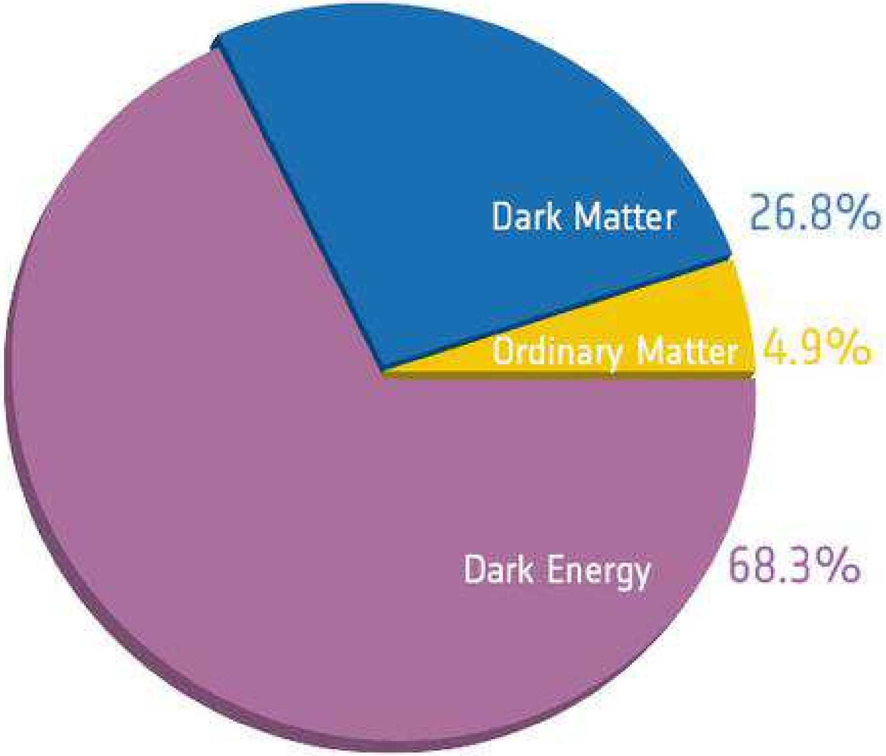
Baryogenesis

David Morrissey

Lake Louise Winter Institute, February 10, 2016

Baryons in the Universe

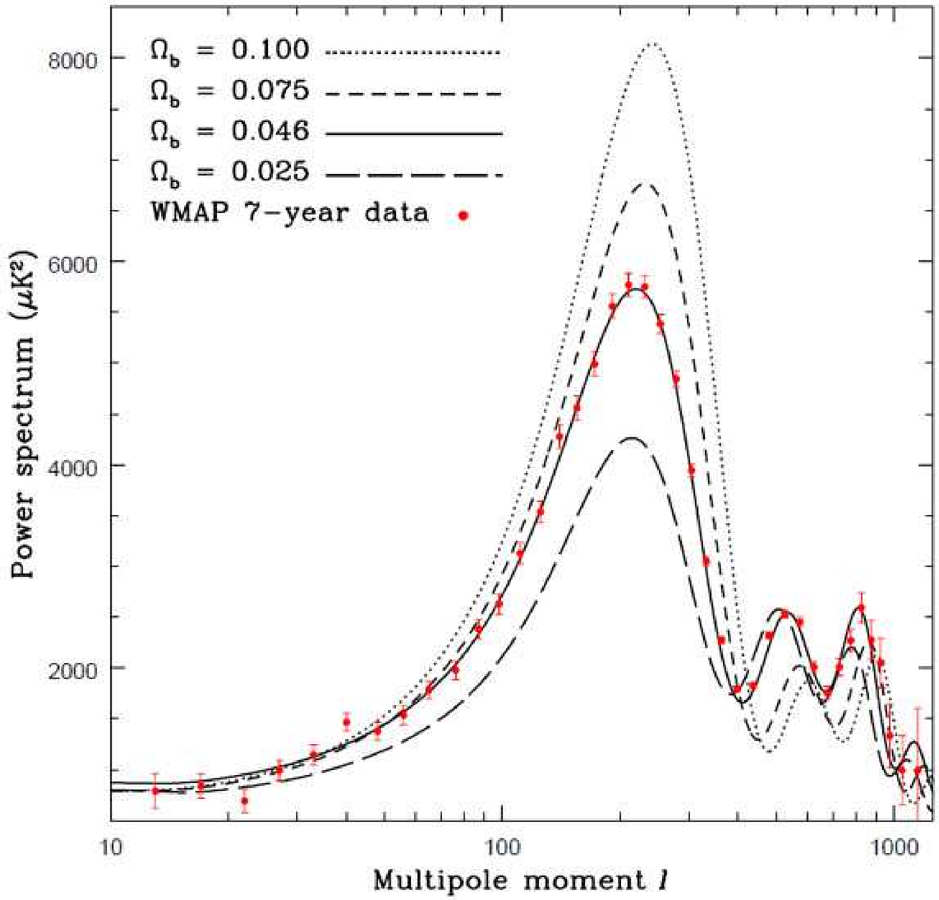


- Ordinary Matter = almost all baryons, by mass.
- Problem: we don't even understand this!

Baryons in the Universe: Evidence

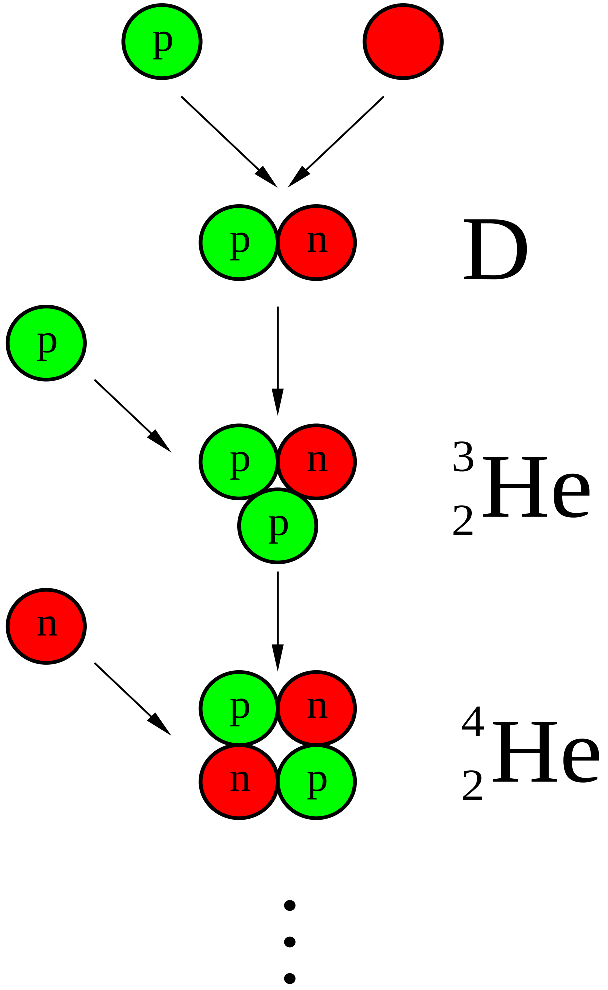
- CMB Temperature Fluctuations:

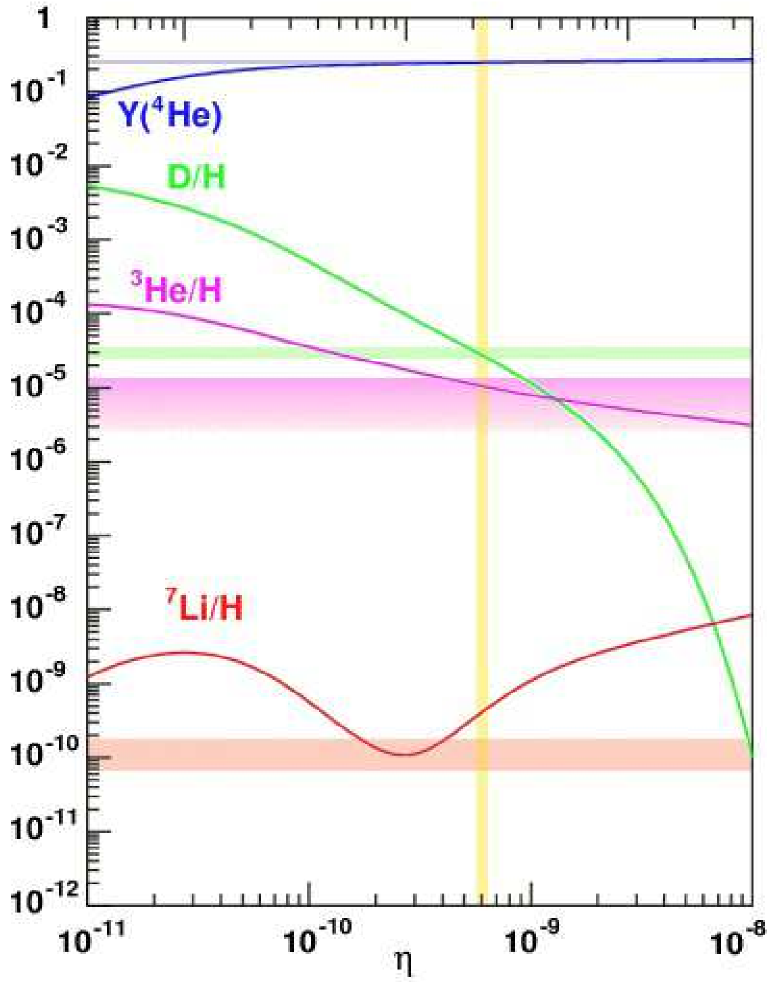
$$\eta \equiv \frac{n_B}{n_\gamma} = (6.1 \pm 0.3) \times 10^{-10}$$



[Garrett+Duda '10]

- Primordial Nucleosynthesis also takes η as an input.





[E. Vangioni]

- Consistent (mostly) with light element abundances.

Baryons and Antibaryons

- Suppose the early Universe contained equal numbers of baryons and antibaryons.
- These annihilate very efficiently down to $T \simeq 50\,\mathrm{MeV}$. Prediction:

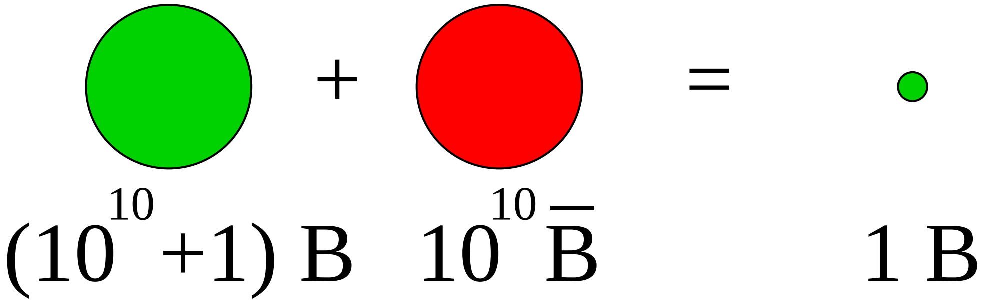
$$\eta \sim 10^{-20}$$

  Also, both baryons and antibaryons leftover today.

- Clearly incorrect!

Baryons and Antibaryons

- Suppose instead that the early Universe contained $10^{10}+1$ baryons for every 10^{10} antibaryons.
- Annihilation would remove nearly all the antibaryons.



$$(10^{10}+1)\,\mathrm{B} \quad + \quad 10^{10}\,\overline{\mathrm{B}} \quad = \quad 1\,\mathrm{B}$$

- Prediction: $\eta \simeq 10^{-10}$, only baryons.
- But how do we explain the $1/10^{10}$ asymmetry?

Baryogenesis!

Baryogenesis Basics

Ingredients for Baryogenesis

[Sakharov '67]

1. B Violation:

   $|B=0\rangle \longrightarrow |B\neq 0\rangle$ obviously requires B violation

2. C and CP violation

   Without violating both, B-violating processes would make just as many baryons as antibaryons

3. Departure from thermodynamic equilibrium

   $\langle B\rangle = constant$ in equilibrium

BG Ingredients and the Standard Model

- The Standard Model (SM) has all three ingredients:
  - spacetime expansion gives a departure from equilibrium
  - C is violated by the chiral fermion structure of the SM

    CP is violated by the phase in the CKM matrix
  - B is violated by non-perturbative processes!!!

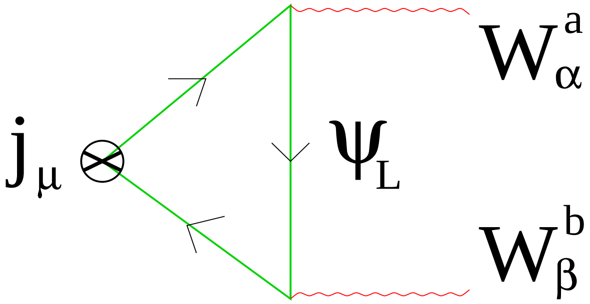
B Violation in the SM

- B and L seem like symmetries of the SM Lagrangian.

  $\Rightarrow$ expect current conservation: $\partial_\mu j^\mu_B = \partial_\mu j^\mu_L = 0$.

- Quantum corrections with $SU(2)_L$:

$$\partial_\mu j^\mu_B = \partial_\mu j^\mu_L \;=\; n_g \frac{g^2}{32\pi^2} W^a_{\alpha\beta}\widetilde{W}^{b\,\alpha\beta}$$



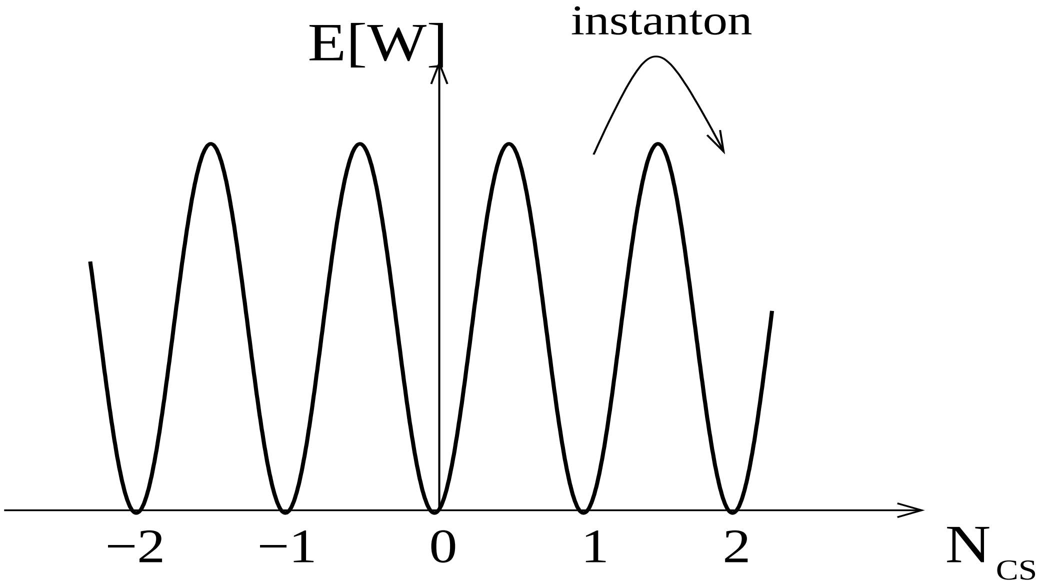
- But maybe we're still alright?

$$\begin{aligned} W^a_{\mu\nu}\tilde{W}^{a\,\alpha\beta} &= \partial_\mu K^\mu, \\ K_\mu &= \epsilon^{\mu\nu\alpha\beta}\left[W^a_{\nu\alpha}W^a_\beta - \frac{g}{3}\epsilon_{abc}W^a_\nu W^b_\alpha W^c_\beta\right] \end{aligned}$$

- Still contributes non-perturbatively . . .

- Non-Abelian gauge theories have multiple vacua characterized by the integer N_{CS}: [Belavin *et al.*, Jackiw+Rebbi '76]

$$N_{CS} = \int d^3x \, \frac{g^2}{32\pi^2} K^0 \qquad (\in \mathbb{Z} \text{ by topology})$$

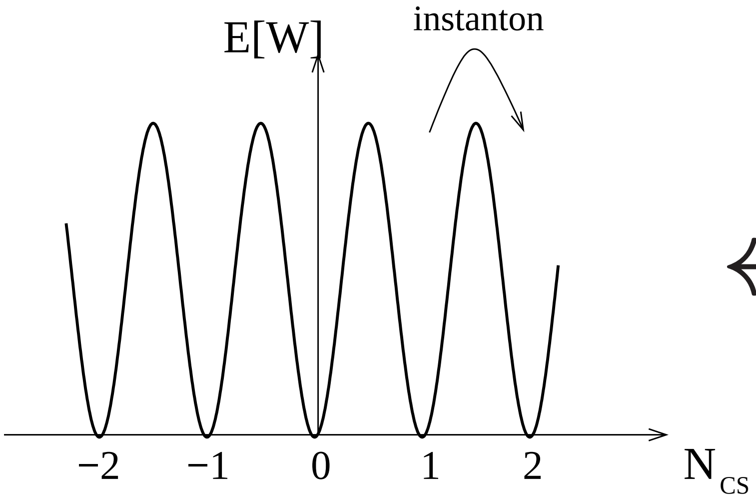


- Instantons = tunnelling between vacua: $\Delta N_{CS} \neq 0$.

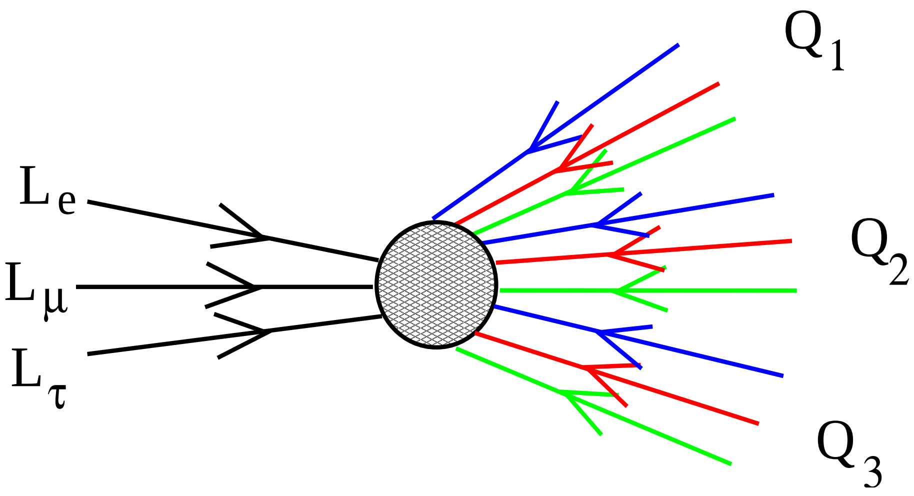
- For each instanton transition, ['t Hooft '76]

$$\Delta B = \Delta L = n_g \, \Delta N_{CS}$$

- Instantons violate $(B+L)$!



$\leftrightarrow$



[Cline '06]

- Instanton rate at zero temperature ($T = 0$): ['t Hooft '76]

$$\Gamma_{inst} \propto e^{-16\pi^2/g_2^2} \simeq 10^{-320}$$

- At finite temperature T, $\Delta N_{CS} \neq 0$ transitions can go via classical thermal fluctuations. [Klinkhamer+Manton '84]

$$\Gamma_{sp} \sim \begin{cases} T^4\, e^{-4\pi\langle H\rangle/g\,T} & \langle H\rangle \neq 0 \quad \text{[Arnold+McLerran '87]} \\ \kappa\,\alpha_w^5\,T^4 & \langle H\rangle = 0 \quad \text{[Bodeker,Moore,Rummukainen '99]} \end{cases}$$

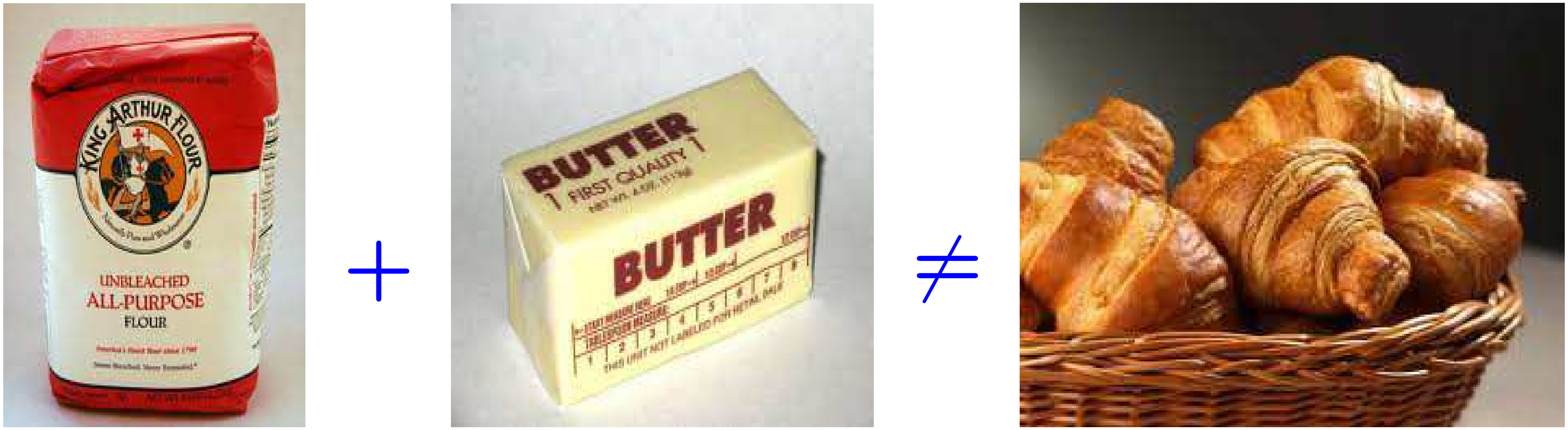
$\langle H\rangle$ = Higgs field expectation value.

- Called "sphaleron transitions".

- Result: $(B + L)$ violation is active in the early Universe for $T \gtrsim 100\,\text{GeV}$ (when EW symmetry is unbroken).

Ingredients Are Not Enough

- Baryogenesis requires a mechanism with these ingredients.



- We don't know of any mechanisms that work using the Standard Model alone.

Some Promising Mechanisms

- Leptogenesis

  → BG related to the origin of neutrino masses

- Electroweak Baryogenesis

  → BG created during the EW phase transition

- GUT Baryogenesis

  → BG from B-violating decay of heavy GUT stuff

- Affleck-Dine

  → BG from rolling scalars carrying B charges

- Hidden Sector Asymmetric Baryogenesis

  → BG in an exotic sector related to dark matter

Some Promising Mechanisms

- Leptogenesis

  → BG related to the origin of neutrino masses

- Electroweak Baryogenesis

  → BG created during the EW phase transition

Leptogenesis

Leptogenesis (and Neutrino Masses)

- We need new physics beyond the SM for neutrino masses.
- Minimal Requirement: new gauge singlet “RH” Neutrino N.

  Dirac Mass Term:

$$\begin{aligned} -\mathcal{L} &\supset y_\nu \bar{L} H\, N \\ &\to (y_\nu v)\, \bar{L} N, \qquad \text{after} \quad H \to v + h/\sqrt{2} \end{aligned}$$

H = Higgs breaking EW symmetry, $v = \langle H \rangle \simeq 174\,\text{GeV}$

- Neutrino Mass: $m_\nu = y_\nu v$
- But $m_\nu \lesssim 1\,\text{eV}$ – why is $y_\nu \sim 10^{-11}$ so small?

- Alternative Option: Seesaw Mechanism (Type I)

  [Mikowski; Gell-Mann,Ramond,Yanagida '79]

$$-\mathcal{L} \supset y_\nu \bar{L} H\, N + \frac{1}{2} M_N \bar{N}^c N$$

For $M_N \gg v$ integrate out the heavy RH state to give

$$-\mathcal{L}_{eff} \supset \frac{y_\nu^t y_\nu}{M_N} (\bar{L}^c H)(LH)$$

- Light neutrino masses:

$$m_\nu = \frac{(y_\nu v)^2}{M_N}$$

- Gives $m_\nu \sim \text{eV}$ for $y_\nu \sim 1$, $M_N \sim 10^{14}\,\text{GeV}$.

- Note: N is Majorana so that $\bar{N} \sim N$.

Leptogenesis: Step #1 [Fukugita+Yanagida '86]

- Heavy neutrinos N_i $(i = 1, 2, \ldots)$ decay in the early Universe.

- Two decay modes (related to neutrino masses):

$$\begin{aligned} N_i &\to H + \ell_L & \qquad (L = +1) \\ N_i &\to H^* + \bar{\ell}_L & \qquad (L = -1) \end{aligned}$$

- These decays violate lepton number L.

- Total decay width of N_i $(i = 1, 2, \ldots)$:

$$\begin{aligned} \Gamma_{N_i} &= \Gamma(N_i \to H + \ell_L) + \Gamma(N_i \to H^\dagger + \bar{\ell}_L) \\ &= \frac{(y_\nu y_\nu^\dagger)_{ii}}{8\pi} M_{N_i} \end{aligned}$$

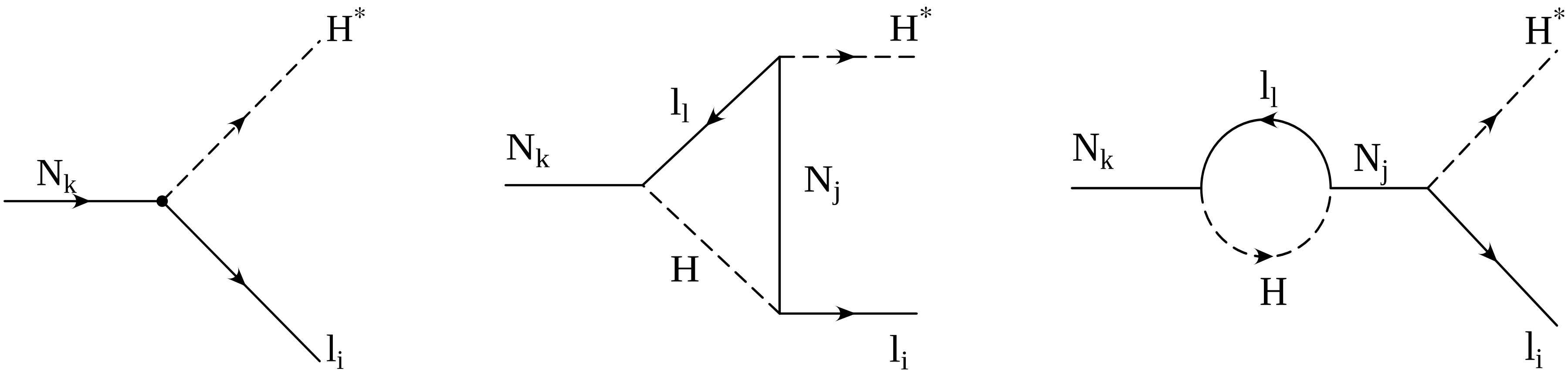
Leptogenesis: Step #2

- CP violation in N decays gives :

$$\epsilon_1 \equiv \frac{\Gamma(N_1 \to H\ell_L) - \Gamma(N_1 \to H^*\bar{\ell}_L)}{\Gamma(N_1 \to H\ell_L) + \Gamma(N_1 \to H^*\bar{\ell}_L)}$$

$$\simeq \frac{3}{16\pi}\sum_{i>1}\frac{Im(y_\nu y_\nu^\dagger)_{1i}}{(y_\nu y_\nu^\dagger)_{11}} \qquad (M_2, \ldots \gg M_1)$$

- Non-zero ϵ_1 comes from tree-loop interference:



- Lepton Asymmetry from N_1 decays:

$$\eta_L \;=\; \frac{n_L}{n_\gamma} \;\simeq\; \epsilon_1\,\kappa$$

$\kappa \;=\;$ "efficiency factor"

- Non-zero κ requires out-of-equlibrium decays of N_1.

  Decays occur mainly when $t = t_{decay} = 1/\Gamma_{N_1}$.

- If $T \gg M_{N_1}$ at t_{decay}, inverse decays drive N_1 to equilibrium.

  e.g. $\ell_L + H \to N_1,\ \bar{\ell}_L + H^* \to N_1$

  $\Rightarrow$ asymmetry is washed out, $\kappa \to 0$.

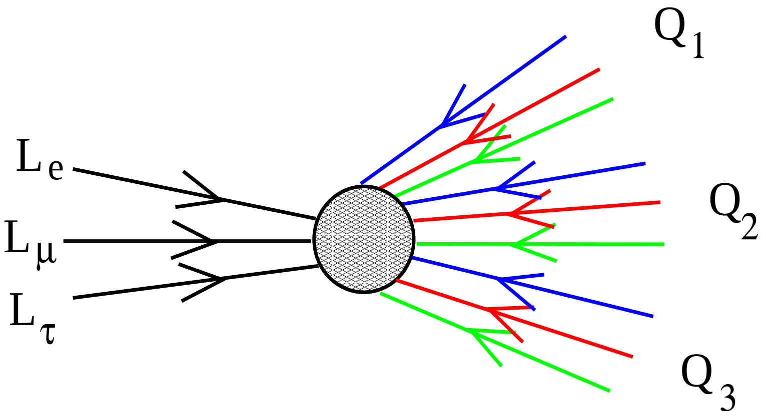
- If $T \ll M_{N_1}$ at t_{dec}, inverse decays are turned off.

  $\Rightarrow$ N_1 density can be larger than equilibrium, $\kappa \geq 1$.

Leptogenesis: Step #3

- Sphalerons are active at $T \gtrsim 100\,\text{GeV}$.

  They violate $(B+L)$ and convert some L to B.



[Cline '06]

- After sphaleron reprocessing, [Harvey+Turner '90]

$$\begin{aligned} \eta_B(final) &= \mathcal{C}\,[\eta_B(initial) - \eta_L(initial)] \\ &= -\mathcal{C}\,\eta_L(initial) \qquad \text{(Leptogenesis)} \end{aligned}$$

$\mathcal{C} \sim 1$ depends on the degrees of freedom in the plasma

- Final Answer:

$$\eta_B = -\mathcal{C}\,\epsilon_1\,\kappa$$

- BG Ingredients:
  - $\mathcal{C} \neq 0$ requires B violation (sphalerons)
  - $\epsilon_1 \neq 0$ requires C and CP violation
  - $\kappa \neq 0$ requires departure from equilibrium

- Neutrino studies might give clues about leptogenesis.

Electroweak Baryogenesis

Electroweak Baryogenesis [Kuzmin,Rubakov,Shaposhnikov '85]

- Equilibrium can be lost during phase transitions.
- Really Important PT: electroweak symmetry breaking

$$SU(2)_L \times U(1)_Y \to U(1)_{em}$$

- Electroweak Baryogenesis (EWBG)

  $\to$ B production during the electroweak PT

- Three Steps:

  1. First-order EWPT produces expanding bubbles.
  2. CP violation near bubbles creates a chiral asymmetry.
  3. Sphalerons reprocess this asymmetry into B.

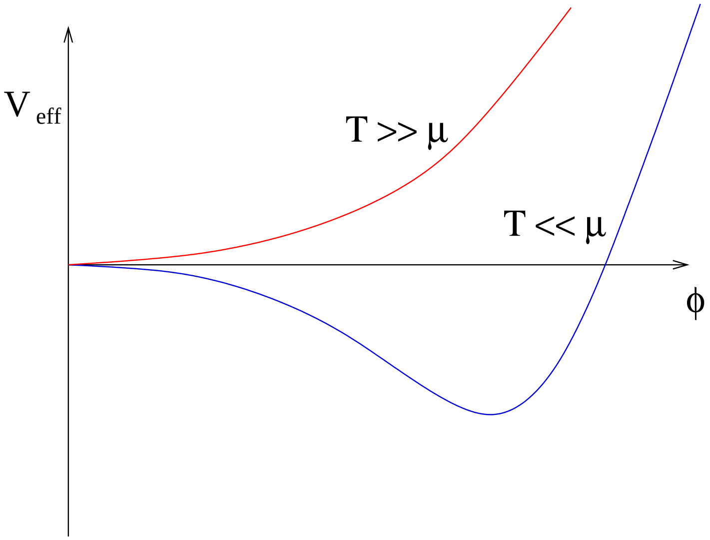
The EW Phase Transition

- Order parameter ∼ Higgs VEV $\langle H \rangle \equiv \phi$:

$$\begin{aligned} \langle H \rangle &= 0 \Rightarrow SU(2)_L \times U(1)_Y \text{ is unbroken.} \\ \langle H \rangle &\neq 0 \Rightarrow SU(2)_L \times U(1)_Y \to U(1)_{em}. \end{aligned}$$

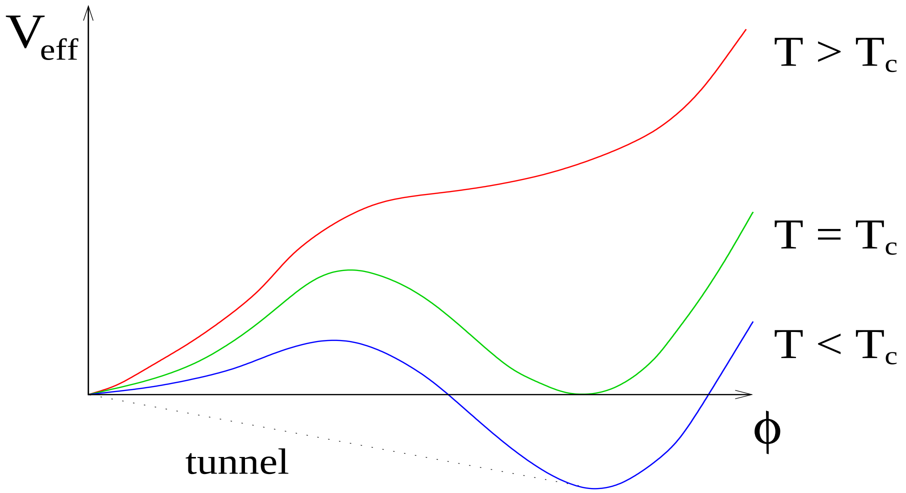
- Effective potential:

$$V_{eff} \simeq (-\mu^2 + \xi T^2)\phi^2 + \frac{\lambda}{4}\phi^4 + \ldots$$

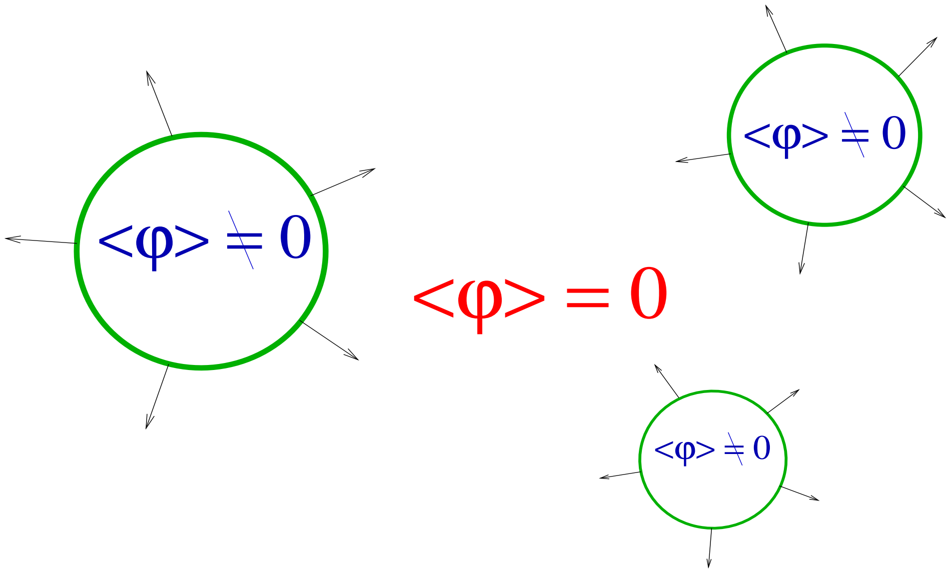


Step 1: Bubble Nucleation

- First order phase transition:



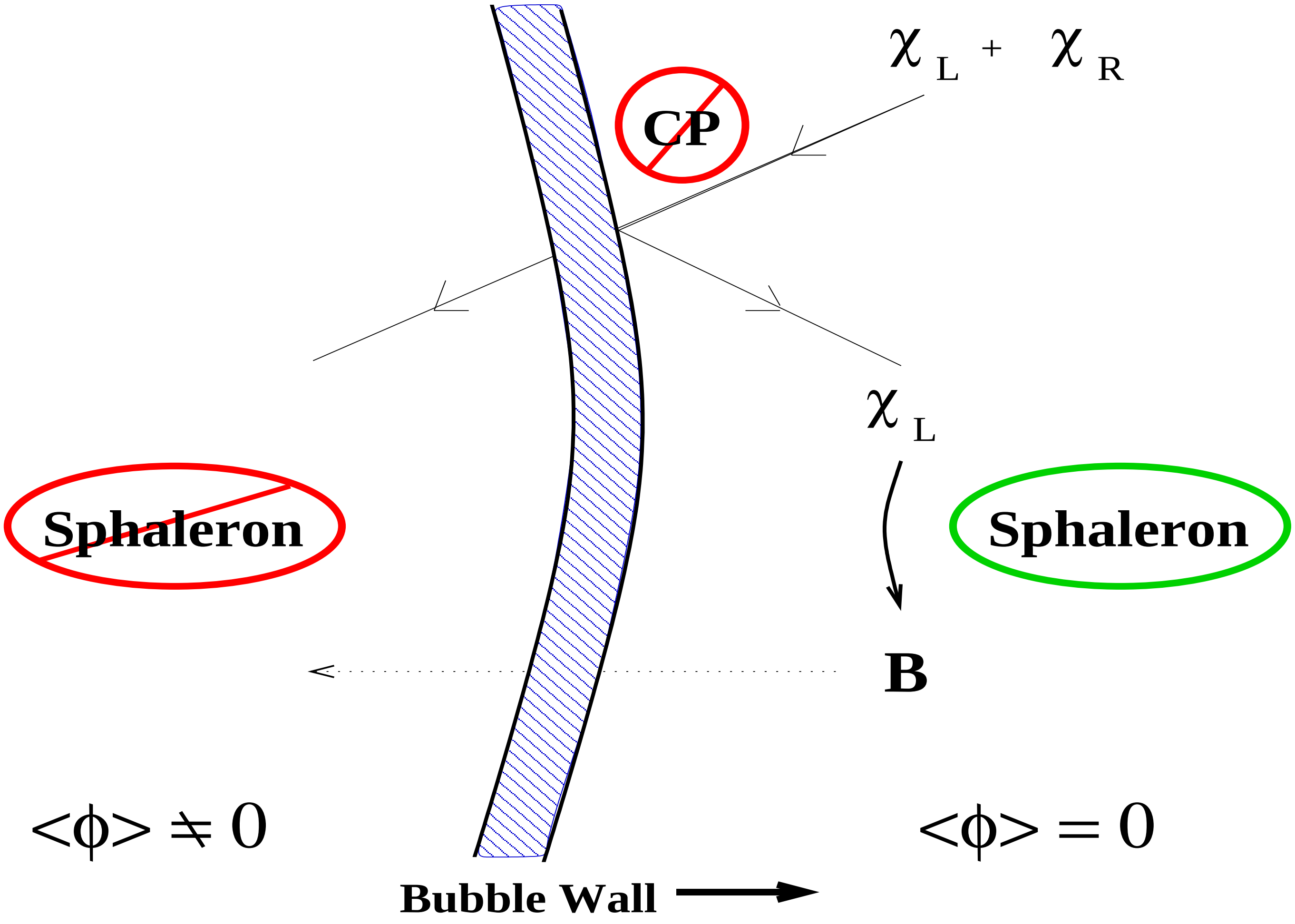
- Bubbles of broken phase are nucleated at $T < T_c$.



Step 2: CP Violation and Chiral Asymmetries

- CPV in the bubble wall creates a chiral asymmetry.

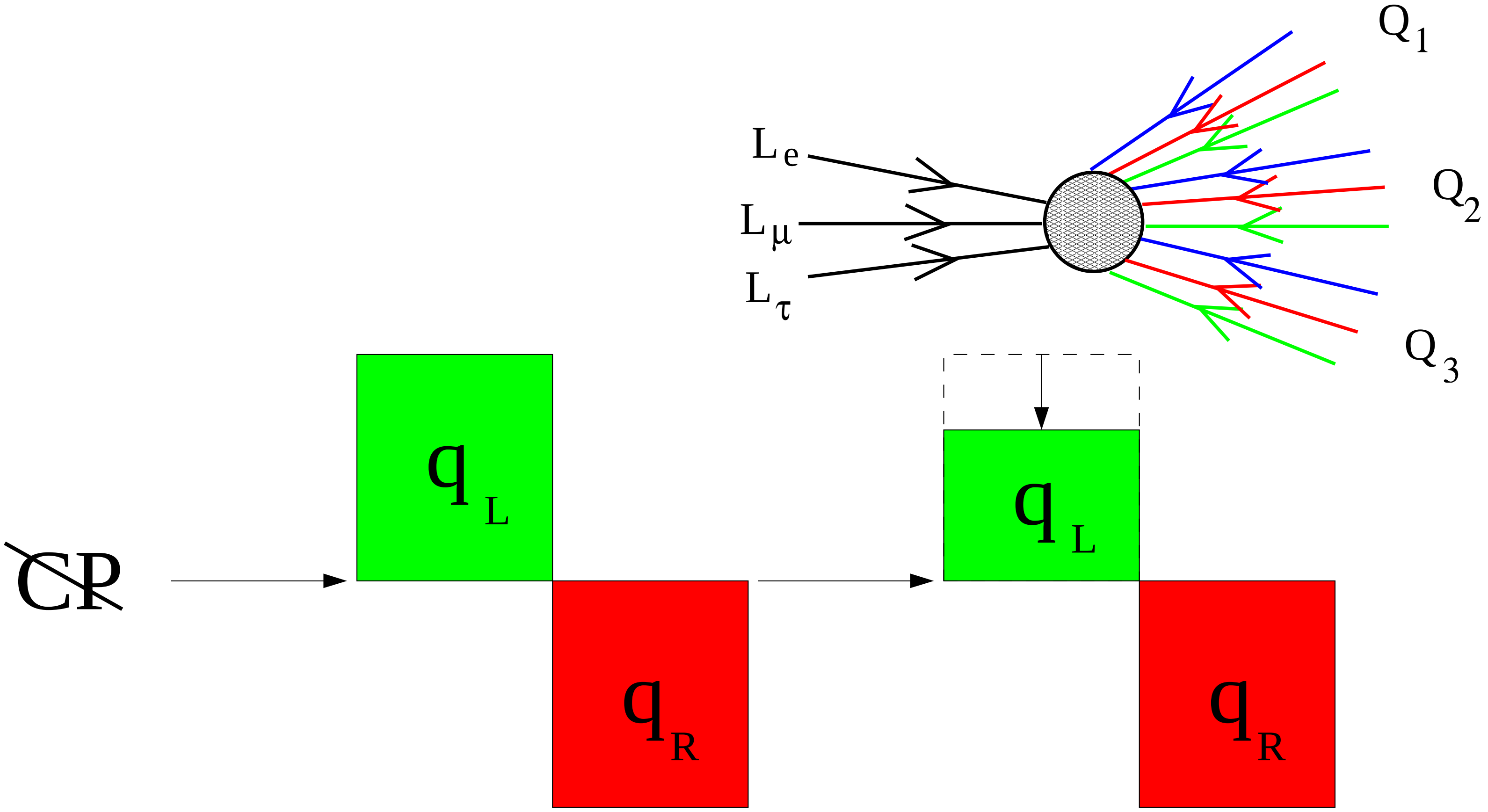
  Chiral Asymmetry $= n(\text{LH quarks}) - n(\text{RH quarks})$.



Step 3: Making Baryons

- Chiral Asymmetry $= n$(LH quarks) $- \, n$(RH quarks).
- Sphalerons ($SU(2)_L$) only act on *LH* quarks.

  These reduce the density of LH quarks but not RH quarks.



EWBG in the Standard Model and Beyond

- It does not work in the SM:

  1. The EW PT is not first-order for $m_h = 125\,\text{GeV}$.

     [Kajantie, Laine, Rummukainen, Shaposhnikov '98]

  2. Not enough effective CP violation.

     [Gavela, Hernandez, Orloff, Pené '94; Huet+Sather '95]

- EWBG can work with new physics beyond the SM.

  e.g. Minimal Supersymmetric Standard Model (MSSM)

  1. A light scalar top partner can make the PT first-order.

     [Carena,Quirós,Wagner '96;Delepine, Gérard, Gonzalez, Wyers '96]

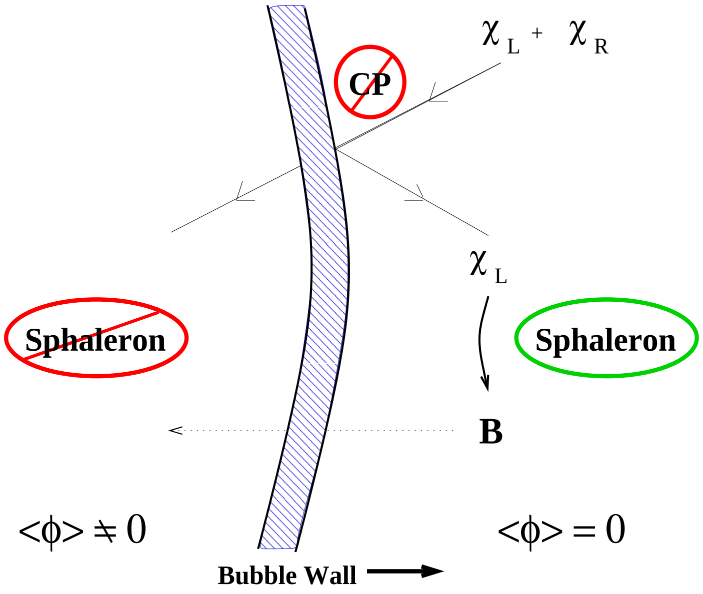
  2. SUSY breaking can give new sources of CP violation.

     [Carena,Quirós,Riotto,Vilja,Wagner '97; Cline+Kainulainen '97]

Phase Transition “Strength”

- Electroweak PT must be “strongly” first order to prevent sphaleron washout of B in the broken phase.

$$\Gamma \sim T^4 \, \mathrm{exp}(-8\pi\langle\phi\rangle/g_w T)$$



- For bubble nucleation near the critical temperature T_c:

$$\frac{\langle\phi_c\rangle}{T_c} \gtrsim 1.0 \ .$$

[Bochkarev, Kuzmin, Shaposhnikov ’91; Patel + Ramsey-Musolf ’11]

A Light MSSM Stop and the EW Phase Transition

- Light (RH) stop coupling to the Higgs field:

$$-\mathcal{L}_{eff} \supset Q|H|^2|\tilde{t}_1|^2 \ .$$

- The new coupling Q modifies the thermal Higgs potential:

$$V_{eff}(\phi,T) \simeq -(\mu^2 - \xi T^2)\phi^2 - \frac{T}{4\pi}Q^{3/2}\phi^3 + \frac{\lambda}{4}\phi^4$$

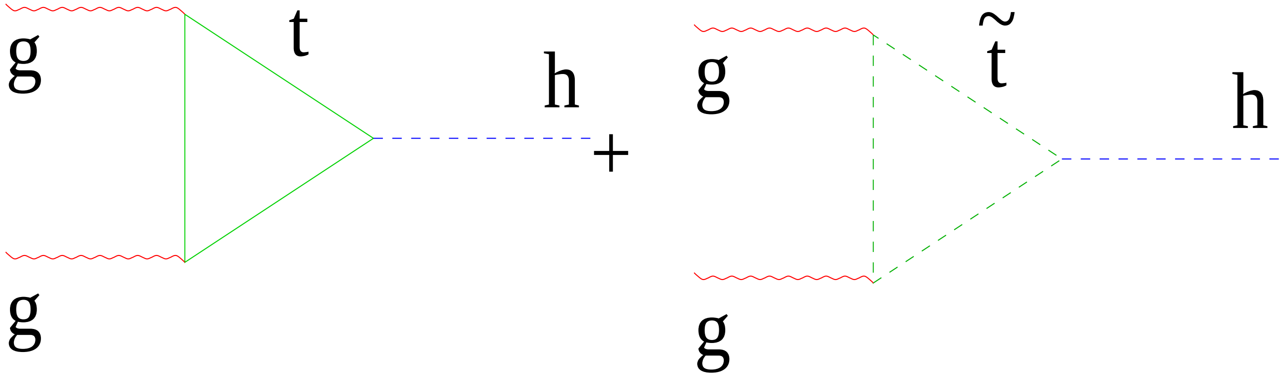
- Large Q gives a strongly first-order phase transtion:

$$\text{Strength} \sim \frac{\phi_c}{T_c} \sim \frac{Q^{3/2}}{\lambda} \geq 1 \ .$$

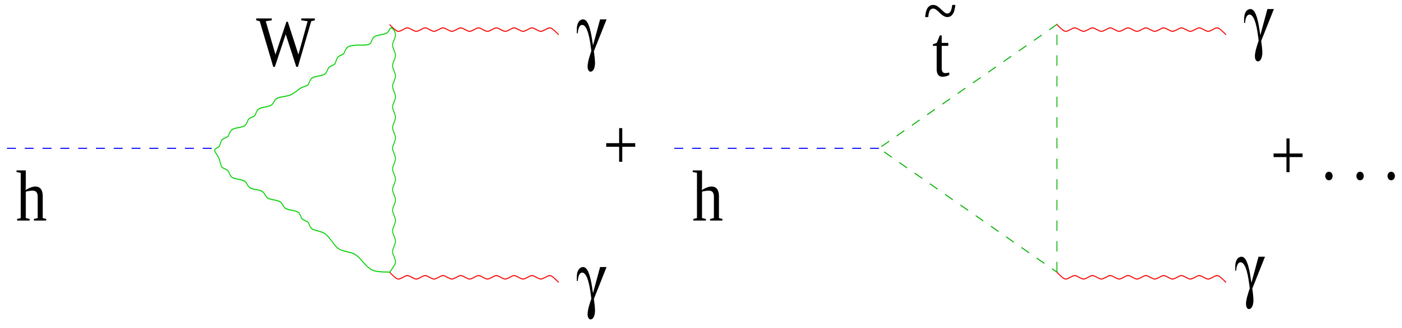
- Only works for a very light stop, $m_{\tilde{t}_1} \lesssim 150\,\text{GeV}$.

Light Stops and the Higgs

- $\sigma(gg \to h)$: constructive with top loop for $Q > 0$.



- $\Gamma(h \to \gamma\gamma)$: destructive with top loop for $Q > 0$.



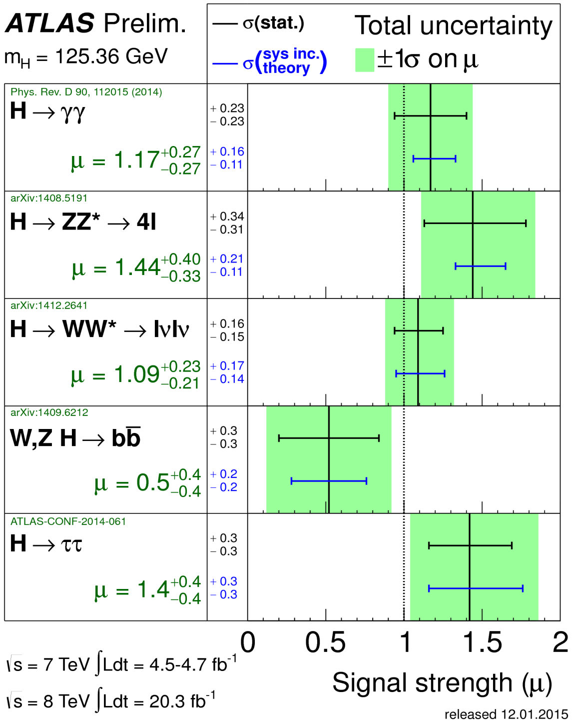
Phase Transition vs. Higgs Rates

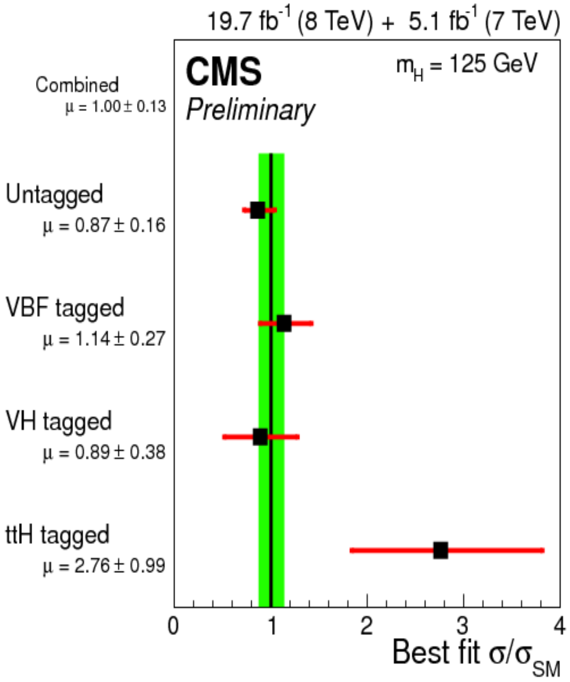
- MSSM EWBG: [Menon,DM '09; Cohen,DM,Pierce '12]

$$\sigma(gg \to h) \gtrsim 1.6 \times SM$$

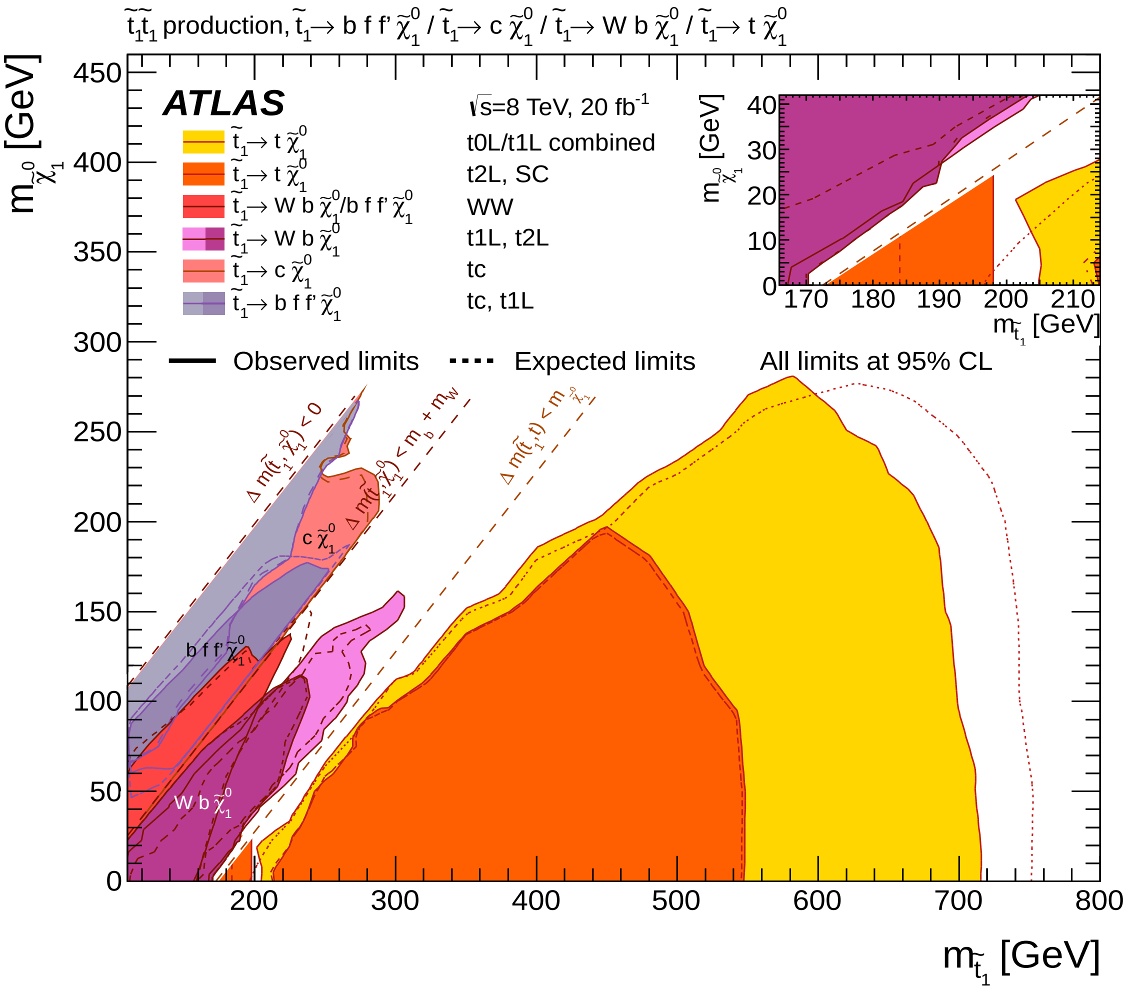
$$\sigma \times BR(h \to \gamma\gamma) \gtrsim 1.3 \times SM$$

- Inconsistent with measured Higgs rates.[Curtin,Jaiswal,Meade '12]





Direct Searches for Light Stops

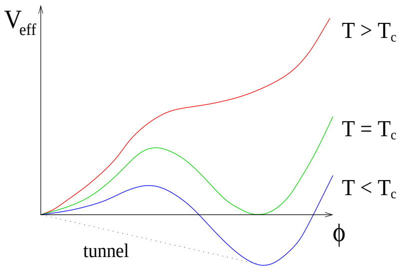
- 

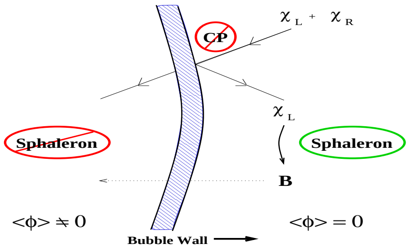
- LHC searches rule out the light stop for MSSM EWBG.

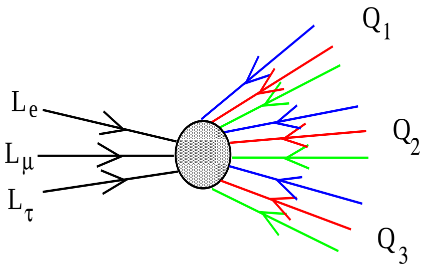
[Krizka,Kumar,DM ’12; Delgado,Guidice,Isidori,Pierini, Strumia ’12]

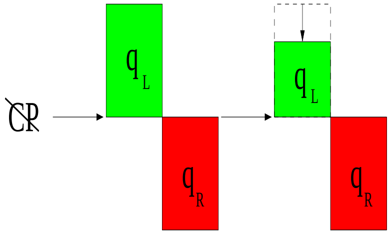
EWBG Summary

- EWPT → bubbles → chiral asymmetry → baryons









- Does not work in the SM.
- Could work in the MSSM, but ruled out by LHC searches.
- Still viable in other SM extensions but strongly constrained.
- Also requires new CP violation: electric dipole moments?

Other Popular Baryogenesis Mechanisms

- GUT Baryogenesis (*e.g.* $SU(3)_c \times SU(2)_L \times U(1)_Y \subset G_{simple}$)
  - can have quarks and leptons in the same representation
  - heavy GUT decays can violate B, like leptogenesis
- Affleck-Dine Baryogenesis
  - excite scalar field directions carrying $(B-L)$ charge
  - scalar condensates decay to particles with net B
- Asymmetric Dark Matter
  - $\Omega_{DM} \simeq 5\Omega_B$ – could they be related?
  - DM carries a net conserved charge related to B
  - density of DM set by the B charge asymmetry

Summary

- More matter than antimatter in the Universe.
- No known explanation within the Standard Model.
- Leptogenesis: baryon production from heavy neutrinos.

  → may be related to neutrino masses and mixings
- Electroweak BG: baryon production during the EWPT.

  → currently being tested at the LHC
- If we're lucky, we'll see evidence of new physics soon!

Extra Slides


OMG, is fulla starz.
ICANHASCHEEZBURGER.COM

Some Reviews

- A. Ritto, hep-ph/9807454
- M.Quirós, hep-ph/9901312 (electroweak BG)
- M. Dine, A. Kusenko, hep-ph/0303065
- W.Buchmüller, R. Peccei, T. Yanagida, hep-ph/0502169 (leptogenesis)
- A. Strumia, F. Vissani, hep-ph/0606054 (neutrinos and leptogenesis)
- J. Cline, hep-ph/0609145
- S. Davidson, E. Nardi, Y. Nir, hep-ph/0802.2962 (leptogenesis)
- DM, M. Ramsey-Musolf, hep-ph/1206.2942 (electroweak BG)

Simple Toy Model of Baryogenesis

- Massive particles X and $\bar{X}$ decay at $T \ll m_X$.
- Start with $n_X = n_{\bar{X}} \sim T^3 \gg n_X^{eq}$

  → departure from thermodynamic equilibrium
- Decay modes:

$$X \;\rightarrow\; \begin{cases} A + B & ; \quad B = B_1 \\ C + D & ; \quad B = B_2 \end{cases}$$

$$\bar{X} \;\rightarrow\; \begin{cases} \bar{A} + \bar{B} & ; \quad B = -B_1 \\ \bar{C} + \bar{D} & ; \quad B = -B_2 \end{cases}$$

$B_1 \neq B_2$ requires B violation

- Decay rates*:

$$\Gamma(X \to A + B) \;=\; \Gamma_{AB} + \Delta\Gamma_{AB}$$

$$\Gamma(X \to C + D) \;=\; \Gamma_{CD} - \Delta\Gamma_{CD}$$

$$\Gamma(\bar{X} \to \bar{A} + \bar{B}) \;=\; \Gamma_{AB} - \Delta\Gamma_{AB}$$

$$\Gamma(\bar{X} \to \bar{C} + \bar{D}) \;=\; \Gamma_{CD} + \Delta\Gamma_{CD}$$

C and CP violation needed for $\Delta\Gamma_{ij} \neq 0$

- $\Gamma_X^{tot} = \Gamma_{\bar{X}}^{tot}$ by CPT conservation.

$\Rightarrow\; \Delta\Gamma_{AB} = \Delta\Gamma_{CD} \equiv \Delta\Gamma$

* Recall that $BR(X \to ij) = \Gamma(X \to ij)/\Gamma_X^{tot}$

- Net baryon density produced by decays of X, $\bar{X}$:

$$\begin{aligned} n_B &= n_X \left[B_1\, BR(X \to AB) + B_2\, BR(X \to CD) \right. \\ &\qquad \left. - B_1\, BR(\bar{X} \to \overline{AB}) - B_2\, BR(\bar{X} \to \overline{CD}) \right] \\ &= 2\frac{\Delta\Gamma}{\Gamma_X}(B_1 - B_2)\, n_X \end{aligned}$$

- $(B_1 - B_2) \neq 0$ from B violation
- $\Delta\Gamma \neq 0$ requires C and CP violation
- $n_X \gg n_X^{eq}$ requires departure from equilibrium
  Decay of X at $T \ll m_X$ means that washout is turned off.
  (*e.g.* $A + B \to X^{(*)} \to \bar{C} + \bar{D}$ scatterings)