Cosmology 3: Electroweak Baryogenesis

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People and References

Nice review: hep-ph/9807454, hep-ph/0609145

An incomplete list of ewbgenesis people:

Ambjorn, Arnold, Bodeker, Brhlik, Carena, Chang, Cirigliano, Cline, Cohen, Davoudiasl, de Carlos, Dine, Dolan, Elmfors, Enqvist, Espinosa, Farrar, Gavela, Giudice, Gleiser, Good, Grasso, Hernandez, Huet, Huber, Jakiw, Jansen, Joyce, Kane, Kainulainen, Kajantie, Kaplan, Keung, Khlebnikov, Klinkhamer, Kolb, Konstandin, Kuzmin, Laine, Lee, Linde, Losada, Moore, Moreno, Multamaki, Murayama, Nelson, Olive, Orloff, Oaknin, Pietroni, Quimbay, Quiros, Pene, Pierce, Prokopec, Profumo, Rajagopal, Ramsey-Musolf, Ringwald, Riotto, Rubakov, Rummukainen, Sather, Schmidt, Seco, Servant, Shaposhnikov, Singleton, Tait, Thomas, Tkachev, Trodden, Tsypin, Tulin, Turok, Vilja, Vischer, Wagner, Westphal, Weinstock, Worah, Yaffe...

Motivation

- In minimal SM, EW phase transition is inevitable!

  $T > T_c \sim m_h$ EW symmetry restoration

- An exciting era:

  probing at LHC (and LC?) its microphysics

  Nearly everything at T_c associated with SM may be measurable

- Almost no cosmological probe to this era
  - baryon asymmetry of the universe
  - Gravity wave generation during EWPT

Basic Baryon Asymmetry Problem

- SM contains nonperturbative baryon number violating operators that erase B+L
- These become efficient when $T > T_c \sim 100\, GeV$

  erases preexisting B+L

- Otherwise, an aesthetic initial condition problem
- Starting from $n_B \equiv n_b - n_{\bar{b}} = 0$ initial conditions

$$6.7 \times 10^{-11} < Y_B < 9.2 \times 10^{-11} \quad (95\%\ \text{C.L.}) \quad \text{BBN [1]}$$

$$8.36 \times 10^{-11} < Y_B < 9.32 \times 10^{-11} \quad (95\%\ \text{C.L.}) \quad \text{CMB [1,2]}$$

[1] W. M. Yao *et al.* [Particle Data Group], J. Phys. G **33** (2006) 1.

[2] J. Dunkley *et al.* [WMAP Collaboration], arXiv:0803.0586 [astro-ph].

Why worry about electroweak baryogenesis scenario instead of leptogenesis?

100 GeV << 10^9 GeV

EW Baryogenesis is physics at 100 GeV – 1 TeV

- Almost everything about it might be probable experimentally
- In SM and MSSM, EW phase transition occurred!
- It is typically not a shock if electroweak baryogenesis gives the right baryon asymmetry in a BSM consistent with the SM.

Sakharov conditions

- Baryon number violation: SU(2) sphaleron

$$O_{B+L} = C \tilde{h}_{L_1} \tilde{h}_{L_2} \widetilde{w}_L^4 \prod_i (q_{L_i} q_{L_i} q_{L_i} l_{L_i})$$

e.g. 1 generation

$$\bar{u}_L \rightarrow d_L d_L \nu_e$$

- CP violation: Many sources beyond SM

e.g. soft SUSY breaking phases

$$\Im(M_2 \mu)$$

Electroweak Phase Transition

Because thermal bath is interacting with Higgs, at T>100 GeV

$$V = V_{T=0} + V_1 + V_{\rm daisy}$$

$$V_1(\phi_{cli};T) = \sum_b g_b f_B\left(\tilde{m}_b^2(\phi_c l);T\right) + \sum_f g_f f_F\left(\tilde{m}_f^2(\phi_c l);T\right)$$

$$f_B(m^2,T) = -\frac{\pi^2}{90}T^4 + \frac{1}{24}m^2T^2 - \frac{1}{12\pi}\left(m^2\right)^{3/2}T - \frac{(m^2)^2}{64\pi^2}\ln\left(\frac{Q^2}{\tilde{a}_B T^2}\right) \qquad m/T < 2.2$$

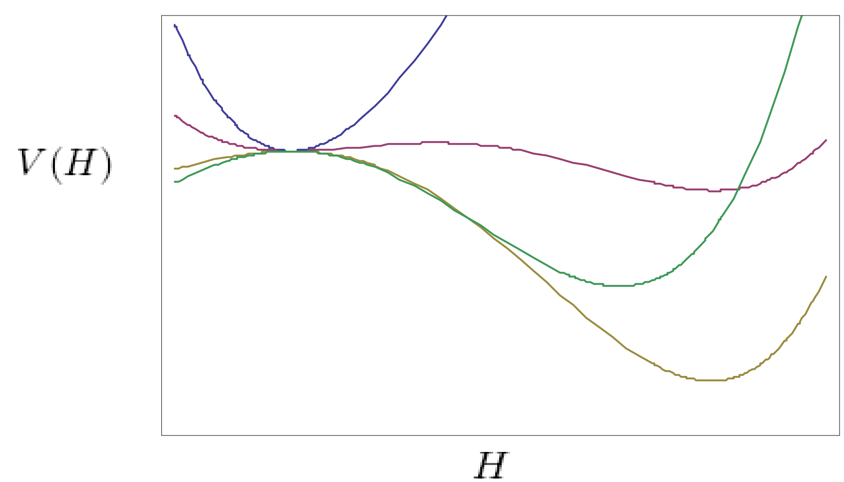
$$f_B(m^2,T) = \frac{(m^2)^2}{64\pi^2}\left[\ln\left(\frac{m^2}{Q^2}\right) - \frac{3}{2}\right] - \left(\frac{m}{2\pi T}\right)^{3/2} T^4 e^{-m/T}\left(1 + \frac{15}{8}T/m + \cdots\right) \qquad m/T > 2.2$$

$$f_F(m^2,T) = -\frac{7\pi^2}{720}T^4 + \frac{1}{48}m^2T^2 + \frac{(m^2)^2}{64\pi^2}\ln\left(\frac{Q^2}{\tilde{a}_F T^2}\right) \qquad m/T < 1.9$$

$$f_F(m^2,T) = -\frac{(m^2)^2}{64\pi^2}\left[\ln\left(\frac{m^2}{Q^2}\right) - \frac{3}{2}\right] - \left(\frac{m}{2\pi T}\right)^{3/2} T^4 e^{-m/T}\left(1 + \frac{15}{8}T/m + \cdots\right) \qquad m/T > 1.9$$

$$V_{daisy} = -\frac{T}{12\pi}\sum g_b\left(\bar{m}_b^2(\phi_{cl};T) - \tilde{m}_b^2(\phi_{cl})\right)$$

$$V(H) = D(T^2 - T_0^2)H^2 - ETH^3 + \frac{\lambda(T)}{4}H^4$$



e.g. MSSM:

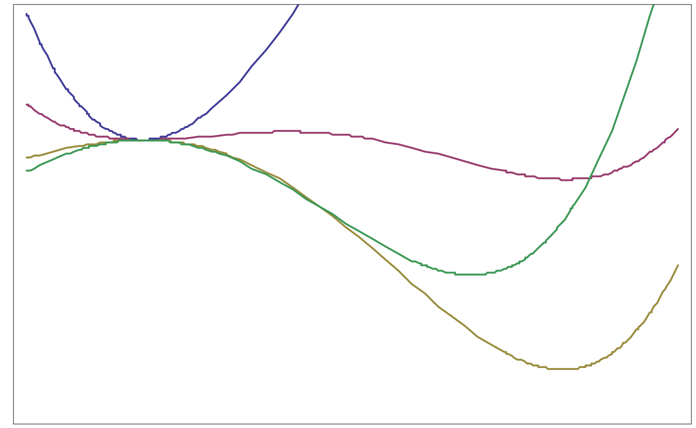
$$m_{\tilde{t}}^2 \simeq m_U^2 + 0.15 M_Z^2 \cos 2\beta + m_t^2\left(1 - \frac{\widetilde{A}_t^2}{m_Q^2}\right)$$

$$E \simeq E_{\rm SM} + \frac{h_t^3 \sin^3\beta\left(1 - \widetilde{A}_t^2/m_Q^2\right)^{3/2}}{4\sqrt{2}\pi}$$

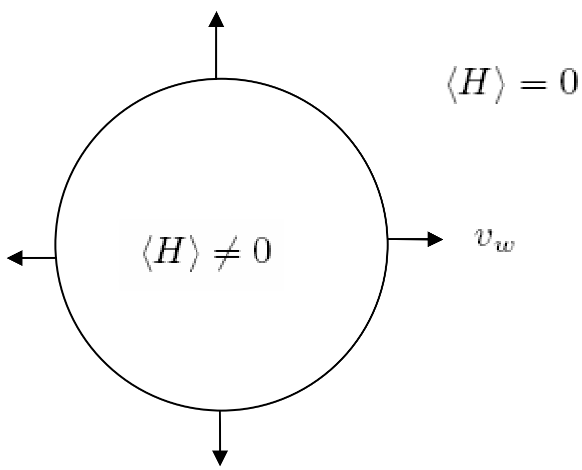
M. Carena, M. Quiros and C.E.M. Wagner, *Phys. Lett.* **B380** (1996) 81

$$\Gamma(t) = A(t)e^{-S(t)}$$

$$S_3 = \int 4\pi r^2 dr \left[\frac{1}{2}\left(\frac{d\phi_b}{dr}\right)^2 + V(\phi_b, T)\right]$$



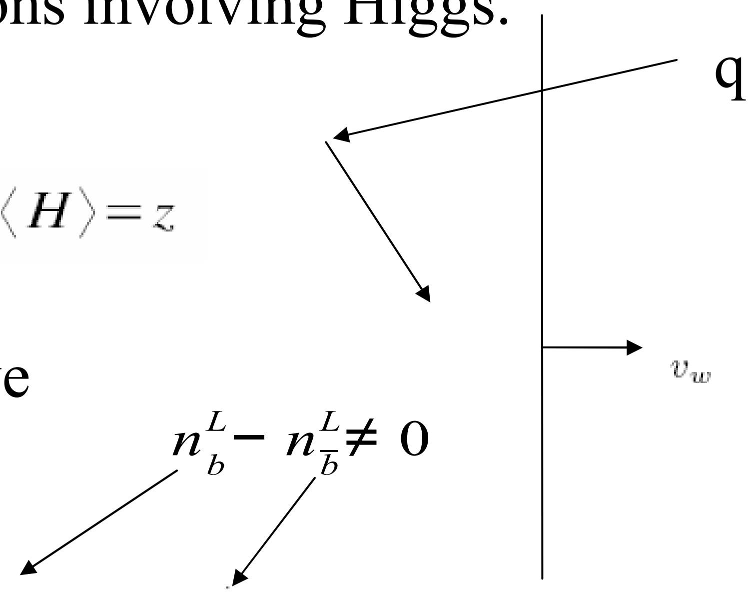
$$\frac{d^2\phi_b}{dr^2} + \frac{2}{r}\frac{d\phi_b}{dr} - \frac{\partial V}{\partial \phi_b} = 0, \quad \text{with} \quad \left.\frac{d\phi_b}{dr}\right|_{r=0} = 0 \ \text{ and } \ \phi_b|_{r=\infty} = 0$$



Bubble collisions may even generate observable gravity waves.

EW B creation step 1

1. Pick up CP/chiral asymmetry through mixing or interactions involving Higgs.



$\langle H \rangle = z$

$\langle H \rangle = 0$

sphalerons inactive

$n_b^L - n_{\bar{b}}^L \neq 0$

sphalerons active

$n_b - n_{\bar{b}} = n_b^L + n_b^R - n_{\bar{b}}^L - n_{\bar{b}}^R = 0$

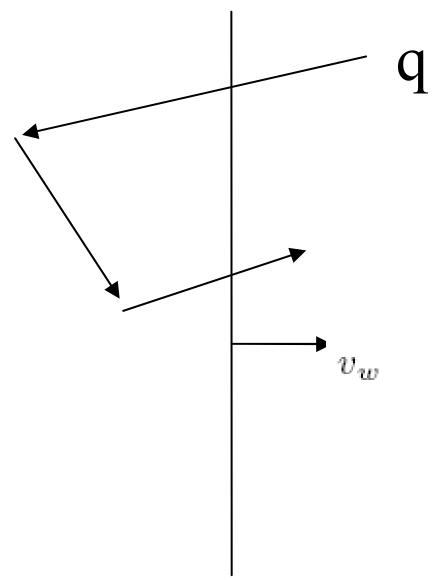
e.g. 1 generation

$\bar{u}_L u_R$ $\quad\quad$ $B = 0$

EW B creation step 2

2. Diffuse out to front of bubble wall.

$\langle H \rangle = z$



$\langle H \rangle = 0$

sphalerons active

$\Delta(n_b^L - n_{\bar{b}}^L)$

sphalerons inactive

$$n_b - n_{\bar{b}} = n_b^L + n_b^R - n_{\bar{b}}^L - n_{\bar{b}}^R \neq 0$$

e.g. 1 generation

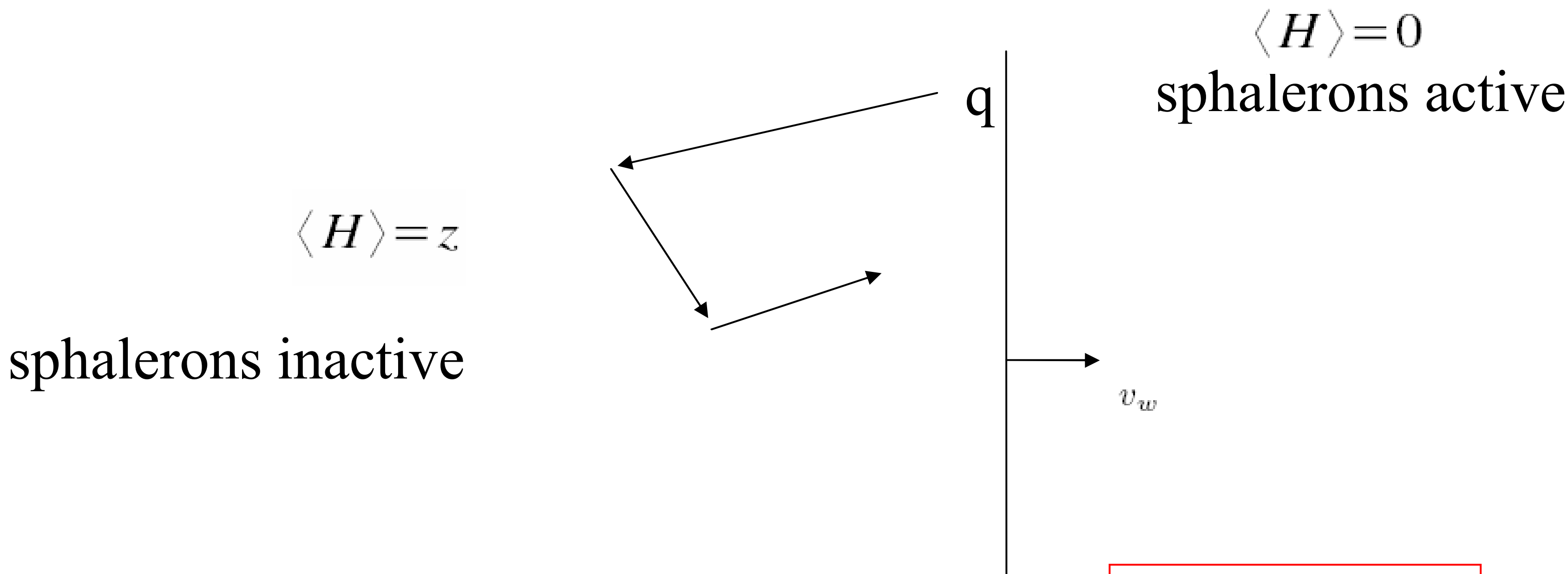
$u_R \to u_R$

$\bar{u}_L \to d_L d_L \nu_e$ $\qquad B=1$

$\quad \hookrightarrow \overline{u_L}\,\overline{d_L}\,\overline{\nu_e}$ $\qquad B=0$

EW B creation step 3

3. Preserver CP asymmetry as bubble wall passes over.



Prevents washout.

$$n_b - n_{\bar{b}} = n_b^L + n_b^R - n_{\bar{b}}^L - n_{\bar{b}}^R \neq 0$$

Phenomenological Viability

- Strong first order phase transition typically requires light scalars
  - Washout constraint on Higgs sector:

$$\frac{\varphi_c}{T_c} \gtrsim 1$$

φ_c stays close to zero temperature vev and T_c stays close to Higgs mass

  - Finite temperature corrections that enhance phase transitions decouple if masses are heavier than T_c
  - Fermion 1-loop finite temperature effects do not directly give cubic terms.
- Non-observation of EDMs constrain CP violation.
  - MSSM is practically ruled out because of this
  - Spontaneous CP violations help, but may not be measureable in lab

Most people would not be surprised if EW bgenesis were correct.

What Have Some People Been Up to Lately Regarding This?

- Better understanding collider implications of strongly first order phase transition in singlet scalar extensions of the SM [0705.2425,0711.3018].
- More complete search for phase transition possibilities in theories with singlets [hep-ph/0701145].
- Effects of inhomogeneities on phase transition rate. [0708.3844].
- EDM bounds on dimension 6 operator enhancements of CP violation [hep-ph/0610003].
- Bubble wall reanalysis in nMSSM [hep-ph/0606298].
- Improvements on two Higgs doublet model analysis [hep-ph/0605242].
- Improve transport equations [hep-ph/0603058].
- Improved global parameter constraints for MSSM [hep-ph/0603246].
- Improved Boltzmann transport treatment [C., Garbrecht, Tulin, Ramsey-Musolf 08]

Attend SUSY08 talk by Garbrecht and Tulin.

Are We Theoretically Ready to Compare Data with Cosmology if We are Lucky with LHC?

"Even an order of magnitude estimate of the baryonic asymmetry in this particular mechanism is a very difficult task, due to a poor knowledge of many high temperature effects." - Shaposhnikov 1994

Even in the last 7 years there have been revisions of baryon asymmetry numbers exceeding 100.

Why Complicated?

- Lorentz-noninvariant physics
  - Finite temperature.
  - Spatial inhomogeneity of the bubble wall.
  - Time translation broken by expanding bubble wall.
- Non-perturbative physics
  - Weak and strong sphalerons
  - Bubble nucleation and percolation
- Many body effects
  - Back reaction due to bubble interactions with plasma
  - Standard model embeddings have many different types of particles in the plasma.

Simulations will in general be invaluable for bubble properties.

Transport may be handled largely semi-analytically.

Typical Computational Steps

- Diffusion equations for (s)quarks and higgs(inos): relatively fast process relative to the weak sphaleron
- Hence, solve for SU(2) charged left handed fermions without baryon number violation.
- Integrate weak sphaleron transition diffusion equation sourced by the solution to above.

Diffusion Equations

Some reasons people give for using the real time formalism:
- Quantities of interest in cosmology are in-in expectation values.
- Spacetime dependent background can introduces non-adiabaticity (breaks the assumption of adiabatic turn-on/off function for S-matrix)
- In principle, allows one to deal with out of equilibrium nearly thermal multiparticle dynamics more easily.

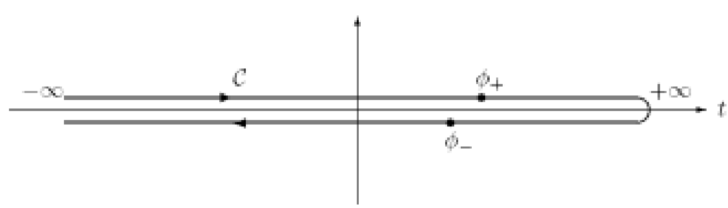
(caveat: Many calculable situations reduce to semiclassical kinetic eq.)

[reviewed in **Phys.Rept.118:1,1985**, hep-ph/9807454, hep-ph/0507111, hep-ph/9803357]

$$S_{\rm int} = T\exp\left(i\int d^4x\,\mathcal{L}_{\rm int}\right) \qquad \langle n|\mathcal{O}|n\rangle = \langle n|S^\dagger_{int}\mathcal{T}\{\mathcal{O}_{int}S_{int}\}|n\rangle$$

$$\widetilde{G}(x,y) = \begin{pmatrix} G^t(x,y) & -G^<(x,y) \\ G^>(x,y) & -G^{\bar{t}}(x,y) \end{pmatrix}$$

$$\begin{aligned}
G^{++}(x,y) &\equiv G^t(x,y) = \langle T\left[\phi(x)\phi^\dagger(y)\right]\rangle \\
G^{+-}(x,y) &\equiv G^<(x,y) = \langle\phi^\dagger(y)\phi(x)\rangle \\
G^{-+}(x,y) &\equiv G^>(x,y) = \langle\phi(x)\phi^\dagger(y)\rangle \\
G^{--}(x,y) &\equiv G^{\bar{t}}(x,y) = \langle\bar{T}\left[\phi(x)\phi^\dagger(y)\right]\rangle
\end{aligned}$$



Since $j^\mu_\phi(x) = i\langle :\phi^\dagger(x)\overleftrightarrow{\partial}_\mu\phi(x):\rangle \equiv (n_\phi(x), \mathbf{j}_\phi(x))$

Green's function contains current info: $(\partial^\mu_x - \partial^\mu_y)G^<(x,y)\big|_{x=y\equiv X} = -ij^\mu_\phi(X)$

Schwinger-Dyson:

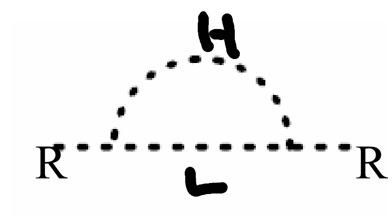
$$\widetilde{G}(x,y) = \widetilde{G}^0(x,y) + \int d^4w \int d^4z\ \widetilde{G}^0(x,w)\widetilde{\Sigma}(w,z)\widetilde{G}(z,y)$$

$$\widetilde{G}(x,y) = \widetilde{G}^0(x,y) + \int d^4w \int d^4z\ \widetilde{G}(x,w)\widetilde{\Sigma}(w,z)\widetilde{G}^0(z,y)$$

$$\frac{\partial n_\phi}{\partial X_0} + \nabla\cdot\mathbf{j}_\phi(X) = \int d^3z \int_{-\infty}^{X_0} dz_0\ \Big[\Sigma^>(X,z)G^<(z,X) - G^>(X,z)\Sigma^<(z,X) + G^<(X,z)\Sigma^>(z,X) - \Sigma^<(X,z)G^>(z,X)\Big]$$

Example: [hep-ph/0603058]

$$\mathcal{L}_{\rm int} = \lambda_s A_s \phi_L \phi_R^* \phi_H + \text{h.c.}$$



$$\Sigma_R^{>,<}(x,y) = -|\lambda_s A_s|^2\, G_L^{>,<}(x,y)\, G_H^{>,<}(x,y)$$

$$G_i^>(x,y) = \int \frac{d^4k}{(2\pi)^4} e^{-ik\cdot(x-y)}\Big[1 + f_B(k_0,\mu_i)\Big]\ \rho_i(k_0,\mathbf{k})$$

$$G_i^<(x,y) = \int \frac{d^4k}{(2\pi)^4} e^{-ik\cdot(x-y)} f_B(k_0,\mu_i)\ \rho_i(k_0,\mathbf{k})$$

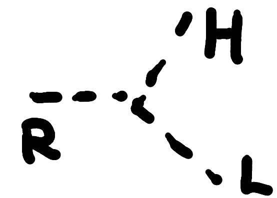
$$\rho_i(k_0,\mathbf{k}) = \pi/\omega_\mathbf{k}\left[\delta(k^0-\omega_\mathbf{k}) - \delta(k^0+\omega_\mathbf{k})\right]$$

$$\omega_\mathbf{k} = \sqrt{|\mathbf{k}|^2 + m^2}$$

$$f_B(k_0,\mu_i) \approx \frac{1}{\exp[(k_0-\mu_i)/T] - 1}$$

← Back in thermal equilibrium limit.

Here, it reduces to computing thermally averaged



Use (or derive) Fick's law: $\vec{j}_R = -D\vec{\nabla} n_R$

Assume a planar bubble wall profile varying in the z direction + assume Moving in with a constant bubble wall velocity v_w: $n_R(\bar{z}) = n_R(z + v_w t)$

$$v_w n'_R(\bar{z}) - D n''_R(\bar{z}) = \underbrace{-\Gamma\left(\frac{n_R(\bar{z})}{k_R} - \frac{n_L(\bar{z})}{k_L} - \frac{n_H(\bar{z})}{k_H}\right)}_{\text{"Source term"}}$$

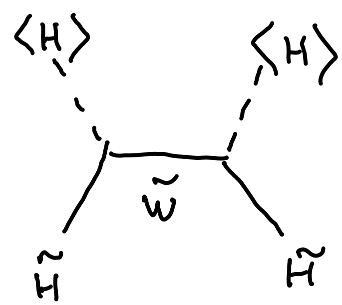
$$n_X = \frac{T^2}{6} k\left(\frac{m_X}{T}\right)\mu$$

$$k_i(m_i/T) = k_i(0)\,\frac{c_{F,B}}{\pi^2}\int_{m_i/T}^{\infty} dx\,x\,\frac{e^x}{(e^x \pm 1)^2}\sqrt{x^2 - m_i^2/T^2}$$

$$c_{F\,(B)} = 6(3)$$

$$\Gamma \equiv -\frac{3|A_s|^2}{8\pi^3 T^3}\int_{m_R}^{\infty} d\omega_R \int_{\omega_L^-}^{\omega_L^+} d\omega_L \{n_B(\omega_R)(1 + n_B(\omega_L))n_B(\omega_L - \omega_R)[\Theta(m_R - (m_H + m_L)) - \Theta(m_L - (m_R + m_H))] - n_B(\omega_L)n_B(\omega_R)(1 + n_B(\omega_L + \omega_R))\Theta(m_H - (m_L + m_R))\}$$

A favourite CP violating source for MSSM:



Calcuated in the leading approximation in Higgs vev insertion.

$$\Gamma_{\tilde G} \sim 0.3 \frac{|m^2_{\tilde G} + m^2_Q - m^2_{\tilde Q}|}{T} \exp\{\frac{-\max(m_Q, m_{\tilde G}, m_{\tilde Q})}{T}\}$$

$$\Gamma_{\tilde V} \sim 10^{-2} \frac{|m^2_{\tilde H} + m^2_{\tilde W} - m^2_H|}{T} \exp\{\frac{-\max(m_{\tilde H}, m_{\tilde W}, m_H)}{T}\}$$

$$\Gamma_Y(\tilde t_R, \tilde Q_L, H_2) \sim \frac{0.07}{T} |y_t|^2 |A_t|^2 \exp(-\max[m_{\tilde t_R}, m_{\tilde t_L}, m_{H_2}]/T)$$

$$\partial_\mu \widetilde{q}^\mu \;=\; -\Gamma_Y^{(\widetilde{t},\widetilde{q},H_1)} \left(\frac{\widetilde{q}}{k_{\widetilde{q}}} - \frac{\widetilde{t}}{k_{\widetilde{t}}} + \frac{H_1}{k_{H_1}}\right) + \ldots$$

$$\tau_{\rm diff} \equiv \frac{\bar D}{v_w^2} \qquad \tau_{chem\ equil} = \left(\frac{\Gamma_Y^{(\tilde t, \tilde q, H_1)}}{k_{\tilde q}}\right)^{-1}$$

$$k_i(m_i/T) = k_i(0) \frac{c_{F,B}}{\pi^2} \int_{m_i/T}^{\infty} dx\, x \frac{e^x}{(e^x \pm 1)^2} \sqrt{x^2 - m_i^2/T^2}$$

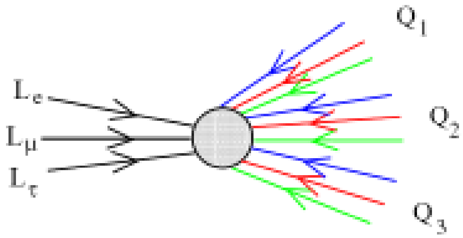
$$c_{F\,(B)} = 6(3)$$

If $\tau_{chem\ equil} = \left(\frac{\Gamma_Y^{(\tilde t, \tilde q, H_1)}}{k_{\tilde q}}\right)^{-1}$ system the quantities in parantheses vanishes.

$$\begin{aligned}
\partial_\mu t^\mu &= -\Gamma_M^{(t_R,q)} \left(\frac{t}{k_t} - \frac{q}{k_q}\right) - \Gamma_Y^{(t,q,H_1)} \left(\frac{t}{k_t} - \frac{q}{k_q} - \frac{H_1}{k_{H_1}}\right) - \Gamma_{\widetilde V}^{(t,\widetilde t)} \left(\frac{t}{k_t} - \frac{\widetilde t}{k_{\widetilde t}}\right) \\
&\quad -\Gamma_Y^{(t,q,H_2)} \left(\frac{t}{k_t} - \frac{q}{k_q} - \frac{H_2}{k_{H_2}}\right) - \Gamma_Y^{(t,\widetilde q,\widetilde H)} \left(\frac{t}{k_t} - \frac{\widetilde q}{k_{\widetilde q}} - \frac{\widetilde H}{k_{\widetilde H}}\right) + \Gamma_{\rm ss} N_5 \\
\partial_\mu \widetilde t^\mu &= -\Gamma_Y^{(\widetilde t,\widetilde q,H_1)} \left(\frac{\widetilde t}{k_{\widetilde t}} - \frac{\widetilde q}{k_{\widetilde q}} - \frac{H_1}{k_{H_1}}\right) - \Gamma_Y^{(\widetilde t,\widetilde q,H_2)} \left(\frac{\widetilde t}{k_{\widetilde t}} - \frac{\widetilde q}{k_{\widetilde q}} - \frac{H_2}{k_{H_2}}\right) + S_{\widetilde t}^{\not{CP}} \\
&\quad -\Gamma_Y^{(\widetilde t,q,\widetilde H)} \left(\frac{\widetilde t}{k_{\widetilde t}} - \frac{q}{k_q} - \frac{\widetilde H}{k_{\widetilde H}}\right) - \Gamma_{\widetilde V}^{(t,\widetilde t)} \left(\frac{\widetilde t}{k_{\widetilde t}} - \frac{t}{k_t}\right) - \Gamma_M^{(\widetilde t,\widetilde q)} \left(\frac{\widetilde t}{k_{\widetilde t}} - \frac{\widetilde q}{k_{\widetilde q}}\right) \\
\partial_\mu q^\mu &= -\Gamma_M^{(t_R,q)} \left(\frac{q}{k_q} - \frac{t}{k_t}\right) - \Gamma_Y^{(t,q,H_1)} \left(\frac{q}{k_q} - \frac{t}{k_t} + \frac{H_1}{k_{H_1}}\right) - \Gamma_{\widetilde V}^{(q,\widetilde q)} \left(\frac{q}{k_q} - \frac{\widetilde q}{k_{\widetilde q}}\right) \\
&\quad -\Gamma_Y^{(t,q,H_2)} \left(\frac{q}{k_q} - \frac{t}{k_t} + \frac{H_2}{k_{H_2}}\right) - \Gamma_Y^{(\widetilde t_R,q,\widetilde H)} \left(\frac{q}{k_q} - \frac{\widetilde t}{k_{\widetilde t}} + \frac{\widetilde H}{k_{\widetilde H}}\right) - 2\,\Gamma_{\rm ss} N_5 \\
\partial_\mu \widetilde q^\mu &= -\Gamma_Y^{(\widetilde t,\widetilde q,H_1)} \left(\frac{\widetilde q}{k_{\widetilde q}} - \frac{\widetilde t}{k_{\widetilde t}} + \frac{H_1}{k_{H_1}}\right) - \Gamma_Y^{(\widetilde t_R,\widetilde q,H_2)} \left(\frac{\widetilde q}{k_{\widetilde q}} - \frac{\widetilde t}{k_{\widetilde t}} + \frac{H_2}{k_{H_2}}\right) - S_{\widetilde t}^{\not{CP}} \\
&\quad -\Gamma_Y^{(t,\widetilde q,\widetilde H)} \left(\frac{\widetilde q}{k_{\widetilde q}} - \frac{t}{k_t} + \frac{\widetilde H}{k_{\widetilde H}}\right) - \Gamma_{\widetilde V}^{(q,\widetilde q)} \left(\frac{\widetilde q}{k_{\widetilde q}} - \frac{q}{k_q}\right) - \Gamma_M^{(\widetilde t,\widetilde q)} \left(\frac{\widetilde q}{k_{\widetilde q}} - \frac{\widetilde t}{k_{\widetilde t}}\right) \\
\partial_\mu H_i^\mu &= -\Gamma_Y^{(t_R,q,H_i)} \left(\frac{H_i}{k_{H_i}} - \frac{t}{k_t} + \frac{q}{k_q}\right) - \Gamma_Y^{(\widetilde t_R,\widetilde q,H_{1,2})} \left(\frac{H_i}{k_{H_i}} - \frac{\widetilde t}{k_{\widetilde t}} + \frac{\widetilde q}{k_{\widetilde q}}\right) \\
&\quad -\Gamma_{\widetilde V}^{(H_i,\widetilde H)} \left(\frac{H_i}{k_{H_i}} - \frac{\widetilde H}{k_{\widetilde H}}\right) - \Gamma_H^{(H_1,H_2)} \left(\frac{H_i}{k_{H_i}}\right)\,, \qquad i=1,2 \\
\partial_\mu \widetilde H^\mu &= -\Gamma_H^{(\widetilde H,\widetilde V)} \left(\frac{\widetilde H}{k_{\widetilde H}}\right) - \Gamma_Y^{(t,\widetilde q,\widetilde H)} \left(\frac{\widetilde H}{k_{\widetilde H}} - \frac{t}{k_t} + \frac{\widetilde q}{k_{\widetilde q}}\right) - \Gamma_Y^{(\widetilde t,q,\widetilde H)} \left(\frac{\widetilde H}{k_{\widetilde H}} - \frac{\widetilde t}{k_{\widetilde t}} + \frac{q}{k_q}\right) \\
&\quad -\Gamma_{\widetilde V}^{(H_1,\widetilde H)} \left(\frac{\widetilde H}{k_{\widetilde H}} - \frac{H_1}{k_{H_1}}\right) - \Gamma_{\widetilde V}^{(H_2,\widetilde H)} \left(\frac{\widetilde H}{k_{\widetilde H}} - \frac{H_2}{k_{H_2}}\right) + S_{\widetilde H}^{\not{CP}} \\
\partial_\mu q_i^\mu &= -\Gamma_{\widetilde V}^{(q_i,\widetilde q_i)} \left(\frac{q_i}{k_{q_i}} - \frac{\widetilde q_i}{k_{\widetilde q_i}}\right) - 2\,\Gamma_{\rm ss} N_5\,, \qquad i=1,2 \\
\partial_\mu \widetilde q_i^\mu &= -\Gamma_{\widetilde V}^{(q_i,\widetilde q_i)} \left(\frac{\widetilde q_i}{k_{\widetilde q_i}} - \frac{q_i}{k_{q_i}}\right)\,, \qquad i=1,2 \\
\partial_\mu u_i^\mu &= -\Gamma_{\widetilde V}^{(u_i,\widetilde u_i)} \left(\frac{u_i}{k_{u_i}} - \frac{\widetilde u_i}{k_{\widetilde u_i}}\right) + \Gamma_{\rm ss} N_5\,, \qquad i=1,2 \\
\partial_\mu \widetilde u_i^\mu &= -\Gamma_{\widetilde V}^{(u_i,\widetilde u_i)} \left(\frac{\widetilde u_i}{k_{\widetilde u_i}} - \frac{u_i}{k_{u_i}}\right)\,, \qquad i=1,2 \\
\partial_\mu d_i^\mu &= -\Gamma_{\widetilde V}^{(d_i,\widetilde d_i)} \left(\frac{d_i}{k_{d_i}} - \frac{\widetilde d_i}{k_{\widetilde d_i}}\right) + \Gamma_{\rm ss} N_5 \qquad i=1,2,3 \\
\partial_\mu \widetilde d_i^\mu &= -\Gamma_{\widetilde V}^{(d_i,\widetilde d_i)} \left(\frac{\widetilde d_i}{k_{\widetilde d_i}} - \frac{d_i}{k_{d_i}}\right) \qquad i=1,2,3\,.
\end{aligned}$$

Sphaleron/Baryon Number Violation

B+L violated in the SM by $F\tilde{F}_{\mathrm{SU}(2)}$:



$$\partial_\mu J^\mu_{B_L+L_L} = \frac{3g^2}{32\pi^2}\epsilon_{\mu\nu\alpha\beta}F^{\alpha\beta}_{(a)}F^{\mu\nu}_{(a)}$$

Unbroken phase (lattice computation):

$$\frac{\Gamma}{V} = (25.4 \pm 2.0)\alpha_w^5 T^4 = (1.06 \pm 0.08) \times 10^{-6} T^4$$

D. Bodeker, G. D. Moore and K. Rummukainen, "Chern-Simons number diffusion and hard thermal loops on the lattice," Phys. Rev. D **61**, 056003 (2000) [arXiv:hep-ph/9907545].

Broken phase: Transitions are dominated by path integral contributions from unstable classical configurations which can be thermally excited.

e.g. in SM: $(D_j F_{ij})^a = -\frac{1}{2} ig \left[\phi^\dagger \sigma^a D_i \phi - (D_i\phi)^\dagger \sigma^a \phi\right]$

$$D_i D_i \phi = \frac{\partial V(\phi)}{\partial \phi^\dagger} = 2\lambda(\phi^\dagger\phi - \frac{1}{2}v^2)\phi$$

B.C. controls the interpolation between vacua with different B+L

$$W_i^a \sigma^a dx^i = -\frac{2i}{g} f(gvr) dU^\infty (U^\infty)^{-1} \qquad \phi = \frac{v}{\sqrt{2}} h(gvr) U^\infty \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$h(\xi \to 0) \to 0 \qquad h(\xi \to \infty) = 1$$
$$f(\xi \to 0) \to 0 \qquad f(\xi \to \infty) = 1$$

$$U^\infty = \frac{1}{r}\begin{pmatrix} z & x+iy \\ -x+iy & z \end{pmatrix}$$

$$\delta N_{\mathrm{CS}} = \frac{1}{24\pi^2}\int d^3x \,\mathrm{Tr}\left[(\partial_i U)U^{-1}(\partial_j U)U^{-1}(\partial_k U)U^{-1}\right]\epsilon^{ijk} \rightarrow \delta N_{CS} = 1$$

$$\frac{\Gamma}{V} \sim 2.8 \times 10^5 T^4 \left(\frac{\alpha_W}{4\pi}\right)^4 \kappa \frac{\zeta^7}{B^7} e^{-\zeta}$$

$$\zeta = E_{sph}(T)/T, \; 10^{-4} \leq \kappa \leq 10^{-1}$$

B is a radiative correction factor.

Prevention of washout: $\frac{E_{\rm sph}(T_c)}{T_c} \gtrsim 45$ for $\kappa = 10^{-1}$

L. Carson, Xu Li, L. McLerran and R.-T. Wang, *Phys. Rev.* **D42** (1990) 2127.

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

Example: $V_T(\phi) \approx (-\frac{1}{2}\mu^2 + c_1 T^2)\phi^2 + (E + FT)\phi^3 + \frac{\lambda}{4}\phi^4$

$$\frac{v(T_c)}{T_c} \approx \frac{\sqrt{c_1}x}{\sqrt{\lambda}\sqrt{1+x^2}} + \frac{F}{\lambda(1+x^2)}$$

$$x \equiv \frac{\sqrt{2}E}{\mu\sqrt{\lambda}}$$

If we take $v_0 \sim \frac{m_H}{\sqrt{\lambda}}$

$$\frac{v(T_c)}{T_c} \approx \frac{v_0\sqrt{c_1}x}{m_H\sqrt{1+x^2}} + \frac{v_0^2 F}{m_H^2(1+x^2)}$$ and $$x \sim \frac{v_0\sqrt{2}E}{m_H^2}$$

Hence, if $E \ll v_0$ and $F \ll 1$, we need $m_H \ll v_0$ to obtain a sizeable v/T_c.

$$D\partial_z^2 n_B(z) - v_w \partial_z n_B(z) = \theta(-z)\left(\frac{3T^2\mu_L^{\rm diff}(z)}{4} + \frac{24}{7}n_B(z)\right)\Gamma_{ws} \qquad \Gamma_{ws} \sim 6 \times 10^{-6} T$$

$\mu_L^{\rm diff}$ = Sum of all the chemical potentials solved through the baryon numberconserving diffusion equation.

In the MSSM

$120\,GeV < m_{\tilde{t}_R} < m_t$

$0.2\, m_Q \leq A_t \leq 0.4\, m_Q$

$m_h < 115\,GeV$

$\tan\beta > 4$

$m_Q > 1\,TeV$

$\mu\,,\, M_{1,2} < m_Q$

$\Im[\mu\, M_{1,2}]/T_c^2 > 0.05$

$\mu\,,\, M_{1,2} < 2\,T_c$

- strong enough phase transition
- charge and color breaking minima
- if $m_h > 114\,GeV$ (suggestive)
- sufficient diffusion
- sufficient CP violation
- sufficient density processed by the sphaleron

MSSM almost ruled out by EDM constraints:

experimental EDM bounds

Sensitive to $\Im(M_2\mu)$

$|d_e| < 1.6 \times 10^{-27}\ e\ cm$ [Regan et al 2002] [Chang et al., 2002]

$|d_n| < 12 \times 10^{-26}\ e\ cm$ [Lamoreaux et al 2002]

$|d_{Hg}| < 2.33 \times 10^{-28}\ e\ cm$ [Romalis et al 2001]

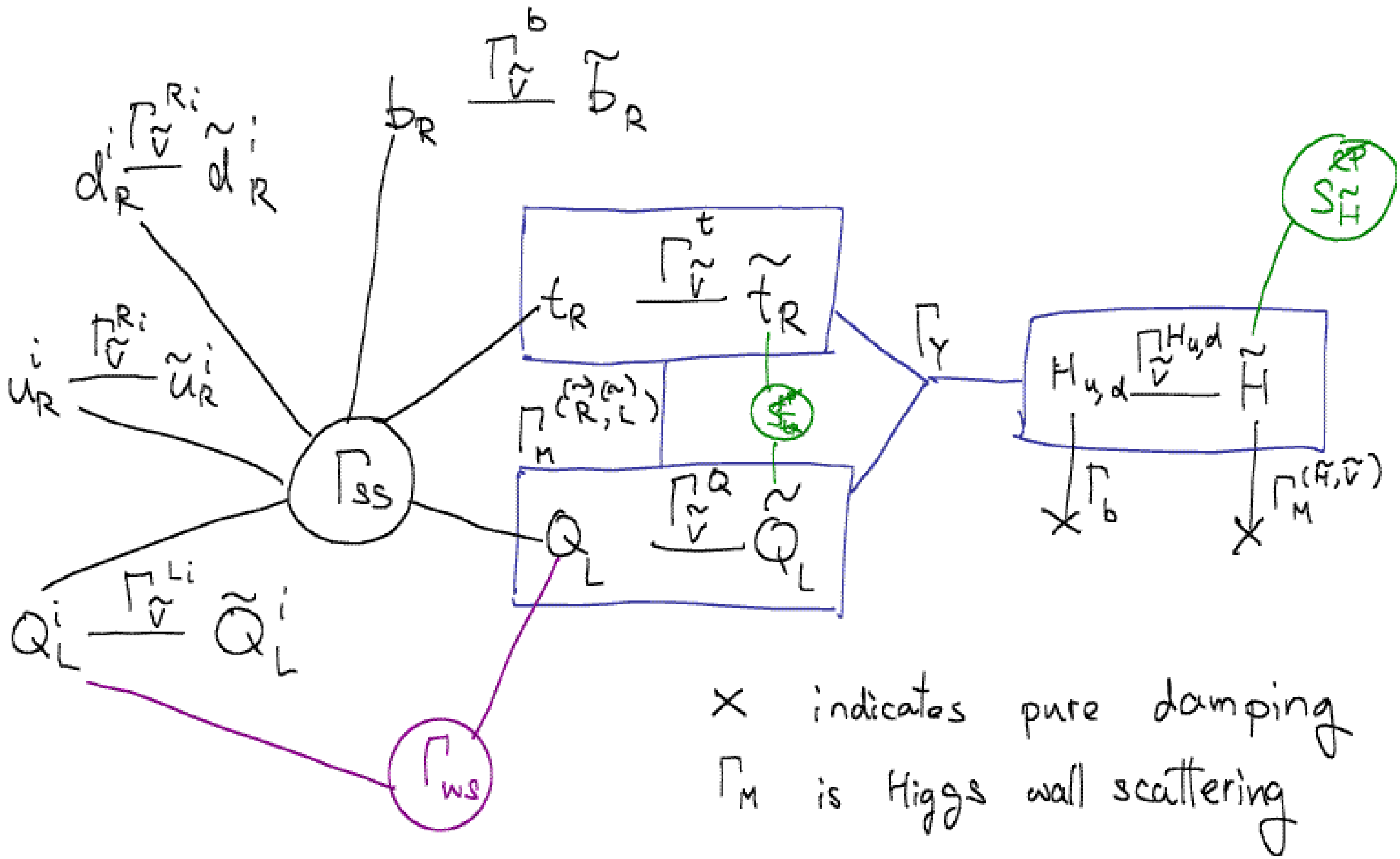
Theoretical constraints complicated & uncertain

- e.g. without cancellations,

$Arg(M_2 \mu) < 0.05$ [Chang et al 2002; Pilaftsis 2002]

[Recall the approximate requirement of B-genesis is $\Im[\mu M_{1,2}]/T_c^2 > 0.05$]

[Uncertainties significant in both EDM and b-genesis computations]



$$n_B = -\frac{n_F \Gamma_{ws}}{2\Lambda_+} \int_{-\infty}^{0} dx\, n_L(x)\, e^{\Lambda_- x}$$

$$n_L \sim f(\{m_i\} S_{\widetilde{H}}^{\not{CP}}$$

$$s \sim g_* T^3$$

$$S_{\widetilde{H}}^{\not{CP}} \simeq -21 \text{ GeV} \times \sin\phi_\mu \, v_w \, \beta'(z)\, v(z)^2$$

$$\Lambda_\pm = \frac{1}{2D_q}\left[v_w \pm \sqrt{v_w^2 + 4\mathcal{R}\, D_q}\right]$$

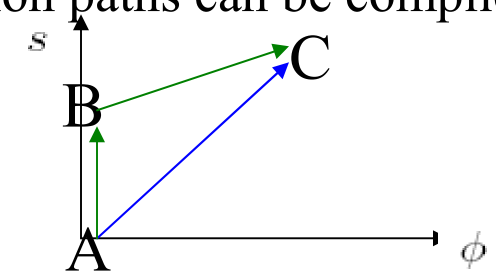
$$\Gamma_{ws} \sim 6 \times 10^{-6} T \qquad D_q \sim \frac{6}{T} \qquad v_w \sim 0.1$$

Phase Transition in Singlet Extensions

- The strength enhanced at tree level by mixing with singlets:

$$V_{eff}(\phi, s; T) = \frac{1}{2}\left(m_\phi^2 + g_\phi T^2\right)\phi^2 + \bar{\lambda}_0\phi^4 + \frac{1}{2}\left(m_s^2 + g_s T^2\right)s^2 + \frac{a_1}{2}\phi^2 s + \frac{a_2}{2}\phi^2 s^2 + \frac{b_3}{3}s^3 + \frac{b_4}{4}s^4$$

- To enhance phase transitions mixing must be large
- Mass stability of scalars bound mixing from above.
- Phase transition paths can be complicated.



- Spontaneous CP violation during EW phase transition can help evade

EDM bounds.

Summary

- Electroweak baryogenesis is exciting because it may be verifiable by near future collider experiments.
- CP violation places very strong constraints
- Much theoretical work needs to be done to make sure we achieve order of magnitude accuracy for the baryon asymmetry computations.

Collaborative score card

- ✓Why is the Higgs field light?
- ✓What is the origin of electroweak symmetry breaking?
- ✓Is it simply an accident that the gauge couplings seem to meet?
- How is gravity incorporated into the SM?
- ✓Why is the CP violation from QCD small?

- What is the dark energy?
- ✓✓What is the CDM?
- ✓Why more baryons than antibaryons?
- If inflation solves the cosmological initial condition problems, what is the inflaton?
- Classical singularities of general relativity?
- Why is the observed cosmological constant small when SM says it should be big?
- Origin of ultra-high energy cosmic rays?

✓with SUSY

✓with PQ

Many other speculative connections exist.
Not very convincing yet, unfortunately.
Restricting to particle physics.