Lecture 4

ELECTROWEAK BARYOGENESIS

We observe a Universe made mostly of matter (no anti-matter) on local / galactic / cosmological scales.

$$\text{BBN} + \text{CMB} + \text{LSS} \ldots \Rightarrow \frac{n_B - n_{\bar{B}}}{s} \simeq 5 \cdot 10^{-10}$$

↳ Big Bang Nucleosynthesis: number of photons per baryon determines the conditions under which nuclear fusion occurs: light element abundances

[MATTER - ANTIMATTER ASYMMETRY]

Could it be due to initial conditions? ⇒ NO

⇒ Initial conditions (abundances) are washed-out by inflation

⇒ At $T \gg 100\ \text{GeV}$, $n_B - n_{\bar{B}} \neq 0$ could also be washed-out by Electroweak processes (sphalerons)

[Need Dynamical Generation of Matter - Antimatter Asymmetry in Early Universe!]

↳ BAU (Baryon asymmetry of Universe)

Sakharov Conditions (for dynamical generation of BAU)

(Sakharov, 1967)

- Baryon Number (B) Violation
- C / CP Violation

  If C and/or CP are conserved, processes producing more baryons than antibaryons are counterbalanced (at equal rates) by processes producing more antibaryons than baryons.

- Out of Equilibrium

  In thermal equilibrium, $n_B = n_{\bar{B}}$

Possible to generate BAU at EW Scale!

(Kuzmin, Rubakov, Shaposhnikov, 1985, 1987)

$\Rightarrow$ **B Violation in the SM**

- $U(1)_B$ and $U(1)_L$ are symmetries at classical level (B and L conserved)

  However they are anomalous:

$$\partial_\mu J^\mu_B = \partial_\mu J^\mu_L = N_f \left(\frac{g^2}{32\pi^2} \underbrace{Tr\left(W_{\rho\sigma} \tilde{W}^{\mu\sigma}\right)}_{SU(2)_L} - \frac{g'^2}{32\pi^2} \underbrace{B_{\rho\sigma} \tilde{B}^{\rho\sigma}}_{U(1)_Y} \right)$$

- The vacuum structure of the SU(2) gauge theory is characterized by an infinite set of vacua, each labelled by the winding number $n = 0, \pm 1, \pm 2 \ldots$

- Due to the anomaly, there is a change in B and L in going from one SU(2) gauge vacuum to another $\Rightarrow$ Transitions between SU(2) gauge vacua violate B and L!!

At $T = 0$, SU(2) vacuum-to-vacuum transitions via quantum tunneling

Transition rate from a path integral (in euclidean space), dominated by a stationary solution A^a_μ such that $\frac{g^2}{32\pi^2}\int d^4x\, W^a_{\mu\sigma}\tilde{W}^{\mu\sigma a} = 1$

↓

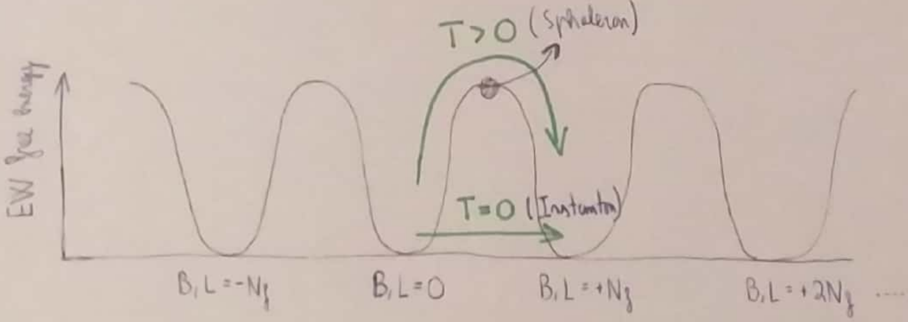
Instanton

$$\Gamma \sim e^{-S_E(A^a_\mu)} \longrightarrow S_E(A^a_\mu) = \frac{16\pi^2}{g^2} = \frac{4\pi}{\alpha_W} \simeq 370$$

(B and L violation at $T=0$ is extremely suppressed!)

At $T \neq 0$, SU(2) vacuum-to-vacuum transitions via thermal fluctuations

Transition rate dominated by the field configuration at the top of the potential barrier between gauge vacua. This field configuration is called the Sphaleron → Static, unstable solution to the classical eqs of motion (Saddle point of EW free energy)



(see e.g. Cohen, Kaplan, Nelson, "Progress in electroweak baryogenesis", 1993
Trodden, "Electroweak baryogenesis", 1999)

Parenthesis: The Sphaleron

For SU(2) gauge theory (no hypercharge) the sphaleron field profile, gauge and Higgs field, is:

$$A^a_i t^a dx^i = \frac{-i}{g} f(g v r)\, dU U^{-1},$$

$$\Phi = \frac{v}{\sqrt{2}} h(g v r)\, U \cdot \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

with $U = \frac{1}{r}\begin{pmatrix} z & x+iy \\ x-iy & z \end{pmatrix}$ and h, f are functions that are determined requiring the sphaleron to be a solution of the equs. of motion.

Sphaleron (Free) Energy (pure SU(2))

$$E_{sph} = \int d^3x \left[-\frac{1}{2g^2} \mathrm{Tr}(W_{\mu\nu}W^{\mu\nu}) + D_\mu \Phi^\dagger D^\mu \Phi + \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2 \right]$$

The sphaleron free energy at finite is given by $E_{sph}(T) = \frac{2 m_W(T)}{\alpha_W} B(\lambda/g^2)$

$B(0) = 1.5$

$B(\infty) = 2.7$

At $T \neq 0$, the thermal energy of the system can allow for jumps over the energy barrier of between different gauge vacua (an alternative way of understanding this, is that $m_W(T) \propto v(T)$ and so $v(T)$ controls E_{sph} and thus the height of the barrier. As T increases, $v(T) \to 0$ and the barrier shrinks).

The transition rate between gauge vacua at $T \neq 0$ is

$$\Gamma \sim e^{-E_{sph}/T} = e^{-(4\pi B(\lambda/g^2) g^{-1}) \cdot \frac{v(T)}{T}}$$

(This is the transition rate for $v(T) \neq 0 \Rightarrow$ Broken EW symmetry)

For $v = 0$ (Symmetric phase), the transition rate between gauge vacua is much more difficult to compute $\Rightarrow$ Can be estimated (Lattice) to be

$$\Gamma \sim \kappa \cdot (\alpha_W T)^4$$

κ: 0.1-1

$\Rightarrow$ **C and CP Violation**

- In the SM, CP violation from a phase in CKM matrix (δ) (also PMNS?)
- CP violation in SM is very suppressed for $T \sim 100$ GeV:

Basis-independent measure of CP violation (Jarlskog)

(if two quarks are mass degenerate, δ is not physical)

$$J_{CP} = \prod_{\substack{q=u,c,t\\ q'=u,c,t\\ q\neq q'}} (m_q^2 - m_{q'}^2) \prod_{\substack{q=d,s,b\\ q'=d,s,b\\ q\neq q'}} (m_q^2 - m_{q'}^2) \cdot C_{12} C_{23} C_{13} S_{12} S_{23} S_{13} \sin\delta$$

$C = \cos$; $S = \sin$

(if any of the 3 CKM mixing angles vanishes, δ is not physical)

For $T \sim 100$ GeV, $\frac{J_{CP}}{T^{12}} \sim 10^{-20}$ $\rightarrow$ Compare with $\frac{n_B - n_{\bar{B}}}{s} \sim 10^{-10}$!

(CP violation in SM is too small for BAU)

$\Downarrow$

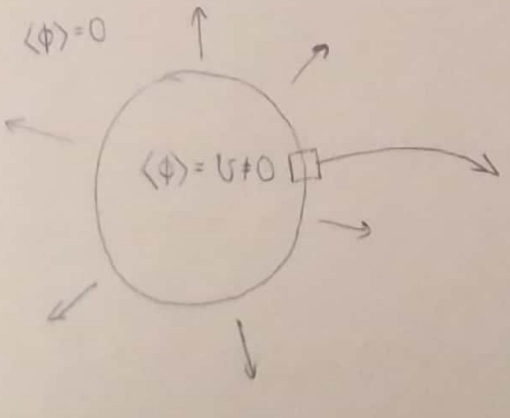
Need BSM physics!

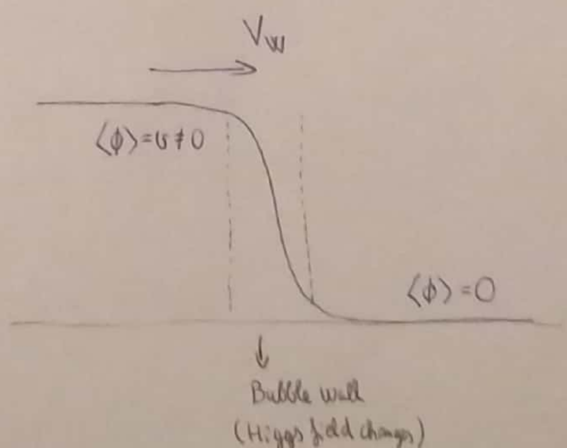
$\Rightarrow$ **Departure from equilibrium**

- The electroweak phase transition, if of first order, could provide the required departure from thermal equilibrium to generate the BAU

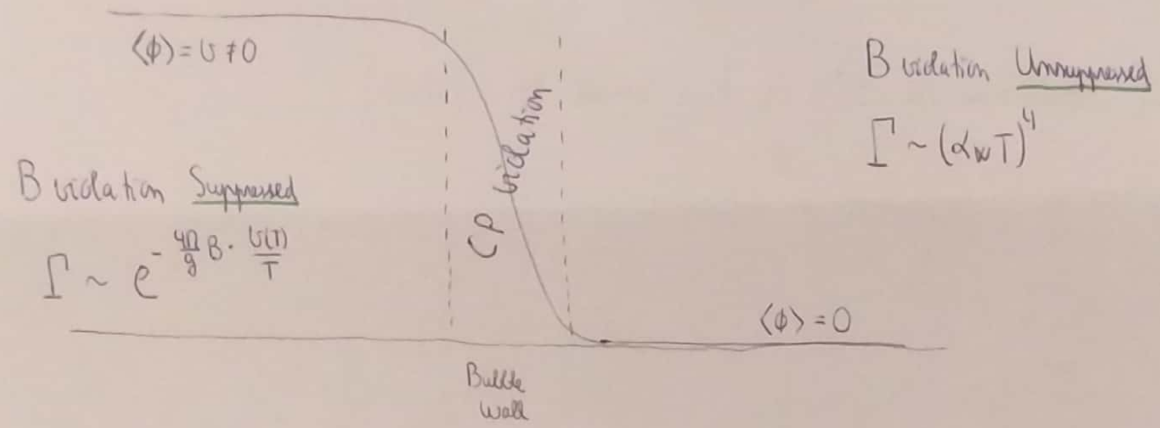
Let us look in some detail into the mechanism of Electroweak baryogenesis (to create the BAU) and the special role of the electroweak phase transition in it!

$\Rightarrow$ First order phase transition: Nucleation & Growth of Higgs bubbles





The Electroweak Baryogenesis mechanism



Initially $\quad n_B - n_{\bar{B}} = n_B^L + n_B^R - n_{\bar{B}}^L - n_{\bar{B}}^R = \underbrace{n_B^L - n_{\bar{B}}^L}_{0} + \underbrace{n_B^R - n_{\bar{B}}^R}_{0} = 0$

After $\not{CP}$ $\quad n_B - n_{\bar{B}} = \underbrace{n_B^L - n_{\bar{B}}^L}_{\neq 0} + \underbrace{n_B^R - n_{\bar{B}}^R}_{\neq 0} = 0$

After $\not{B}$ $\quad n_B - n_{\bar{B}} = \underbrace{n_B^L - n_{\bar{B}}^L}_{\to\, = 0} + \underbrace{n_B^R - n_{\bar{B}}^R}_{\neq 0} \neq 0$

↓

The B/L anomaly comes from SU(2) (only left-handed baryon number changes!)
"Sphalerons" do not act on SU(2)-singlets

- "Local" Baryogenesis: Baryons are produced when the B violating processes and CP violating processes occur together near/inside/close to the bubble wall

- "Non-local" Baryogenesis: Particles undergo CP violating interactions with the bubble wall (chiral splitting). The generated CP asymmetry is carried by diffusion/transport into the symmetric region, where B violating processes are active and produce baryons.

In both cases, after the net excess of baryons (over anti-baryons) has been created, the bubble wall sweeps through and the created baryons are in the broken phase, inside the bubble.

$\Downarrow$

In order for the mechanism to work, the B-violating transitions have to be shut-off inside the bubble! (to prevent erasure of the generated BAU)

$\downarrow$

Recall B violating transition rate in broken phase:

$$\Gamma \sim e^{-\frac{4\pi}{g} B(\lambda/g^2) \cdot \frac{v(T)}{T}}$$

$\downarrow$

A suppression requires a "large" $\frac{v(T)}{T}$ at the electroweak phase transition temperature! T_N

$\leftarrow$

Sufficient suppression is

$$\xi \equiv \frac{v(T_N)}{T_N} \gtrsim 1$$

Now, the role of the EW phase transition in EW Baryogenesis is clear:

1) A first order EW phase transition proceeds via bubble nucleation & growth. The bubble wall and its surroundings provide the environment for EW Baryogenesis to work!

2) A first order EW phase transition with $\frac{v(T_N)}{T_N} \gtrsim 1$ ("Strong") shuts-off the Sphaleron transitions (B violation) in the broken phase, making EW baryogenesis possible! (→ out of equilibrium!)