Progress in Electroweak Baryogenesis

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Electroweak Baryogenesis References

- Incomplete list of ewbgenesis people:
  Ambjorn, Arnold, Ashoorion, Baek, Blum, Bochkarev, Bodeker, Brhlik, Carena, Chang, Cirigliano, Cline, Cohen, Davies, Davoudiasl, de Carlos, Dine, Dolan, Elmfors, Enqvist, Espinosa, Farrar, Froggatt, Gavela, Garbrecht, Giudice, Good, Grasso, Grinstein, Grojean, Hernandez, Huet, Huber, Jakiw, Jansen, Joyce, Kane, Kainulainen, Kajantie, Kaplan, Keung, Khlebnikov, Klinkhamer, Ko, Kolb, Konstandin, Kuzmin, Laine, Langacker, Lee, Linde, Liu, Losada, Menon, Moore, Moorhouse, Moreno, Morrissey, Multamaki, Murayama, Nelson,Nir, No, Olive, Orloff, Oaknin, Pietroni, Quimbay, Quiros, Pene, Pierce, Pilaftsis, Prokopec, Profumo, Rajagopal, Ramsey-Musolf, Ringwald, Riotto, Rubakov, Rummukainen, Sather, Schmidt, Seco, Senaha, Servant, Shaposhnikov, Shaughnessy, Singleton, Thomas, Tkachev, Trodden, Trott, Tsypin, Tulin, Turok, Vilja, Vischer, Wagner, Westphal, Weinstock, Wells, Worah, Yaffe...

- Some overview references
  - hep-ph/0609145
  - hep-ph/0312378
  - hep-ph/0303065
  - hep-ph/0208043
  - hep-ph/0006119
  - hep-ph/9901362
  - hep-ph/9901312
  - hep-ph/9802240
(Lack of) Rigidity

- **inflaton** ("solves" flatness + horizon + relic; generates density perturbations)
- **(re)heats** (couples to SM)
  - Moduli oscillate
  - gravitino
  - Leptogenesis
- **Anticipated new landmark**
  - **EWPT**
  - Baryon chemical potential freeze in
  - **LHC**
  - WIMP freeze out
  - QCD PT
  - axion oscillate
- **Old landmark**
  - **BBN**
  - Lab + cosmo
  - Neutrinos decouple
  - **matter dominate**
  - neutral H
  - Clean, linear
  - **stars reionize**
  - **DE dominates**
    - Hot baryons, lensing
    - More challenging systematic errors (nonlinearities, plasma physics)

- **Lab + cosmo**
- More challenging systematic errors (nonlinearities, plasma physics)
Implications of EWPT?

- **Electroweak Baryogenesis**: Bubble plasma dynamics
  - Good: Overconstraint possible
  - Bad: 1 number, mild tuning of parameters

- **Leptogenesis**: B-L to B conversion
  - Good: Connection to a lot of “natural” UV physics
  - Bad: Overconstraint unlikely

- **Gravity Waves**: Bubble stirs up fluid
  - Good: Overconstraint possible
  - Bad: Measurability is uncertain

- **DM**: Freeze out physics can be affected
  - Good: Overconstraint possible
  - Bad: narrow parametric window

- **CC**: IR contribution
  - Good: Overconstraint possible
  - Bad: narrow parametric window, and dependence on multiple discoveries

- **Clustering**: too small scale and effects easily washed out
Electroweak Bgenesis

[Kuzmin, Rubakov, Shaposhnikov 85]

1) Bubble nucleate
2) CP violating scattering in bubble $\rightarrow$ source of CP asymmetry
3) CP charge diffuse out in front of bubble generating B through sphalerons
4) True vacuum phase captures the B-asymmetry created

e.g. MSSM neglecting leptons

For a more complete set, see [DC, Garbrecht, Ramsey-Musolf, Tulin 09]
Ingredient 1

- Universe reheats to a high enough temperature such that B-violating sphalerons are unsuppressed:

  [Kuzmin, Rubakov, Shaposhnikov 85; Arnold, McLerran 87; Bodeker, Moore, Rummukainen 00]

Plausible since low scale inflationary models are more fine tuned.

Note the smallness of baryon number comes partly from $10^{-5}$.
Ingredient 2

- Bubble nucleation from EWSB sector or concurrently from another sector as long as bubble percolation completes nearly simultaneously:
  e.g. [Moreno, Quiros, Seco 98; John, Schmidt 00; Moore 00; Csikor, Fodor, Hegedus, Jakovac, Katz, Piroth 00]

\[ S^{(3)}(T) \approx 13.7 \frac{\mathcal{E}}{T} \left( \frac{\alpha}{\lambda} \right)^{3/2} f(\alpha) \]

\[ f(\alpha) = 1 + \frac{\alpha}{4} \left( 1 + \frac{2.4}{1 - \alpha} + \frac{0.26}{(1 - \alpha)^2} \right) \]

\[ \alpha(T) = \alpha_0 \left( 1 - T^2 / T_0^2 \right) \]

\[ T_0 = \sqrt{\frac{-M^2}{2c}} \quad \alpha_0 \equiv \lambda M^2 / 2\mathcal{E}^2 \]
Ingredient 3

- Unsuppressed bubble (i.e. $\phi = v(t, \vec{x})$) coupling to CP violating physics.

e.g. one popularly considered source in MSSM

Physics: local mass eigenstates do not remain mass eigenstates over $L_w$

VEV insertion approx [Riotto 96; Carena, Quiros, Riotto, Vilja, Wagner 97]

$$V(x) \equiv v_2(x) - \frac{M}{m_{\phi}} v_1(x)$$

$$\alpha_i \Im (m M_i) \left[ v_1(y) v_2(x) - v_1(x) v_2(y) \right]$$

$\beta'(z) v^2(x)$

CP asymmetry carriers must be thermally populated.
Ingredient 4

- Efficient diffusion is useful [Cohen et al 94; Joyce, Prokopec, Turok 94]

More charge gets out with less damping

\[ D_i \sim \frac{1}{\Gamma_i} \frac{\langle p_z E^2 \frac{\partial f_0}{\partial E} \rangle}{\langle \frac{\partial f_0}{\partial E} \rangle} \]

Weakly interacting CP asymmetry carrier. (Higgs compared to quarks)
Ingredients 5 & 6

• Efficient transfer of CP asymmetry to the B-violating sector e.g. MSSM and similar scenarios: top Yukawa
  
  \[ y_b \text{ for } \tan \beta \gtrsim 5 \]
  
  \[ y_\tau \text{ for } \tan \beta \gtrsim 15 \]

  [DC, Garbrecht, Ramsey-Musolf, Tulin, 08,09]

• Strong enough phase transition to prevent wash-out

\[ \Gamma = A(T) \exp \left[ -E_{\text{sph}}(T)/T \right] \rightarrow \frac{v(T_c)}{T_c} \gtrsim 1 \]

Requires O(0.1) parametric tuning/hierarchy

Mass about origin.

\[ T_c \sim \frac{M_{\text{scalar}}}{O(y/5)} \]

\[ M_{\text{scalar}} \ll v \]

Can utilize approximate discrete symmetry to guide parametric tuning.

[DC, Long 10] Pragmatic also for big field space dimension (e.g.8).
Enhanced Symmetry

e.g. 1D

\[ V(\phi, T) \approx \left[ \frac{M^2}{2} + c_1 T^2 \right] \phi^2 - E\phi^3 + \frac{\lambda}{4}\phi^4 \]

At \( T = T_c \)

\[ V(\phi, T_c) = \frac{\phi^2}{4\lambda} (\lambda\phi - 2E)^2 \]

At this temperature there is an enhanced \( \mathbb{Z}_2 \) symmetry:

\[ \phi \rightarrow -\phi + \frac{2E}{\lambda} \]

Choose a parameter to build in this enhanced symmetry at \( T=0 \).

\[ \frac{\langle \phi(T_c) \rangle}{T_c} \rightarrow \infty \]

Ideal parametric point!

Note even in the non-renormalizable operator scenario, there is a symmetry.
BSM ingredients (blue = not generic without singlets; red = tuned):

1) High T; 2) bubbles nucleate; 3) bubble coupling to CPV; 4) efficient diffusion; 5) CP charge $\rightarrow$ quarks + leptons; 6) B-violating sphaleron suppression in broken phase

Not much room: $\alpha_w^6 \times 10^{-1} \sim 10^{-10}$

Maybe enhanced through extra dim?
BSM ingredients (blue = not generic without singlets; red = tuned):

1) High T; 2) bubbles nucleate; 3) bubble coupling to CPV; 4) efficient diffusion;
5) CP charge → quarks + leptons;
6) B-violating sphaleron suppression in broken phase

\[
\frac{n_B}{s} \sim O(10) \alpha_w^5 \times \alpha_p \sin(\delta) f_1 \left( v_w, \frac{\hat{v}}{v^2}, \frac{m_i}{T_c} \right) \times f_2 \left( D_i \Gamma_j, \frac{\Gamma_i}{T_c}, \frac{m_i}{T_c}, v_w \right) \times W \left( \frac{v(T_c)}{T_c} \right) \times \frac{N}{g_*}
\]

\( \alpha_w \) in MSSM

coupled. transport/source calc problem

Light \( m_{\tilde{t}_R} \) for cubic coupling

Higgs mass lower bd

→ large \( m_{\tilde{t}_L} \) → decouple

→ chargino sector

\( W \left( \frac{v(T_c)}{T_c} \right) \) corners parameter spaces.
BSM ingredients (blue = not generic without singlets; red = tuned):

1) High T; 2) bubbles nucleate; 3) bubble coupling to CPV; 4) efficient diffusion; 5) CP charge \rightarrow quarks + leptons;
6) B-violating sphaleron suppression in broken phase

\[ \frac{n_B}{s} \sim O(10) \alpha_w^5 \times \alpha_p \sin(\delta) f_1 \left( v_w, \frac{\dot{v}}{v^2}, \frac{m_i}{T_c} \right) \times f_2 \left( D_i \Gamma_j, \frac{\Gamma_j}{T_c}, \frac{m_i}{T_c}, v_w \right) \times W \left( \frac{v(T_c)}{T_c} \right) \times \frac{N}{g_*} \]

Enlarge param space with singlets [Anderson and Hall 92; Pietroni 93; many others since then]

Nonrenormalizable ops [e.g. Zhang 93; Grojean, Servant, Wells 04; \ldots; Blum, Nir 08]
BSM ingredients (blue = not generic without singlets; red = tuned):

1) High T; 2) bubbles nucleate; 3) bubble coupling to CPV; 4) efficient diffusion; 5) CP charge $\rightarrow$ quarks + leptons; 6) B-violating sphaleron suppression in broken phase

Where the phase occurs allows weaker EDM bounds either through coupling suppression or sector sequestering and/or spontaneous CP violation.

[e.g. recently in sMSSM (4 SM singlets + 2 doublets) Kang, Langacker, Li, Liu 09]
BSM ingredients (blue = not generic without singlets; red = tuned):
1) High T; 2) bubbles nucleate; 3) bubble coupling to CPV; 4) efficient diffusion; 5) CP charge \rightarrow\text{quarks + leptons}; 6) B-violating sphaleron suppression in broken phase

$$\frac{n_B}{s} \sim O(10) \alpha_w^5 \times \alpha_p \sin(\delta) f_1 \left( \frac{v_w}{v^2}, \frac{m_i}{T_c} \right) \times f_2 \left( D_i \Gamma_j, \frac{\Gamma_j}{T_c}, \frac{m_i}{T_c}, v_w \right) \times W \left( \frac{v(T_c)}{T_c} \right) \times \frac{N}{g_*}$$

Picture that emerges:
1) The scalar sector will be non-minimal in either d.o.f. and/or physics.
2) Either by discrete symmetry or accidental cancellation (0.1 tuning)

$$\frac{v(T_c)}{T_c} \gtrsim 1$$

3) CP violation sector is either secluded or we will see EDMs if we continue to push experimental sensitivity.
A popularly discussed source of technical challenges [Riotto 96; Carena, Quiros, Riotto, Vilja, Wagner 97; Carena, Moreno, Quiros, Seco, Wagner 00; Prokopec, Schmidt, Weinstock 01, 03; Kainulainen, Prokopec, Schmidt, Weinstock 01; Konstandin, Prokopec, Schmidt 04; Huber, Konstandin, Prokopec, Schmidt 06; …]
Theoretical Uncertainties

Transport challenges:
1) spatially inhomogeneous
2) out of equilibrium
3) messy thermal kinematics
4) many order 1 effects
5) BSM can have large number of dof

Approximations involve expansions that can be subtle:

\[ \partial_\mu \langle j^\mu (x) \rangle = \int d^4z \left[ \Pi^> (x, z) \Delta^< (z, x) - \Delta^> (x, z) \Pi^< (z, x) + \Delta^< (x, z) \Pi^> (z, x) - \Pi^< (x, z) \Delta^> (z, x) \right] \]

Collisions and mixing

Ideally, want to begin with above

\[ v_w \partial_z n_H - D_R \partial_z^2 n_H = -\Gamma_Y \left( \frac{n_H}{k_H} - \frac{n_t}{k_t} + \frac{n_q}{k_q} \right) + S_{CPV} + ... \]
Theoretical Uncertainties

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Collisions and mixing

Ideally, want to begin with above

approximations sometimes very uncertain

\[ \nu_w \partial_z n_H - D_R \partial^2 z n_H = -\Gamma_Y \left( \frac{n_H}{k_H} - \frac{n_t}{k_t} + \frac{n_q}{k_q} \right) + S_{CPV} + ... \]

e.g. Resonant regime in MSSM
Numerical treatment with fewer approx in a stop sector toy model..

\[
(u \cdot \partial_x + F \cdot \nabla_k) f_m(k, x) = -[i \omega_k + u \cdot \Sigma, f_m(k, x)] + \mathcal{G}_m[f_m, \bar{f}_m](k, x)
\]

\[
[\Sigma, f] = \begin{pmatrix}
\Sigma_{12} f_{21} - \Sigma_{21} f_{12} & -\Sigma_{12} (f_{11} - f_{22}) + (\Sigma_{11} - \Sigma_{22}) f_{12} \\
\Sigma_{21} (f_{11} - f_{22}) - (\Sigma_{11} - \Sigma_{22}) f_{21} & \Sigma_{21} f_{12} - \Sigma_{12} f_{21}
\end{pmatrix}
\]

\[
[\Sigma, f]_{\text{Ref. [9]}} = \begin{pmatrix}
0 & -\Sigma_{12} (n_B(\omega_1) - n_B(\omega_2)) \\
\Sigma_{21} (n_B(\omega_1) - n_B(\omega_2)) & 0
\end{pmatrix} + \mathcal{O}(\varepsilon_{\text{wall}}^2)
\]

\[
\frac{\varepsilon_{\text{wall}}^2}{\varepsilon_{\text{coll}} v_w} \text{ unsuppression due to integration}
\]

\[
\varepsilon_{\text{coll}} \equiv \frac{L_{\text{int}}}{L_f}
\]

\[
\varepsilon_{\text{wall}} \equiv \frac{L_{\text{int}}}{L_w}
\]
FIG. 7: Charge density profiles $n_L(z)$ from the solution of the full equations (solid line) and the approximate decoupled equations (dashed line) that mimic the procedure of Ref. [9]. The left panel correspond to the off-resonance regime $m_L/T = 2.6, m_R/T = 2$, while the right panel corresponds to the resonant regime $m_L/T = 2.2, m_R/T = 2$. 
MSSM still viable based on more approximate treatment.

Figure 1: $\eta/\eta_{BRN}$ as function of $\tan\beta$ for several values of $\mu$ and imposing $\phi(T^0_H)/T^0_H \simeq 1$, $M_1 = M_2 = 200$ GeV, $L_u \simeq 1.7$ and $v_u \simeq 0.1$.

MSSM unlikely to be viable

Although all agree that the window is small, its viability is still unclear.

FIG. 6: This plot shows $\eta_0 = 10^{10}\eta$ as a function of $\mu_c$, $M_2 = \mu_c - 20$ GeV, $m_A = 150$ GeV and for several values of $\tan\beta$. 
EDM Constraints

[Baker et al 06; Griffith et al 09; Hudson et al 11]

\[ |d_{\text{Hg}}| < 2.9 \times 10^{-20} \text{ e cm} \]

\[ |d_{\text{n}}| < 3.5 \times 10^{-26} \text{ e cm} \]

\[ |d_{e}| < 10.5 \times 10^{-28} \]

1.5 improvement

\[ d_e \]

\[ ^{199}\text{Hg} \rightarrow \text{neutron} \]

\[ d_{u,d} \]

\[ d_G \]

\[ d_{u,d} \]

\[ YbF \]

\[ d_{e} \]

\[ d_L \rightarrow d_R \]

\[ e_L \rightarrow e_R \]
One Loop MSSM

BSM such as MSSM has phases in sectors too “close” to the light particles.

\[
\left( \frac{d_{u,d}}{e} \right) \sim 10^{-25} \text{ cm} \quad \frac{\Theta m(M_{\tilde{u},\tilde{d}})}{M_{\tilde{u},\tilde{d}}} \left( \frac{1 \text{ TeV}}{M_{\tilde{u},\tilde{d}}} \right)^2 \left( \frac{m_{u,d}}{10 \text{ MeV}} \right)
\]

[Ellis, Ferrara, Nanopoulos 82; Buchmueller and Wyler 83; Polchinski and Wise 83]

Can make small by taking first two generation sfermion masses large.
2-loops & MSSM Bino

[Barr, Zee (90); Chang, Keung, Pilaftsis (99); Pilaftsis (02)]

\[
de_e \propto \tan \beta, \arg(\mu M_2), \frac{1}{M_a}
\]

[Li, Profumo, Ramsey-Musolf 08] considered the subdominant neutralino contributions.

\[
d_1/d_2 \sim 0.02
\]

B-genesis source term is suppressed less, making the tradeoff a good deal.
NMSSM EDM 2-Loop Analysis

[Cheung, Hou, Lee, Senaha 11]

\[ W_{NMSSM} = \hat{U}^C h_u \hat{Q} \hat{H}_u + \hat{D}^C h_d \hat{H}_d \hat{Q} + \hat{E}^C h_e \hat{H}_d \hat{L} + \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{k}{3} \hat{S}^3 \]

\[ (\phi'_\lambda - \phi'_\kappa) \]

Figure 5: The observable EDMs taking \(|\alpha| = 0.81, |\beta| = 0.08, |A_\lambda| = 575 \text{ GeV}, \text{ and } A_\kappa = 110 \text{ GeV}. \text{ The other parameters are fixed as in Eq. (51)}\]
PT Phenomenon can be correlated

- Electroweak Baryogenesis
- Gravity Waves: Bubble stirs up fluid
- DM: Freeze out physics can be affected
- CC: IR contribution

\[ \delta n_X(t_0) = c_1 \epsilon_1 + c_2 \epsilon_2 + c_{31} \epsilon_{31} + c_{32} \epsilon_{32} + c_4 \epsilon_4 \]

Change in observed DM density

\[ \text{CC} \rightarrow \text{Increases } H \rightarrow \text{Converts into entropy} \]

Has to fight \[ \frac{1}{g^*} \lesssim O(10^{-2}) \]

Same degree of model tuning $\Rightarrow$ $O(1)$ effect

E.g. DM can be used to probe phase transitions [DC, Long, Wang 11]
For this program to work: reconstruct EWSB PT from collider measurements.

A remarkable feat if possible.

\[ U(\phi) \]

\[ \langle \phi_0, \vec{p} | \phi_+, \vec{k} \rangle \propto \lim_{\Omega \to \infty} \exp(-\Omega^n c) = 0 \]

Because Legendre transformation breaks down, no linear source induced shift \( \phi_+ \to \phi_0 \) is possible. Dim 0, 1, 2 UV-IR mixing \( \rightarrow \) ambiguity in tachyonic region

Hence, remarkable if few particle collisions \( \rightarrow \) non-perturbative condensation information

Question: What are the implicit assumptions that are used in the literature and what alternative assumptions might exist? [work in progress]
Conclusions

1) Electroweak Bgenesis predictions:
   a) The scalar sector will be non-minimal either in d.o.f. and/or physics.
   b) There is likely to be a discrete symmetry or an accidental cancellation
      in the scalar sector.
   c) CP violation sector is either secluded or we will see EDMs
      if we continue to push experimental sensitivity. If secluded, richer
      spectrum is likely explaining why we do not see EDMs.

2) CPV source/diffusion computation technology is converging, although still
   incomplete.

3) Reconstructibility of the EWPT without non-perturbative data is not obvious.
   Correlated probes such as DM and gravity waves might provide complementary
   data.