition between renormalizable and non-renormalizable operators)
1) Scenario where the 1st order phase transition is thermally driven

most famous example: light stop scenario in MSSM

consider effect of new scalar coupled to the Higgs via

\[ V \propto \kappa |\Phi|^2 |H|^2. \]

Its effect on the thermal Higgs effective potential is:

\[ V_{\text{eff}}(\varphi; T) = V_0(\varphi) + V_T(\varphi; T) \approx \frac{1}{2} \left( -\mu^2 + \frac{g_\Phi \kappa T^2}{24} \right) \varphi^2 - \frac{g_\Phi \kappa^{3/2} T}{24 \sqrt{2\pi}} \varphi^3 + \frac{\lambda}{4} \varphi^4. \]

as the mass of \( \Phi \) in presence of background higgs field \( \varphi \) is:

\[ m_\Phi^2(\varphi) = m_0^2 + \frac{\kappa}{2} \varphi^2. \]
At the same time the $\Phi$ loop contributes to the Higgs-gluon coupling

$\rightarrow$ A strong 1st order PT leads to sizable deviations in Higgs production rate and decays in $\gamma\gamma$

$\rightarrow$ typically excluded
A number of studies have presented results combining measurements from different facilities [88, 89]. A general observation is that the precision in the measurement of many Higgs coupling at a new facility are reasonably or significantly improved, and these quickly dominate the combined results and overall knowledge of the relevant coupling parameters. Exceptions are the measurements of the branching fractions of rare decays such as \( H \to \gamma \gamma \) and \( H \to \gamma \gamma \) where results from new lepton colliders would not significantly improve the coupling precisions driving these decays. However, precision measurements of the ratio of \( \kappa_W \) at hadron colliders combined with the high-precision and model-independent measurements of \( \kappa_Z \) at a lepton collider would substantially increase the precision on \( \kappa_Z \).
And if BSM scalar is neither colored nor electrically charged?

still induces a 1-loop contribution to Higgs wave function renormalization and affect $e^+e^- \rightarrow hZ$ cross section

$$\delta_{hZ} = - \frac{g_\Phi \kappa^2 v^2}{24 \pi^2 m_h^2} (1 + F(\tau_\Phi))$$

expected deviation: $\sim 0.6\%$

can be probed at upgraded ILC-500 and at TLEP

(similarly for colored and/or electrically charged BSM scalars)

still induces a deviation in the Higgs cubic self-coupling

expected deviation: $\sim 10-20\%$

difficult to test with proposed facilities
Estimated per-experiment precision
on Higgs triple self-coupling $\lambda (1310.8361)$

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>HL-LHC</th>
<th>ILC500</th>
<th>ILC500-up</th>
<th>ILC1000</th>
<th>ILC1000-up</th>
<th>CLIC1400</th>
<th>CLIC3000</th>
<th>HE-LHC</th>
<th>VLHC</th>
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<tr>
<td>$\int \mathcal{L} dt$ (fb$^{-1}$)</td>
<td>14000</td>
<td>500</td>
<td>500</td>
<td>500/1000</td>
<td>500/1000</td>
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<td>1600+2500$^\dagger$</td>
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<td>+2000</td>
<td>3000</td>
<td>3000</td>
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<tr>
<td>$\lambda$</td>
<td>50%</td>
<td>83%</td>
<td>46%</td>
<td>21%</td>
<td>13%</td>
<td>21%</td>
<td>10%</td>
<td>20%</td>
<td>8%</td>
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Estimated precision
from combined facilities (1310.8361)

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<tbody>
<tr>
<td>21%</td>
<td>12.6%</td>
<td>15.2/9.8%</td>
<td>18.6%</td>
<td>7.9%</td>
<td>10.9%</td>
</tr>
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<td>21%</td>
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<td>18.6%</td>
<td>7.9%</td>
<td>10.9%</td>
</tr>
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Indirect constraints on Higgs self-coupling at TLEP via its contribution to Higgsstrahlung

1312.3322

constrains deviations of order ~ 30%
2) Tree level modifications of the Higgs potential:

the SM+ a real scalar singlet: the nightmare scenario?

\[ V_0 = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2} \mu_S^2 S^2 + \lambda_{HS} |H|^2 S^2 + \frac{1}{4} \lambda_S S^4. \]

S has no VEV today:
no Higgs-S mixing -> no EW precision tests , no modifications of higgs couplings as experimental probes of the EW phase transition
m_S > m_H/2: no modified Higgs decay

from F. Riva -> Espinosa et al, 1107.5441
\[ V_0 = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2} \mu_S^2 S^2 + \lambda_{HS} |H|^2 S^2 + \frac{1}{4} \lambda_S S^4. \]

Besides:
\[ \delta \sigma_{Zh} = \frac{1}{2} \frac{\lambda_{HS}^2 v^2}{16 \pi^2 m_h^2} \left[ 1 + F(\tau_\phi) \right] < 0.5\% \text{ in relevant region} \]

(higgs triple coupling deviation >16% and can be excluded at 100 TeV collider)

\[ \lambda_3 = \frac{m_h^2}{2v} + \frac{\lambda_{HS}^3 v^3}{24 \pi^2 m_S^2} + \ldots \]

(at 1 loop)
very difficult to test at colliders but Xenon 1T can test all relevant parameter space!

\[
\log_{10}\left(\frac{\Omega_S}{\Omega_{CDM}} \times \sigma_S^{SI}\right)
\]
cross section in cm\(^2\)

Figure 9. Dark matter properties of the singlet scalar S, assuming it is a stable thermal relic. Left: magenta contours show contours of \(\log_{10} \frac{\Delta S}{\Delta CDM}\). In practically all of the parameter space viable for EWBG, the singlet scalar is a subdominant dark matter component. Right: green contours show the singlet scalar's direct detection cross section rescaled with relic density, \(\log_{10} \frac{\Delta S}{\Delta CDM} \times \sigma_S^{SI}\). The singlet-nucleon cross section is in units of cm\(^2\). The dark green shaded region is excluded by LUX. The light green shaded region can be probed by XENON1T.

For our model, however, it is possible to tune \(S\) to \(S = \min\) and achieve \(T_c < T_f\). For this case, there are two possibilities for singlet freeze-out in the two-step phase transition region:

• The singlet freezes out in the unbroken phase at temperature \(T_h = 0\). Since the universe resides in the singlet-VEV vacuum before the phase transition, the singlet can decay via \(S \rightarrow hh\). This could deplete the singlet density to values much lower than indicated in Fig. 9 (left).

• The singlet is in thermal equilibrium just before the phase transition at \(T_c < 22\) GeV. If the singlet becomes lighter, it remains in thermal equilibrium and our above freeze-out estimate should apply. If it becomes heavier, it likely freezes out instantly.

Understanding the consequences of the second possibility would require further study, but it is clear that dark matter relic density may be considerably reduced in the two-step region, resulting in lower relic density and correspondingly weaker direct detection bounds than those shown in Fig. 9.

That being said, assuming these direct detection bounds (with \(T_f < T_c\) and a stable thermal relic) apply to our model, the nightmare scenario for EWBG is already excluded for \(m_S < m_h\) by LUX.

Interestingly, the entire EWBG-viable parameter space for both a one- and two-step phase transition is very difficult to test at colliders but Xenon 1T can test all relevant parameter space!
In the parameter space relevant for EW baryogenesis, the singlet scalar is a subdominant dark matter component.

![Graph showing log10(Ω_S/Ω_{CDM}) vs. m_S [GeV] with contours and shaded regions indicating the parameter space relevant for EW baryogenesis.](image)

The large singlet-higgs coupling annihilates away the relic density.
Conclusion 1:

The minimal scalar extension to the SM (adding a real singlet) leads to strong first-order EW phase transition as needed for EW baryogenesis

Very challenging to test at future colliders
(100 TeV collider needed)

Relevant region of parameter space for baryogenesis cannot account for dark matter

Still, large Higgs-singlet interactions enable to test the relevant region with Xenon 1 T.
Standard EW baryogenesis is essentially disconnected from the problem of dark matter generation and does not try to find a unified explanation for dark and visible matter densities.
Dark Matter Candidates

- thermal relic
- superWIMP
- condensate
- gravitationnally produced or at preheating

Log$_{10} \frac{\sigma_{\text{int}}}{\text{pb}}$ vs Log$_{10} M_{\text{GeV}}$

- neutrino sterile $s=1/2$
- axion $s=0$
- axino $s=1/2$
- gravitino $s=3/2$
- KK graviton $s=2$
- WIMPZILLA

Energy scales:
- keV
- GeV
Wimps under pressure from the LHC, Fermi, Xenon, LUX ...

- **FIG. 2.** Upper limits on CGH dataset. 68% CL regions for these limits. Black crosses denote the flux ground spectra, and the gray bands denote the corresponding black lines show the mean expected limits derived from a large arrows with open data points). For both data sets, the solid era pixel amplitudes, and a di

- **FIG. 4.** Limits on the velocity-weighted cross section for DM shown in Fig. 4 and compared to recent results obtained using the astrophysical factors given in [8]. The result is shown for comparison (black arrows with open data points)

- **SUMMARY AND CONCLUSIONS**

- **HESS, PRL 110 (2013)**
constraints on axion

$fa[\text{GeV}]$

$ma[\text{eV}]$

Hot-$\text{DM} / \text{CMB} / \text{BBN}$

Burst Duration

SK

Globular Clusters ($g_{\alpha \gamma}$)

White Dwarfs ($g_{\alpha e}$)

Solar Neutrino flux ($g_{\alpha e}$)

Excluded (too much DM)

ADMX

ADMX-II

IAXO

CAST

Telescope

Beam Dump

SN1987A

White Dwarfs

$10^7$

$10^6$

$10^5$

$10^4$

$10^3$

$10^2$

$10^1$

Axion DM abundance fitting the observations

$0.5$

$1.0$

$1.5$

$2.0$

$10^1$

$10^2$

$10^3$

$10^4$

$10^5$

$10^6$

$10^7$

$10^8$

$10^9$

$10^{10}$

$10^{11}$

$10^{12}$

$10^{13}$

$10^{14}$
WIMP-baryogenesis Connection?

asymmetric dark matter
Matter Anti-matter asymmetry of the universe:

characterized in terms of the baryon to photon ratio

\[ \eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma} \sim 6 \times 10^{-10} \]

The great annihilation between nucleons & anti-nucleons

\[ n + \overline{n} \rightarrow \pi + \pi \rightarrow \gamma + \gamma + ... \]

occurs when

\[ \Gamma \sim (m_N T)^{3/2} e^{-m_N / T} / m_\pi^2 \sim H \sim \sqrt{g_* T^2 / m_{Pl}} \]

corresponding to a freeze-out temperature \( T_F \sim 20 \text{ MeV} \)

In absence of an asymmetry:

\[ \frac{n_N}{S} \approx 7 \times 10^{-20} \]

10^9 times smaller than observed, and there are no antibaryons

\rightarrow need to invoke an initial asymmetry

\[ \frac{10000000001}{10000000000} \]

Matter

Anti-matter

1 (us)
Similarly, Dark Matter may be asymmetric

\[ \frac{\Omega_{dm}}{\Omega_b} \sim 5 \]

If \( n_{dm} - \bar{n}_{dm} \propto n_b - \bar{n}_b \)

Does this indicate a common dynamics?

Initial B asymmetry

\[ \begin{array}{c}
\text{B} \\
\text{B}
\end{array} \]

annihilation

Initial DM asymmetry

\[ \begin{array}{c}
\text{X} \\
\text{X}
\end{array} \]

Residual asymmetric component remains

\[ Q_{DM}(n_{DM} - \bar{n}_{DM}) = Q_b(n_b - \bar{n}_b) \]

conservation of global charge:

if efficient annihilations:

\[ \frac{\Omega_{dm}}{\Omega_b} \sim \frac{Q_b}{Q_{dm}} \frac{m_{dm}}{m_b} \]

typical expected mass \( \sim \) GeV

two possibilities:

1) asymmetries in baryons and in DM generated simultaneously

2) a pre-existing asymmetry (either in DM or in baryons) is transferred between the two sectors
Crucial role played by the Higgs in the 2 major theories of baryogenesis

- **in EW baryogenesis:**
  Higgs bubbles provide out-of-equilibrium dynamics

- **in leptogenesis:**
  Decay into the Higgs of RH neutrinos produce lepton asymmetry

**New proposal**
Servant & Tulin, PRL 111, 151601 (2013)

- Use the Higgs to mediate the asymmetries between the visible and dark sector
In the early universe, at $T \sim 100 \text{ GeV}$, before the EW phase transition, the thermal bath contains both Higgs particles and anti-Higgs particles since (since the Higgs doublet is a complex scalar)

We can therefore define an asymmetry between $H$ and $H^*$, particles and anti-particles of the Higgs field, like we do for leptons and quarks.

If the Higgs couples to the dark sector, it can transfer the asymmetry in the dark sector.
Standard Model equations describing chemical equilibrium in the hot plasma relate chemical potentials of the different species:

EW Sphalerons convert asymmetries between baryon and lepton number

\[ \sum_i (3\mu_{q_i} + \mu_{\ell_i}) = 0 \]

Yukawa interactions can induce a Higgs asymmetry

\[
\begin{align*}
\mu_{q_i} - \mu_H - \mu_{d_j} &= 0, \\
\mu_{q_i} + \mu_H - \mu_{u_j} &= 0, \\
\mu_{\ell_i} - \mu_H - \mu_{e_j} &= 0.
\end{align*}
\]

Total hypercharge of the plasma

\[
\sum_i (\mu_{q_i} + 2\mu_{u_i} - \mu_{d_i} - \mu_{\ell_i} - \mu_{e_i} + \frac{2}{N_f} \mu_H) = 0.
\]
Minimal illustrative example

Just add to the Standard Model 2 vector-like fermions: a singlet $X_1$ (Dark matter) and one EW doublet $X_2$ whose role is to transfer the asymmetries between the visible and dark sectors

$$L \supset \frac{1}{\Lambda_2} (H^\dagger X_2)^2 + y_H \bar{X}_2 X_1 H + h.c$$
Case 1: Asymmetric Dark Matter from Lepto/Baryogenesis

Assume a primordial B-L asymmetry. It induces a Higgs asymmetry which flows into the dark sector.

Such a scenario does not require new states that carry baryon or lepton number, unlike other Asymmetric DM models.
To get $\Omega_{\text{DM}} \sim 25\%$:

- Non-thermal relics, e.g. sterile neutrinos, axions
- Symmetric (WIMP) DM
- Asymmetric dark matter
  - provides a suitable host for DM self-interacting via light species
  - encompasses most of the low-energy parameter space of thermal relic DM → study models and low-energy pheno.

Asymmetric DM

- [Review of asymmetric dark matter; KP, Volkas (2013)]
- (a little simplified)
- Venn diagram of stable / long-lived relics

[Petraki]
Case 2: Baryogenesis from a primordial dark matter asymmetry

A theory of baryogenesis that does not require B nor L violation beyond the SM but by having an asymmetry trapped in spectator $X_2$ we bias sphalerons into generating B+L.
## Tests?

<table>
<thead>
<tr>
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<th>Case 1</th>
<th>Case 2</th>
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<tbody>
<tr>
<td>indirect detection</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>direct detection</td>
<td>✔ only for heavy DM</td>
<td>✔</td>
</tr>
<tr>
<td>invisible higgs decay</td>
<td>✗</td>
<td>✔</td>
</tr>
<tr>
<td>LHC searches of X2</td>
<td>✔</td>
<td>✔</td>
</tr>
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</table>
Visible and WIMP Dark Matter abundances could be explained and related through the asymmetric Dark Matter paradigm.

And what if dark matter is the axion, can it play any role in baryogenesis?
Baryogenesis from Strong CP violation

\[ \mathcal{L} = -\bar{\Theta} \frac{\alpha_s}{8\pi} G_{\mu\nu} a \tilde{G}^{\mu\nu} \]

today \quad |\bar{\Theta}| < 10^{-11} \quad \text{as explained by Peccei-Quinn mechanism:}

\[ \bar{\Theta} \rightarrow \frac{a(x)}{f_a} \quad \text{promoted to a dynamical field which relaxes to zero,} \]
\[ \quad \text{to minimize the QCD vacuum energy.} \]

in early universe, before the axion gets a mass around the QCD scale

\[ |\bar{\Theta}| \sim 1 \]

Could \( \bar{\Theta} \) have played any role during the EW phase transition?
The physics underlying the misalignment mechanism is

$$m_a < 3H$$

axion is frozen

$$m_a \approx 3H$$

axion starts rolling, turns into pressureless matter.

Wantz, Shellard '10
Baryogenesis from Strong CP violation

Effective lagrangian generated by SU(3) instantons

\[ \mathcal{L}_{\text{eff}} = \frac{10}{F_{\pi}^2 m_{\eta}^2} \frac{\alpha_s}{8\pi} G\tilde{G} \frac{\alpha_w}{8\pi} F\tilde{F} \]

A condensate for \( G\tilde{G} \) induces a mass for the axion:

\[ \frac{\alpha_s}{8\pi} \langle G\tilde{G} \rangle = m_a^2(T) f_a^2 \sin \theta \]

this leads to:

\[ \mathcal{L}_{\text{eff}} = \frac{10}{F_{\pi}^2 m_{\eta}^2} \sin \theta \, m_a^2(T) f_a^2 \frac{\alpha_w}{8\pi} F\tilde{F} \]

\[ \equiv \zeta(T) \]

Time variation of axionic mass and field is source for baryogenesis

\[ \mu = \frac{d\zeta}{dt} = \frac{f_a^2}{M^4} \frac{d}{dt} [\sin \bar{\Theta} \, m_a^2(T)] \]
Operator relevant for baryogenesis:

\[
\mathcal{L}_{\text{eff}} = \frac{\alpha_W}{8\pi} \zeta(\varphi) \text{Tr} \ F \tilde{F}
\]

where \( \alpha_W \) is the Weinberg angle, \( \zeta(\varphi) \) is a time-varying function, \( F \) and \( \tilde{F} \) are the field strength tensors. This operator can be simplified to:

\[
\mathcal{L}_{\text{eff}} = \mu \ N_{CS}
\]

where \( \mu \equiv \partial_t \zeta \) is the time derivative of \( \zeta \) and \( N_{CS} = \int d^3 x j^0_{CS} \) is the Chern-Simons number.

The time derivative of \( \zeta \) can be interpreted as a time-dependent chemical potential for Chern-Simons number. This operator has been used with

\[
\zeta = \frac{8\pi}{\alpha_W} \frac{\Phi^\dagger \Phi}{M^2}
\]
Temperature dependence of axion mass

\[ f_a^2 m^2(T) = \frac{\alpha_a \Lambda^4}{(T/\Lambda)^{6.68}}, \quad \Lambda = 400\text{MeV} \]

Different powers lead to different high temperature behaviours.

For \( T > T_t = 0.1 \text{ GeV} \)

\[ m^2(T) = m^2(T = 0) \times \left( \frac{T_t}{T} \right)^{6.68} \]

\[ \Delta \zeta \gtrsim 10^{-3} \rightarrow T \lesssim 0.3 \text{ GeV} \]
B-violation and time-variation of axion mass should occur at the same time...

\[ n_B \propto \int dt \frac{\Gamma(T)}{T} \frac{d}{dt} \left[ \sin \tilde{\Theta} \ m_a^2(T) \right] \]

1) For the axion to be the source of baryogenesis, the EW phase transition should be delayed down to \( \sim 1 \text{ GeV} \). Fine ... but

\[ \frac{n_B}{s} = n_f \alpha_w^4 \left( \frac{T_{\text{eff}}}{T_{\text{reh}}} \right)^3 \Delta \zeta \ \frac{45}{2\pi^2 g_*} \sim 10^{-7} \left( \frac{T_{\text{eff}}}{T_{\text{reh}}} \right)^3 \Delta \zeta \sim \tilde{\Theta}(T_{\text{eff}}) \]

\[ \left( \frac{T_{\text{eff}}}{T_{\text{reh}}} \right)^3 \sim \left( \frac{0.1}{100} \right)^3 \text{ killing factor} \]

2) and there should not be any reheating \( \rightarrow \) unacceptable as \( T_{\text{reh}} \sim m_h \).

\textbf{Kuzmin, Shaposhnikov, Tkachev '92}

Conclusion of the authors:
This kills baryogenesis from strong CP violation.
However,

in 1992, the mechanism of cold baryogenesis was not yet known

Cold baryogenesis cures it all as $$\frac{T_{\text{eff}}}{T_{\text{reh}}} \sim [20 - 30]$$

--> large enough baryon asymmetry even for $$\tilde{\Theta}(T) \gtrsim 10^{-6}$$

$$\frac{n_B}{s} \sim 10^{-8} \left( \frac{T_{\text{eff}}}{T_{\text{reh}}} \right)^3 \sin \Theta |_{\text{EWPT}}$$

key point: $$T_{\text{eff}} \neq T_{\text{EWPT}}$$

So even if $$T_{\text{EWPT}} \lesssim \Lambda_{QCD}$$ we can have $$T_{\text{eff}} \gtrsim T_{\text{reh}} \sim m_H$$

Cold baryogenesis arises naturally in models where EW symmetry breaking is induced by the radion/dilaton vev.
cold baryogenesis: production of baryon number at T=0 from out-of-equilibrium dynamics

Tranberg et al, hep-ph/0610096
However,

in 1992, the mechanism of cold baryogenesis was not yet known

Cold baryogenesis cures it all as

$$\frac{T_{\text{eff}}}{T_{\text{reh}}} \sim [20 - 30]$$

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$$\bar{\Theta}(T) \gtrsim 10^{-6}$$

$$\frac{n_B}{s} \sim 10^{-8} \left( \frac{T_{\text{eff}}}{T_{\text{reh}}} \right)^3 \sin \bar{\Theta}_{\text{EWPT}}$$

key point: \( T_{\text{eff}} \neq T_{\text{EWPT}} \)

So even if \( T_{\text{EWPT}} \lesssim \Lambda_{QCD} \) we can have \( T_{\text{eff}} \gtrsim T_{\text{reh}} \sim m_H \)

Cold baryogenesis arises naturally in models where EW symmetry breaking is induced by the radion/dilaton vev.
Axion dynamics during a supercooled EW phase transition can lead to baryogenesis.

\[ f_a \approx 7 \times 10^{10} \text{ GeV} \]

The prediction for today's B asymmetry as a function of the temperature of the EWPT compared with measured value (dotted line). The case \( T_{\text{eff}} / T_{\text{reh}} = 1 \) (light gray) and \( T_{\text{eff}} / T_{\text{reh}} = 50 \) (red) are shown. Each band corresponds to varying the initial angle value \( \bar{\alpha} \) in the range \( [10^{-2}, \pi/2] \).

The key point in this work is to exploit the fact that effective B violation can take place at temperatures below the sphaleron freeze-out temperature, under strong out-of-equilibrium conditions as provided by a quenched EWPT. We summarize here briefly the main features of cold baryogenesis and refer the reader to the specific literature for more details [17,21–27].

In the standard picture of cold baryogenesis, the tachyonic transition develops when the Higgs mass squared \( m_{\text{eff}}^2 \) changes sign rapidly due to a coupling of the Higgs to an additional scalar field. Just before the EWPT, the universe is relatively cold. The dynamics of spinodal decomposition has been investigated both analytically and numerically [22, 25, 36–40], typically using infinitely fast quench. The Fourier modes of the Higgs field with low momentum \( k < \mu \) are unstable and grow exponentially. The rapid rise of the low momentum modes and the particle number distribution of the Higgs can be seen by solving

\[ \ddot{\phi}(k,t) + (m_{\text{eff}}^2(t) + k^2)\phi(k,t) = 0 \]

assuming instantaneous quenching:

\[ m_{\text{eff}}^2 = +\mu^2 \text{ at } t < 0 \text{ and } m_{\text{eff}}^2 = -\mu^2 \text{ at } t > 0, t = 0 \text{ being to the transition. This leads to } \phi(k,t) \sim \exp[-\mu^2 k^2 t]. \]

Therefore, the energy of the additional scalar field inducing the quench is converted into long wavelength modes of the Higgs field which then contain a large fraction of the total energy of the system. These extended field configurations play a key role in inducing Chern–Simons transitions (see e.g. [31] for a summarized review and references therein). It is difficult to predict the final averaged Chern–Simons number analytically. On the other hand, although we are far from thermal equilibrium, we can use some effective sphaleron rate to roughly estimate the effect of dilaton-induced baryon-number violation.

The rate of Chern–Simons transitions can be approximated by that of a system in thermal equilibrium.
Summary

Strong CP violation from the QCD axion can be responsible for the matter antimatter asymmetry of the universe in the context of cold baryogenesis if the EW phase transition is delayed down to the QCD scale.

These conditions can arise naturally in models with a light dilaton (e.g. Goldberger-Wise radion stabilisation mechanism).

scenario testable at LHC: existence of a O(100) GeV Higgs-like dilaton
LHC constraints on the scale of conformal symmetry breaking (dilaton)

As mentioned in the main text, in addition to the direct detection bounds there are also collider bounds from the LHC and earlier experiments. The dilaton (roughly) mimics a Higgs boson, with couplings to massive SM fields suppressed by the factor $v/f$ compared to that of the Higgs and couplings to massless gauge bosons that involve contributions from the matter content of the conformal sector. Collider bounds on the dilaton can thus be obtained by recasting the results of direct production limits from Higgs boson searches. We use the HiggsBound [44–46] code version 4.1.2, that incorporates all the currently available experimental analyses from LEP, the Tevatron, and the LHC [44–46].

The resulting collider bounds on the conformal symmetry breaking scale $f$ as a function of the dilaton mass is presented in Fig. 7 for the two benchmark models A and B defined in Sec. 2. In obtaining these bounds we assumed, for simplicity, no invisible decay channels for the dilaton. We can see that the collider bounds are strongly model dependent: model A has a large coupling to gluons, and thus is very strongly constrained throughout the parameter space relevant for LHC kinematics. Model B has small couplings to gluons and photons, and is only weakly constrained for dilaton masses above 200 GeV.

The resulting bound on $f$ can be turned into a bound on $m$ using Fig. 2. For example the $f \& \Sigma_{TeV}$ bound for $m = 400$ GeV in model A implies $m = 300$ GeV, with the exception for a narrow resonance region.

[1410.1873]
Smoking gun signature of a strongly first-order phase transition

violent process if \( v_b \sim O(1) \)

\[ f_{\text{peak}} \sim 10^{-2} \text{ mHz} \left( \frac{g_*}{100} \right)^{1/6} \frac{T_*}{100 \text{ GeV}} \frac{\beta}{H_*} \]

\[ \Omega_{GW} \sim \frac{1}{(\beta/H)^2} \kappa^2 \]

characterizes amount of supercooling

Grojean-Servant
hep-ph/0607107
Detection prospects for eLISA

Most sensitive in the region around $10^{10}$ TeV

It can detect GWs from strong PTs, occurring slow

[see review by Caprini et al, 1201.0983]
Conclusion

Baryogenesis and dark Matter:

No lack of theoretical ideas!

- For Standard EW baryogenesis through a $Z_2$ singlet, the connection to the EW phase transition does not make it necessarily easy to test at future colliders. Besides, no unified description of dark matter.

- WIMP-baryogenesis connection through asymmetric dark matter: interesting but no model-independent generic prediction.

- QCD axion-baryogenesis connection: easier to test at the LHC (relies on the existence of a light dilaton) and usual generic dark matter prediction of QCD axion remains unaffected.