Probing Supersymmetric Baryogenesis: from Electric Dipole Moments to Neutrino Telescopes

Based on: V.Cirigliano, SP and M.Ramsey-Musolf, JHEP07(2006)002

SP and M.Ramsey-Musolf (Caltech/Madison) [work in progress]
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Phenomenology of SUSY EW Baryogenesis

Systematic Treatment of Baryon Asymmetry Computation in Electroweak Baryogenesis (*)

Consider a specific, viable Supersymmetric setup

Study the Phenomenology

Outline the MSSM Parameter Space compatible with EW Baryogenesis

Explore the resulting EDM’s (1 and 2 loop)

Connection with Dark Matter (relic abundance and detection)

Prospects for Collider searches (Tevatron-II, LHC and ILC)

(*) Cirigliano, Lee, Ramsey-Musolf, Tulin; see C.Lee’s and M.J.Ramsey-Musolf’s talks
“In so far as a scientific statement speaks about reality, it must be falsifiable: And in so far as it is not falsifiable it does not speak about reality”

Karl Popper, “The Logic of Scientific Discovery”

Supersymmetric Electro-Weak Baryogenesis: a falsifiable theory
In the **Minimal Supersymmetric Extension of the Standard Model (MSSM)**

- **Additional bosonic degrees of freedom** couple to the Higgs (e.g. a light scalar top, $x_6$)
  - A strongly first order \( EW \) Phase Transition occurs for larger, \( LEP \)-viable values of \( m_h \)

- The theory features potential **additional \( CP \)-violating sources**
  - Gaugino/Higgsino sector
  - Scalar quark sector

\textbf{BONUS: the MSSM provides ideal candidates for non-baryonic Dark Matter as well !}

\(^(*)\) see C.Lee’s and M.J.Ramsey-Musolf’s talks
**EWB in the MSSM: Requirements**

In the **MSSM**, successful EW baryogenesis requires:  

...at **odds** with:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Light enough stop</td>
<td>$m_{\tilde{t}} &lt; m_t$</td>
</tr>
<tr>
<td>2. Light enough Higgs</td>
<td>$m_h &lt; 120\text{GeV}$</td>
</tr>
<tr>
<td>3. Strong enough CP-violating sources</td>
<td>$e, n$ and atomic EDM’s</td>
</tr>
</tbody>
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<tr>
<td>$m_{\tilde{t}} &gt; 95\text{GeV}$ (LEP-II)</td>
</tr>
<tr>
<td>$m_h &gt; 114\text{GeV}$ (LEP-II)</td>
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**Interludium: Neutralinos and Charginos**

\[ M_N = \begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix} \]

\[ \chi = N_{11} B^0 + N_{12} W^0 + N_{13} H_d^0 + N_{14} H_u^0 \]

\[ \mu \rightarrow |\mu| e^{i\phi_\mu} \]

\[ M_C = \begin{pmatrix} M_2 & \sqrt{2} m_w \cos \beta \\ \sqrt{2} m_w \sin \beta & \mu \end{pmatrix} \]

\[ g \frac{\nu_d(x)}{\sqrt{2}} \]

\[ g \frac{\nu_u(x)}{\sqrt{2}} \]

**Gaugino Mass Relations**

\[ (M_1 = \alpha M_2) \]

\[ \beta \cos \theta_W \]

\[ m_Z \sin \beta \sin \theta_W \]

\[ -m_Z \sin \beta \sin \theta_W \]

\[ 0 \]

\[ -\mu \]

\[ 0 \]

**T \sim T_{EW}**: scattering of \( H, \tilde{W} \) from background field

**T \ll T_{EW}**: mixing of \( H, \tilde{W} \) to \( \tilde{\chi}^*, \tilde{\chi}^0 \)
EWB in the MSSM: Setup

- **Free parameters** in the game:

  $M_1, M_2, |\mu|, \phi_\mu$
**EWB in the MSSM: Setup**

- **Free parameters** in the game:
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- The second stop must be **heavy**, and mostly "**left-handed**"

  \[ m_{\tilde{t}_1} \approx m_t, \ m_{\tilde{t}_2} = 10 \text{ TeV} \]

- Increase the **Higgs mass**

- Reduce the SUSY contribution to \( \Delta \rho \)
**EWB in the MSSM: Setup**

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- Other **sfermions** must be **heavy** to suppress CP-violating processes (e.g. 1-loop EDM’s)

\[
m_{\tilde{t}_1} \approx m_t, \ m_{\tilde{t}_2} \approx 10 \text{ TeV}
\]

\[
m_{\tilde{f}} \approx 10 \text{ TeV}
\]
**EWB in the MSSM: Setup**

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- Other **sfermions** must be **heavy** to suppress CP-violating processes (e.g. 1-loop EDM’s)
  \[ m_{\tilde{f}} \approx 10 \text{ TeV} \]

- The generated **BAU** also depends on the **heavy** MSSM **Higgs** sector through \( \Delta \beta \)
  \[ m_A = 150 \text{ GeV}, \quad 1000 \text{ GeV} \]
Resonant EW Baryogenesis

...even if all these conditions hold, CP-violating sources are large enough if close-to-resonant conditions are met in the gaugino-higgsino sector.

\[ M_{1,2} \approx \mu \]

Resonant Chargino Source: Well known fact

Resonant Neutralino Source: Novelty!

Connection with Dark Matter

**EW Baryogenesis and DM**

In the \((R\text{-parity conserving})\) MSSM **the LSP is stable**

The LSP must be a phenomenologically viable relic
\((\text{electrically and color neutral, low enough relic abundance and direct detection rates})\)

(a): EWB and DM are **unrelated**

(b): EWB-DM **connection**
Baryon Asymmetry in the MSSM

What we learn:
1. sub-TeV mass parameters
2. \( \sin \phi \mu > 0.01 \)
3. Two-funnel structure

Central WMAP BAU

Neutralino driven baryogenesis

Sub-TeV gaugino mass pattern

\[
M_1 = \frac{5}{3} \frac{\sin^2 \vartheta_W}{1 - \sin^2 \vartheta_W} \approx M_2 / 2
\]

Anomaly mediation gaugino mass pattern

\[
M_1 = \frac{\beta_{g_1}}{\beta_{g_2}} \frac{g_2}{g_1} M_2 \approx 3M_2
\]

“Supergravity”-like

“Anomaly mediation”-like
Electric Dipole Moments

CP-violating interactions in the SUSY sector induce EDMs
In the present setup, the best probe is the **electron** EDM

**1-loop (electron) EDM**

Asymptotically vanish in the limit of large sfermion masses

**2-loop EDM**

Only contribution In, e.g., SplitSUSY
EDMs and EW Baryogenesis

- Only two-loop EDMs (heavy sfermions limit)
- Anomaly mediated case even worse!
- Maximal phases are not compatible with EW Baryogen.

\[ \sin \phi_{\mu} \approx 1 \]

\[ d_e^{\text{exp, cur}} \approx 1.6 \times 10^{-27} \text{ e} \cdot \text{cm} \]
EDMs and EW Baryogenesis

What we learn:
1. EDM and EWB are compatible
2. maximal phases are excluded by current data
3. there is a lower bound on the el. EDM
$$d_e \geq 10^{-28} \text{ e} \cdot \text{cm} \gg d_e^{\text{exp, fut}} \approx 10^{-29\pm30} \text{ e} \cdot \text{cm}$$

EDM experiments will conclusively test the EW Baryogenesis scenario!
**EWB and DM: a closer look**

- The **higgsino mixing** is required to have a low enough **relic abundance** in the $M_1 \approx \mu$ case and fulfill EWB + right thermal $\chi$ production.

- Large higgsino mixing implies large couplings to the Higgses, and hence **large direct detection rates** even with heavy s-quarks.

- Since $m_{\tilde{\chi}_1^0} < m_{\tilde{t}_1^-} < m_t$, the DM particle is **light**

  this means that

  \[ \begin{align*}
  \bullet \text{ the local DM number density is large } & \left( \rho_{\text{DM}} = m_{\text{DM}} \cdot n_{\text{DM}} \right) \\
  \bullet \text{ the number of pair annihilations is large } & \left( \propto n_{\text{DM}}^2 \right)
  \end{align*} \]
The Neutralino Relic Abundance & EWB

$\chi$ Stop coann.

Resonant s(h) ann.

$< \frac{1}{3}$

$\chi$ Bino-Higgsino mixing

$\eta_{\omega}=1$

$\eta_{\omega}=10$

$\eta_{\omega}=20$

$30 \leq \eta_{\omega} \leq 300$

$m_A=1$ TeV, $\sin(\phi_\mu)=0.5$

- **Excessive** relic abundance regions are **ruled out** (caveat: low-$T$ reheating)

- **Low** relic abundance regions are viable assuming either **non-thermal** production or cosmological enhancement

$$\Omega_{\chi}\equiv\frac{\Omega_{CDM}^{\text{WMAP}}-\Omega_{\chi}^{\text{th}}}{\Omega_{\chi}^{\text{th}}}$$

- In the anomaly mediated SUSY bckg. case

**Neutralinos can be responsible for both Baryogenesis and Dark Matter**
**Direct & Indirect Dark Matter Searches**

**DIRECT DETECTION**

Observation of scattering events of WIMPs off nuclei in low background environments

**HIGH ENERGY NEUTRINOS FROM THE SUN / EARTH**

Search for energetic neutrinos produced in $\chi\chi$ pair annihilations in the core of nearby gravitational dips, as the center of the Sun or of the Earth

**XENON 1-t**

**Super-K**

**IceCube**
Dark Matter searches and EWB

- All the parameter space will be within reach of next generation direct detectors and of km$^2$ size neutrino telescopes (e.g., IceCube).
- A sizable portion of the parameter space which we expect to be compatible with EWB is already ruled out by SuperK data on the neutrino flux from the Sun.
- CP phases suppress direct detection and enhance the neutrino flux $f$/Sun.

CP conserving case (no EWB) vs. CP violating case (EWB)
Dark Matter searches and EWB: Zooming Out

Both ton-sized direct detectors AND neutrino telescopes will conclusively probe EW Baryogenesis!

Supergravity mediated SUSY breaking
Anomaly mediated SUSY breaking
Collider Searches

\[ M_2 = 2 M_1 \quad M_A = 1 \text{ TeV} \]

- **LHC LHC – trilepton**
- **ILC LHC – same sign top**
- **LHC – trilepton**
- **ILC**

- **Tevatron**
- **LHC – same sign top**
- **LHC – trilepton**

\[ m_{\tilde{t}_1} < m_{\tilde{t}_1^+} \quad \tilde{t}_1 \rightarrow c\chi_1^0 \]
\[ \tilde{t}_1 \rightarrow \ell^+ t \]
\[ c\chi \quad bW \]
\[ \tilde{\chi}_1^+ \rightarrow l\nu\chi \quad \tilde{\chi}_2^0 \rightarrow l\bar{l}\chi \]
\[ e^+ e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \]
\[ e^+ e^- \rightarrow \tilde{t}_1^* \tilde{t}_1 \]

**EW Baryogenesis in the MSSM: Summary**

- **Two-funnel structure** (chargino & neutralino driven)

  - Will be probed by next generation electron EDM exp
  - Compatible (and/or connected) with Neutralino CDM
  - Could be seen at LHC
  - Will be probed at ILC

- What lies BEYOND?
  - • Already constrained by SuperK
  - • Will be probed at
    - IceCube
    - Ton-Sized Dir. Det.
Beyond the Minimal SUSY SM

Adding a **Gauge Singlet** Superfield $S$ to the Superpotential strongly affects SUSY EWB, adding tree-level cubic terms (*).

$$W = \mu H_d H_u + h_s H_d H_u S + \frac{1}{3}kS^3 + \alpha S + \left( g_u Q u^c H_u + g_d Q d^c H_d g_u + g_e L e^c H_d \right)$$

(as general as possible, including the $\mu$-term, linear and cubic terms in $S$) (**)

The corresponding tree level scalar field potential reads:

$$
\begin{align*}
V_F &= |h_s H_d \cdot H_u + \alpha + \kappa S^2|^2 + \left( |H_d|^2 + |H_u|^2 \right) |\mu^* + h_S S|^2 \\
V_D &= \frac{g_1^2 + g_2^2}{8} \left( |H_d|^2 - |H_u|^2 \right)^2 + \frac{g_2^2}{2} \left( H_d^\dagger H_u \right) \left( H_d H_u^\dagger \right) \\
V_{soft} &= m_d^2 |H_d|^2 + m_u^2 |H_u|^2 + m_s^2 |S|^2 + \\
&\phantom{=} -m_4 \left( H_d \cdot H_u S + h.c. \right) + (b \ H_d \cdot H_u + h.c.) + \\
&\phantom{=} + m_1 (S + h.c.) + m_2 (S^2 + h.c.) + m_3 (S^3 + h.c.)
\end{align*}
$$

**Beyond the Minimal SUSY SM**

1. The **EWPT** is more “naturally” strongly **first order** (e.g. if the singlet Higgs is light)

2. The bound on the **Higgs mass** is alleviated (both for EWB and theoretically)

3. No need for **light stops**

4. Extra possible non-trivial **CP**-structure

**Scopes of the projects:**

<table>
<thead>
<tr>
<th>Study the dynamics of the <strong>EWPT</strong> (bubble walls, diffusion, wash-out...)</th>
<th>Study the <strong>CP-structure</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Assess the new contribution to <strong>EW precision</strong> observables</td>
<td>Evaluate the new contributions to <strong>Electric Dipole Moments</strong></td>
</tr>
<tr>
<td></td>
<td><strong>DM</strong> physics (light singlino...) (*)</td>
</tr>
</tbody>
</table>

(*) F.Ferrer, L.Krauss and S.Profumo, PRD 74 (2006) 115007
The EW Phase Transition in Singlet Models

A **Toy Model** Warm-up: Minimal **Singlet Extension** of the SM Higgs Sector

\[
V(H, S) = \frac{m^2}{2} H^+ H + \frac{\lambda}{4} \left( H^+ H \right)^2 + a_1 S \left( H^+ H \right) / 2 + a_2 S^2 \left( H^+ H \right) / 2 + b_2 S^2 / 2 + b_3 S^3 / 3 + b_4 S^4 / 4
\]

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\]
\[
a_1 S \left( H^+ H \right) / 2 + a_2 S^2 \left( H^+ H \right) / 2 +
\]
\[
b_2 S^2 / 2 + b_3 S^3 / 3 + b_4 S^4 / 4
\]

- **Singlet v.e.v.** before the EW Phase Transition
  \[
  \langle \text{Singlet} \rangle_{T>T_c} \neq 0 \iff R < 2/9
  \]
  \[
  \langle \text{Singlet} \rangle_{T>T_c} = 0 \iff R \geq 2/9
  \]

- Obtain Strongly **First Order** EWPT without tree-level cubic terms \((a_1=b_3=0)\)

- Connect the “**order parameter**” \(\phi_c / T_c\) to low-energy, collider **observables**

Cosmological probes: Gravitational Waves

- When two or more bubbles **collide**, spherical symmetry is broken; A fraction of their kinetic energy is released in **Gravitational Waves**
- **Turbulent motions** provide another source of GW’s
- The **dynamics** of the **EWPT** enter through

\[ \alpha = \Delta V / T^4 \]

**“Latent Heat”**  
(False vacuum energy)  
over Transition T

\[ \beta = \frac{\Gamma}{\Gamma_{T=T_*}} \]

**Bubble Nucleation Time Scale**  
\[ \beta >> H^* \]

\[ f_{\text{coll}} = 5.2 \times 10^{-3} \text{ mHz} \left[ \frac{\beta}{H^*} \right] \left[ \frac{T^*}{100 \text{ GeV}} \right] \left[ \frac{g^*}{100} \right] \]

\[ h_0^2 \Omega_{GW} (f_{\text{coll}}) \propto \left[ \frac{H^*}{\beta} \right]^2 \left[ \frac{1}{1+\alpha} \right]^2 \left[ \frac{g^*}{100} \right]^{-1/3} \]

Cosmological probes: Heavy Relic Abundances

“Super-Cooling” dilutes the abundance of Heavy Relics

- If $T_{\text{f.o.}} \approx \frac{m_\chi}{20} \geq T_c$ the EWPT affects the $\chi$ relic density
Cosmological probes: Heavy Relic Abundances

“Super-Cooling” dilutes the abundance of Heavy Relics

- If $T_{f.o.} \approx \frac{m_\chi}{20} \geq T_c$ the EWPT affects the $\chi$ relic density

With a strongly first order EWPT, the Universe is trapped in a false vacuum $\phi_c = 0$ until quantum tunneling becomes efficient ($T_*$).

The vacuum energy is then released, re-heating the Universe to $T_c$.

$$\frac{s_f}{s_i} \approx \left(\frac{T_c}{T_*}\right)^3$$
$$\frac{(n_\chi)_f}{(n_\chi)_i} \approx \left(\frac{T_*}{T_c}\right)^3$$

Superheavy Relic Density Dilution