Generic Traits of EWBG-ready BSMs

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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, Kozaczuk, Kuzmin, Laine, Langacker, Lee, Leigh, Linde, Liu, Long, Losada, Menon, Moore, Moorhouse, Moreno, Morrissey, Multamaki, Murayama, Nelson,Nir, No, Olive, Orloff, Oaknin, Pietroni, Quimbay, Quiros, Patel, 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, Wainwright, Westphal, Weinstock, Wells, Worah, Yaffe...

- Some overview references
  - 1302.6713
  - 1206.2942
  - hep-ph/0609145
  - hep-ph/0312378
  - hep-ph/0303065
  - hep-ph/0208043
  - hep-ph/0006119
  - hep-ph/9901362
  - hep-ph/9901312
  - hep-ph/9802240

Important for Cosmology

inflaton ("solves" flatness + horizon + relic; generates density perturbations)

(re)heats (couples to SM)

Moduli oscillate

gravitino

Leptogenesis

Anticipated new landmark

LHC

EWPT

Baryon chemical potential freeze in

WIMP freeze out

Lab + cosmo

QCD PT

axion oscillate

Old landmark

BBN

Neutrinos decouple

Lab + cosmo

matter dominate

CDM clusters

neutral H

Clean, linear

stars reionize

DE dominates

Hot baryons, lensing
More challenging systematic errors (nonlinearities, plasma physics)

Advantages of Electroweak Baryogenesis (EWBG)

- BSM is required
  - Fix small CP violation
  - Fix weak phase transition

- Best testability with TeV era lab experiments

Assuming EWBG gives the observed B-asymmetry, what are the generic features of the BSMs that are readily consistent?

Deconstruction of EWBG:

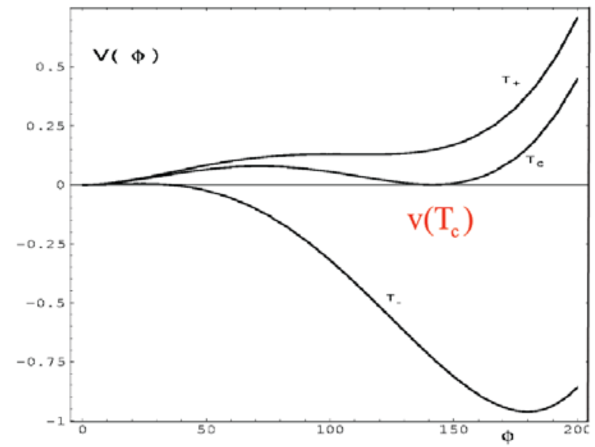
1) High T (B+L)-viol; 2) bubbles nucleate; 3) bubble coupling to CPV;
4) efficient diffusion; 5) CP charge → quarks + leptons;
6) B-violating sphaleron suppression in broken phase

$$\frac{n_B}{s} \sim \overbrace{O(10)\alpha_w^5}^{1} \times \overbrace{\alpha_p \sin(\delta) f_1\left(v_w, \frac{\dot{v}}{v^2}, \frac{m_i}{T_c}\right)}^{2,\,3} \times \overbrace{f_2\left(D_i\Gamma_j, \frac{\Gamma_j}{T_c}, \frac{m_i}{T_c}, v_w\right)}^{4,\,5} \times \overbrace{W\left(\frac{v(T_c)}{T_c}\right)}^{2,\,6} \times \frac{N}{g_*}$$

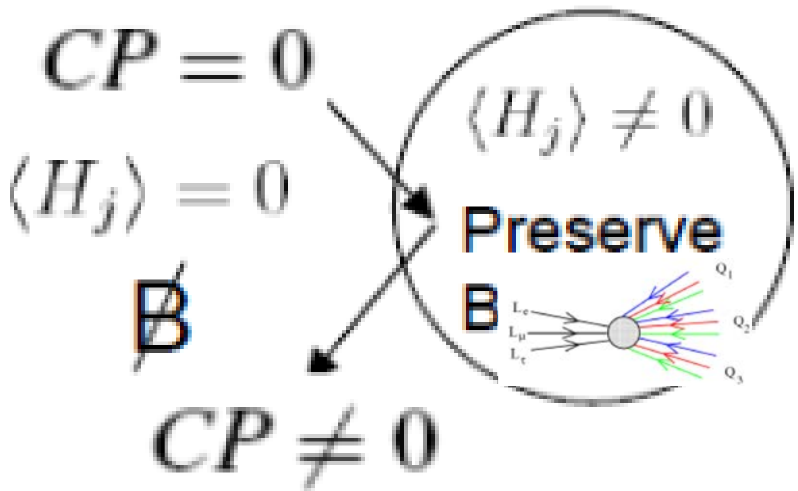
$10^{-10} \sim 10^{-1}\alpha_w^6$ ⟶ Not much room. Need favorable $W\left(\frac{v(T_c)}{T_c}\right) = O(1)$

$$W\left(\frac{v(T_c)}{T_c}\right)$$

$$W\left(\frac{v(T_c)}{T_c}\right)$$



Physics:



1) Bubbles nucleate providing out of equilibrium

2) B preserve: $\frac{v}{T_c} \gtrsim 1$

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

$$\frac{n_B}{s} \sim \underbrace{O(10)\alpha_w^5}_{1} \times \underbrace{\alpha_p \sin(\delta) f_1\left(v_w, \frac{\dot{v}}{v^2}, \frac{m_i}{T_c}\right)}_{2,\,3} \times \underbrace{f_2\left(D_i\Gamma_j, \frac{\Gamma_j}{T_c}, \frac{m_i}{T_c}, v_w\right)}_{4,\,5} \times \underbrace{W\left(\frac{v(T_c)}{T_c}\right)}_{2,\,6} \times \frac{N}{g_*}$$

Cond: $\frac{v}{T_c} \gtrsim 1$

Requires hierarchy in couplings
and/or tuning:
e.g. in SM $\frac{g^3}{6\pi} \gtrsim \lambda$

Incompatible with the Higgs mass

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

Example: $W\left(\frac{v(T_c)}{T_c}\right)$ in MSSM

$$\frac{n_B}{s} \sim \overbrace{O(10)\alpha_w^5}^{1} \times \overbrace{\alpha_p \sin(\delta) f_1\left(v_w, \frac{\dot{v}}{v^2}, \frac{m_i}{T_c}\right)}^{2,\,3} \times \overbrace{f_2\left(D_i\Gamma_j, \frac{\Gamma_j}{T_c}, \frac{m_i}{T_c}, v_w\right)}^{4,\,5} \times \overbrace{W\left(\frac{v(T_c)}{T_c}\right)}^{2,\,6} \times \frac{N}{g_*}$$

Light $m_{\tilde{t}_R}$ for cubic coupling

$$V_{\text{eff}} \ni (-T/12\pi)\left(m^2_{\text{eff}}(h,T)\right)^{3/2}$$

Achieving the right bump for $W\left(\frac{v(T_c)}{T_c}\right)$

- less restrictions/ more scalars: e.g.

  Non-SUSY: more general 2 Higgs doublets satisfying MFV
  [e.g. Cline et al 11]

  SUSY/non-SUSY singlets [e.g. Anderson & Hall 92; Pietroni 93; …; Profumo et al 07; DC & Long 10]

  More scalars → FCNC; EW precision constraints
  (null = worrisome for EWBG with extra scalars)

- nonminmal interactions of SM Higgs: e.g.

  Nonrenormalizable ops
  [e.g. Zhang 93; Grojean, Servant, Wells 04;…; Blum, Nir 08]

Can one more systematically classify BSM's giving favorable $W\left(\frac{v(T_c)}{T_c}\right)$?

A Prediction From "Generic" $W\left(\frac{v(T_c)}{T_c}\right)$

[See Andrew Long's talk and 1209.1819 for more info particularly regarding tuning.]

Thermal Effective Potential Models | Mass Scale Preference

Class I: Thermally (BEC) Driven

New scalars with EW mass scale

$$T_c = \sqrt{\frac{\lambda v^2}{c}}\left[1 - \frac{\lambda}{2c}\left(\frac{e}{6\pi\lambda}\right)^2\right]^{-1/2}$$

Class IIA: Tree-level, renorm op driven

EDSP → new states with EW mass scale

$$m_S^2 = \frac{m_H^2}{4\lambda}(a_2 - 2\lambda)\left(1 - \frac{2\lambda}{a_2 - 2\lambda}\epsilon_{b_2}\right)$$

Class IIB: Tree-level, non-renorm op driven

New states at EW mass scale for 125 GeV Higgs

$$\Lambda < 800\ \mathrm{GeV}$$

Class III: Loop driven

New scalars at EW mass scale

$$-\zeta^2 H^\dagger H \sum_{i=1}^{N} S_i^2$$

Conclusion from $W\left(\frac{v(T_c)}{T_c}\right)$:

BSM has extra states of order EW mass scale coupled appreciably to the Higgs.

Some kind of tuning mechanism seem probable
In this sector (e.g. EDSP – see Andrew Long's talk).

$$\alpha_p \sin(\delta) f_1 \left(v_w, \frac{\dot{v}}{v^2}, \frac{m_i}{T_c} \right)$$

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

$$\frac{n_B}{s} \sim \overbrace{O(10)\alpha_w^5}^{1} \times \overbrace{\alpha_p \sin(\delta) f_1\left(v_w, \frac{\dot{v}}{v^2}, \frac{m_i}{T_c}\right)}^{2,\,3} \times \overbrace{f_2\left(D_i\Gamma_j, \frac{\Gamma_j}{T_c}, \frac{m_i}{T_c}, v_w\right)}^{4,\,5} \times \overbrace{W\left(\frac{v(T_c)}{T_c}\right)}^{2,\,6} \times \frac{N}{g_*}$$

↓

Too small in SM even if Higgs mass were smaller to satisfy $W\left(\frac{v(T_c)}{T_c}\right) = O(1)$

Prediction: New sources of CP violation coupled to the Higgs sector.

Furthermore, since it is heavily constrained by EDMs, it must be sequestered away from the 1^{st} generation leptons/quarks or a delicate tuning must be “enforced.”

[EDM Reviews:e.g. Pospelov, Ritz 05; Ramsey-Musolf, Su 06; Ellis, Lee, Pilaftsis 08]

1) High T (B+L)-viol; 2) bubbles nucleate; 3) bubble coupling to CPV;
4) efficient diffusion; 5) CP charge → quarks + leptons;
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$$\frac{n_B}{s} \sim \overbrace{O(10)\alpha_w^5}^{1} \times \overbrace{\alpha_p \sin(\delta) f_1\left(v_w, \frac{\dot{v}}{v^2}, \frac{m_i}{T_c}\right)}^{2,\,3} \times \overbrace{f_2\left(D_i\Gamma_j, \frac{\Gamma_j}{T_c}, \frac{m_i}{T_c}, v_w\right)}^{4,\,5} \times \overbrace{W\left(\frac{v(T_c)}{T_c}\right)}^{2,\,6} \times \frac{N}{g_*}$$

$$10^{-10} \sim 10^{-1}\alpha_w^6 \longrightarrow \alpha_p \gtrsim \alpha_w$$

Furthermore, since T_c is of the order of EW scale (again, in the absence of tuning), then the new CP violation must come from new fields of the EW scale.

CPV Enhancements May be Achieved Resonantly

[See Chris Lee's talk1106.0747 for more info; see also Carena et al 97]

1) High T (B+L)-viol; 2) bubbles nucleate; 3) bubble coupling to CPV;
4) efficient diffusion; 5) CP charge → quarks + leptons;
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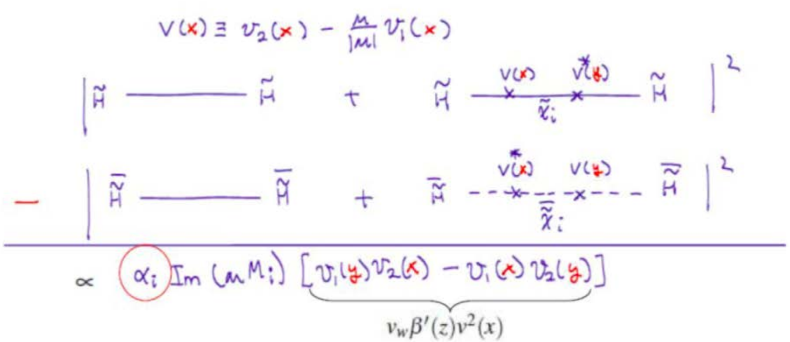
$$\frac{n_B}{s} \sim \underbrace{O(10)\alpha_w^5}_{1} \times \underbrace{\alpha_p \sin(\delta) f_1\left(v_w, \frac{\dot{v}}{v^2}, \frac{m_i}{T_c}\right)}_{2,\,3} \times \underbrace{f_2\left(D_i\Gamma_j, \frac{\Gamma_j}{T_c}, \frac{m_i}{T_c}, v_w\right)}_{4,\,5} \times \underbrace{W\left(\frac{v(T_c)}{T_c}\right)}_{2,\,6} \times \frac{N}{g_*}$$

Can enhance resonantly.



Approximate degeneracy of mass scales → $\frac{T^2}{|m_1^2 - m_2^2|} \sim O(10)$

Conclusion from $\alpha_p \sin(\delta) f_1 \left(v_w, \frac{\dot{v}}{v^2}, \frac{m_i}{T_c} \right)$:

CP violating sector should be appreciably coupled to the Higgs sector and have EW scale masses.

BSMs with degenerate mass spectra in this new CP violating sector are extra favorable for EWBG.

Necessary BSM ingredients

blue = not generic without extra scalars/nonstandard phys;

red = tuned; black = easy in (B)SM and standard cosmo

1) High T (B+L)-viol; 2) bubbles nucleate; 3) bubble coupling to CPV;
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Picture that emerges (i.e. special models are not included):

1) BSM has extra states of order EW mass scale appreciably coupled to the Higgs. Some kind of tuning mechanism built into the model seem probable In this sector (e.g. EDSP – see Andrew Long's talk).
2) A BSM CP violating sector should be appreciably coupled to the Higgs sector and have EW scale masses. BSMs with degenerate mass spectra (again, symmetry opportunity) in this new CP violating sector are extra favorable for EWBG.
3) Lack of hints in FCNC, electroweak precision, and EDMs can be seen as worries or opportunities in the context of EWBG.

[Backup slides]

Given a model, parametric space cornering is correlated.

Necessary BSM ingredients

blue = not generic without extra scalars/nonstandard phys;

red = tuned; black = easy in (B)SM and standard cosmo

1) High T (B+L)-viol; 2) bubbles nucleate; 3) bubble coupling to CPV;
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1 — 2, 3 — 4, 5 — 2, 6

$$\frac{n_B}{s} \sim \underbrace{O(10)\alpha_w^5}_{1} \times \underbrace{\alpha_p \sin(\delta) f_1\left(v_w, \frac{\dot{v}}{v^2}, \frac{m_i}{T_c}\right)}_{2,\,3} \times \underbrace{f_2\left(D_i\Gamma_j, \frac{\Gamma_j}{T_c}, \frac{m_i}{T_c}, v_w\right)}_{4,\,5} \times \underbrace{W\left(\frac{v(T_c)}{T_c}\right)}_{2,\,6} \times \frac{N}{g_*}$$

α_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
→ cannot be stop sector

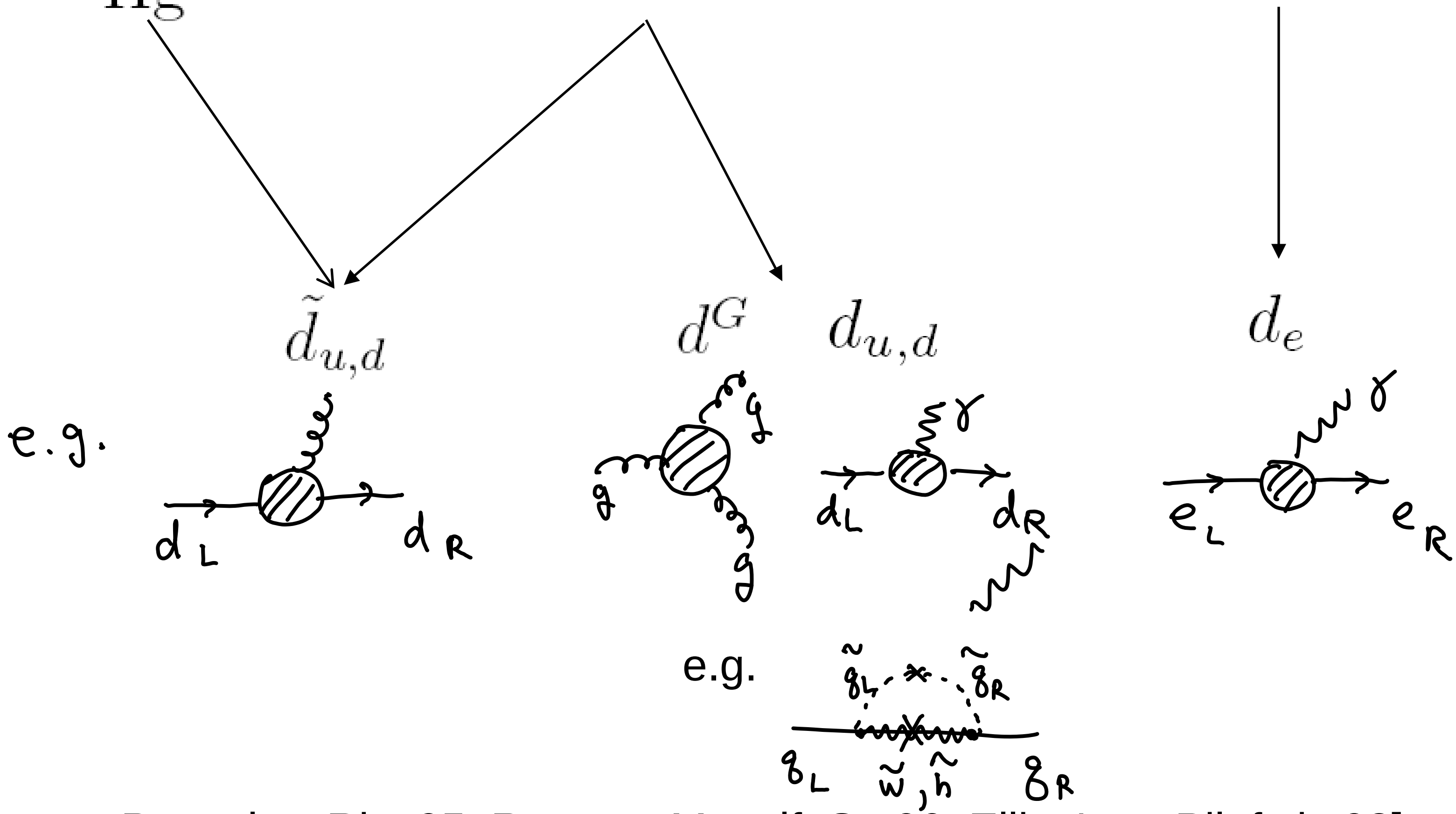
EDM Opportunities

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

1.5 improvement

$|d_{\mathrm{Hg}}| < 2.9 \times 10^{-29}\ e\,\mathrm{cm}$ $\quad$ $|d_n| < 3.5 \times 10^{-26}\ e\,\mathrm{cm}$ $\quad$ $|d_e| < 10.5 \times 10^{-28}$

$^{199}\mathrm{Hg}$ $\quad$ neutron $\quad$ YbF



[Reviews:e.g. Pospelov, Ritz 05; Ramsey-Musolf, Su 06; Ellis, Lee, Pilaftsis 08]

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