Baryogenesis and Leptogenesis (Part I)

Bhupal Dev

Washington University in St. Louis

Post-FPCP School

UoH and IITH, Hyderabad, India

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Outline

Lecture 1

- Sakharov Conditions
- *B* Violation in the SM: Sphalerons
- Electroweak Baryogenesis
- What goes wrong in the SM?
- Need for New Physics
- Leptogenesis and Connection to Neutrino Mass

Suggested Reading

Prerequisites: Basic knowledge of QFT and Cosmology.

- E. W. Kolb and M. S. Turner, *The Early Universe*, Addison-Wesley (1990).
- J. Cline, *Baryogenesis*, hep-ph/0609145 (2006).
- C. Balazs, *Baryogenesis: A small review of the big picture*, arXiv:1411.3398 [hep-ph] (2014).

Matter-Antimatter Asymmetry

- Solution to the Dirac equation
$$i\gamma^{\mu}\partial_{\mu}\psi(\mathbf{x}, t) - m\psi(\mathbf{x}, t) = 0$$
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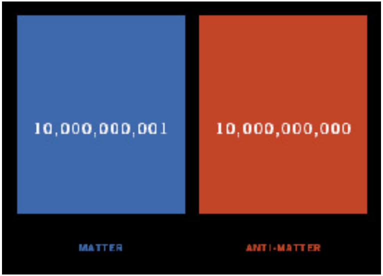
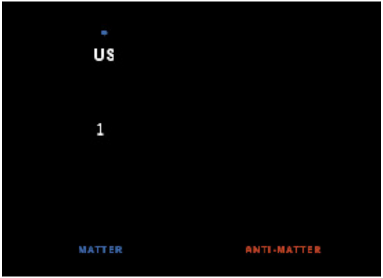
- In a *CPT*-symmetric universe, we expect equal number of particles and antiparticles.
- But the current universe contains mostly matter and no ambient antimatter.
- So an asymmetry between matter and antimatter must have been generated dynamically as the universe evolved.





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- Defined in terms of the quantity

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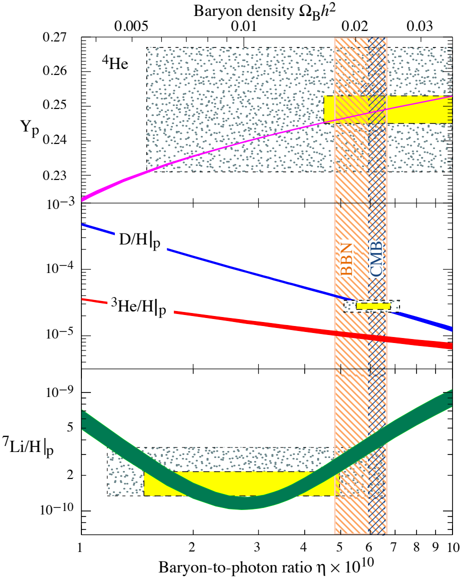
- Using Planck 2015 data,

$$\eta = (6.04 \pm 0.08) \times 10^{-10} \ \text{at } 68\% \ \mathrm{CL}$$

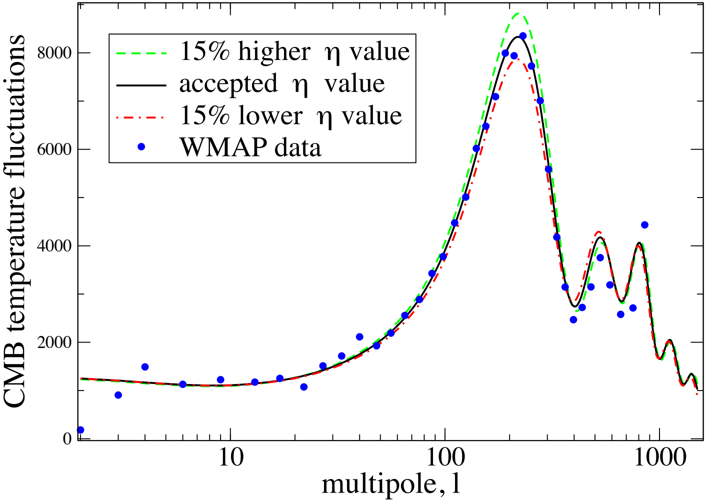
Observed Value

Can be measured at two different epochs: BBN ($t \sim 1$ sec) and CMB ($t \sim 380,000$ yr).



[Particle Data Group '08]

Effect on CMB



[Cline '06]

Sakharov Conditions

- $\eta(t = 0) > 0$ as an initial condition is futile, because
  - Requires huge fine-tuning (1 part in a billion) between quark and anti-quark number densities.
  - Inflation would have exponentially diluted any $\eta(t = 0)$ to negligible values.
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- Three basic conditions must be satisfied. [A. D. Sakharov (JETP Lett. '67)]
  - *B* violation
  - *C* & *CP* violation
  - departure from thermal equilibrium
- Necessary but not sufficient.

Sakharov Conditions Illustrated

Imagine a particle X that decays to quark/lepton final states.

particle		final state	branching ratio	baryon number of final state
X	$\rightarrow$	qq	r	2/3
X	$\rightarrow$	$\bar{q}\bar{l}$	$1-r$	$-1/3$
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- By CPT, X and $\bar{X}$ must have the same *total* decay rate.
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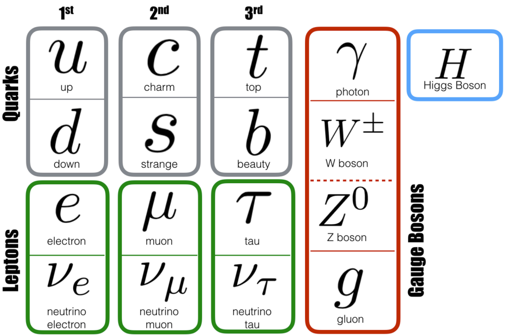
- By CPT, X and $\bar{X}$ must have the same *total* decay rate.
- But C and CP are violated (2nd condition) if $r \neq \bar{r}$.
- Now imagine a box containing equal number of X and $\bar{X}$, i.e. symmetric initial condition.
- Net baryon number produced by X decay is $B_X = r(2/3) + (1-r)(-1/3)$.
- Net baryon number produced by $\bar{X}$ decay is $B_{\bar{X}} = \bar{r}(-2/3) + (1-\bar{r})(1/3)$.
- Net baryon number produced by X,$\bar{X}$ pair is $B_{\rm tot} = B_X + B_{\bar{X}} = r - \bar{r}$.
- For $r \neq \bar{r}$, a net baryon number is generated (2nd condition).
- The out-of-equilibrium decay of X, $\bar{X}$ (3rd condition) is needed to prevent the back reactions from erasing this net asymmetry.

Sakharov in the Standard Model



The Standard Model has the necessary ingredients to satisfy all three Sakharov conditions.

- *B* violation through electroweak sphalerons.
- Maximal *C* violation due to weak interactions being chiral.
- *CP* violation in the quark sector due to the K-M phase $\delta \sim 69^\circ$.
- Out-of-equilibrium dynamics at the electroweak scale due to electroweak phase transition.

The Glashow-Salam-Weinberg model of electroweak interactions is a spontaneously broken QFT based on the $SU(2)_L \times U(1)_Y$ gauge group:

$$\mathcal{L} = (D_\mu \phi)^\dagger D^\mu \phi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} + V(\phi) + \mathcal{L}_{\text{fermions}}$$

where

$$\begin{aligned} D_\mu &= \partial_\mu - i\frac{g}{2}\boldsymbol{\tau} \cdot \boldsymbol{A}_\mu - i\frac{g'}{2} B_\mu, \\ F_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu, \\ W^a_{\mu\nu} &= \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g\varepsilon^{abc} A^b_\mu A^c_\nu \end{aligned}$$

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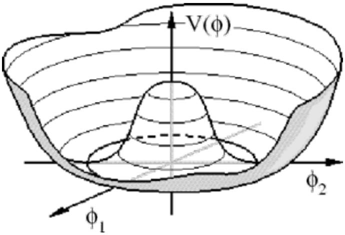
$$V(\phi) = \frac{\lambda}{4}(\phi^\dagger \phi - v^2)^2$$



Baryon Number in the EW Theory

- The SM Lagrangian has accidental global $U(1)_B$ and $U(1)_L$ symmetries.
- Applying Noether's theorem, we obtain the associated symmetry currents J^B_μ and J^L_μ, which are conserved at the Born level:

$$\partial^\mu J^B_\mu = \partial^\mu \sum_q \frac{1}{3} \bar{q}\gamma_\mu q = 0, \qquad \partial^\mu J^L_\mu = \partial^\mu \sum_l \bar{l}\gamma_\mu l = 0.$$

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- However, the gauge-invariant chiral currents are not conserved at the quantum level (Adler-Bell-Jackiw anomaly).

$$\partial^\mu \bar{f}_L\gamma_\mu f_L = -c_L \frac{g^2}{32\pi^2} F^a_{\mu\nu}\widetilde{F}^{a\mu\nu}, \qquad \partial^\mu \bar{f}_R\gamma_\mu f_R = c_R \frac{g^2}{32\pi^2} F^a_{\mu\nu}\widetilde{F}^{a\mu\nu}.$$

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- For $SU(3)_c$, $c_L^{\mathrm{QCD}} = c_R^{\mathrm{QCD}}$, so no anomaly.
- But for $SU(2)_L$, $c_R^W = 0$. Similarly, for $U(1)_Y$, $c_L^Y \neq c_R^Y$.
- Thus for the EW theory, we get the anomalous current

$$\partial^\mu J^B_\mu = \partial^\mu J^L_\mu = \frac{n_f}{32\pi^2} (-g^2 W^a_{\mu\nu} \widetilde{W}^{a\mu\nu} + g'^2 B_{\mu\nu} \widetilde{B}^{\mu\nu})$$

- Thus, $B - L$ is conserved, but neither B nor L nor $B + L$.

B Violation in the SM

- Integrate the anomalous currents over space-time and use Gauss's law (to convert volume integrals into surface integrals).
- The Abelian part makes no contribution to the integral.
- Only the non-Abelian part remains:

$$\Delta B = \Delta L = n_f [N_{\mathrm{CS}}(t_f) - N_{\mathrm{CS}}(0)] \equiv n_f \Delta N_{\mathrm{CS}}$$

where $N_{\mathrm{CS}}(t)$ is the Chern-Simons number, given by

$$N_{\mathrm{CS}}(t) = \frac{g^3}{96\pi^2} \int d^3x \varepsilon_{ijk} \varepsilon_{abc} W^{ai} W^{bj} W^{ck}$$

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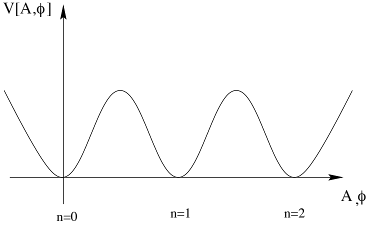
with the temporal gauge condition $W^{a0} = 0$.
- EW vacuum is periodic and the CS number changes by one between adjacent vacua, causing B violation.



Rate of Transition

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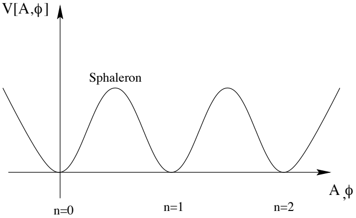
- However, at finite temperatures, can go over the barrier.
- Governed by the smallest possible barrier between vacua – the sphaleron.



$$E_{\text{sph}}(T) = \frac{4\pi}{g} v_T f\left(\frac{\lambda}{g}\right)$$

where v_T is the Higgs VEV at temperature T and the parameter f varies between 1.6 and 2.7 depending on the Higgs self-coupling λ.

- At $T = 0$, $v_T = 246$ GeV and $E_{\text{sph}} \simeq 8 - 13$ TeV.

Rate of Transition

$$\Gamma_{\rm sph}(T) = \kappa \left(\frac{m_W}{\alpha_w T}\right)^3 m_W^4 \exp\left[-\frac{E_{\rm sph}}{T}\right]$$

where $m_W(T) = gv_T/2$ and κ is a dimensionless constant.

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- For $T > T_{\rm EW} \sim 100$ GeV,

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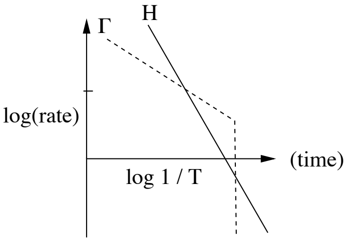
- Sphaleron transitions will be active as long as $\Gamma_{\mathrm{sph}}(T) \gtrsim H(T) \simeq 1.66\sqrt{g_*}\frac{T^2}{M_{\mathrm{Pl}}}$.
- This happens for temperature range $100\ \mathrm{GeV} \lesssim T \lesssim 10^{12}$ GeV.
- B violation is unsuppressed and copious!



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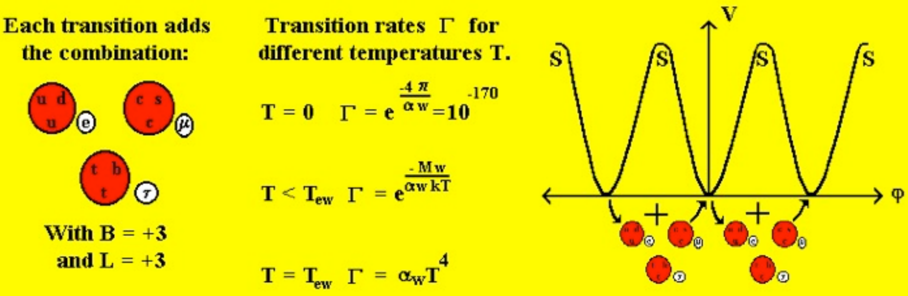

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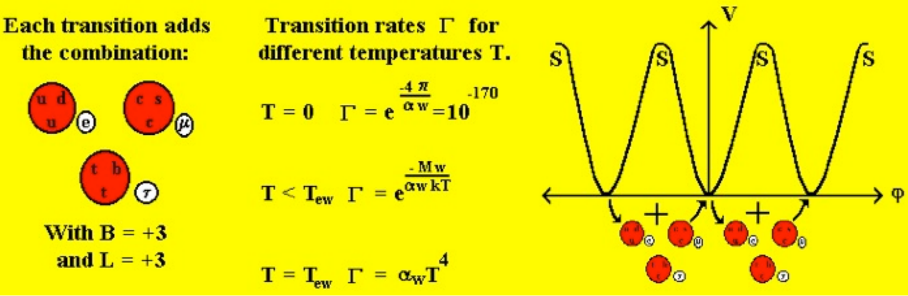
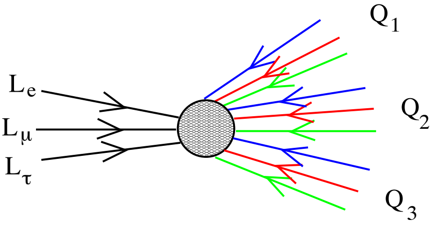
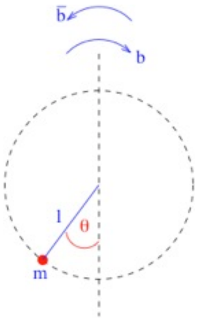




$\boxed{\text{Leads to } \Delta B = \Delta L = 3.}$

A simple pendulum



A Classical Analogy

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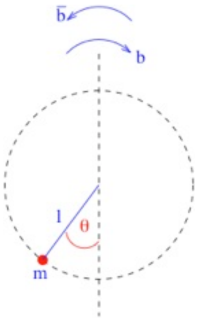

$$L = \frac{1}{2} m l^2 \dot{\theta}^2 - mgl(1 - \cos\theta)$$

- Vacua: $\theta_n = 2n\pi$ with $n \in Z$ (analogous to the CS vacua).
- Periodic potential implies periodic wave-functions.

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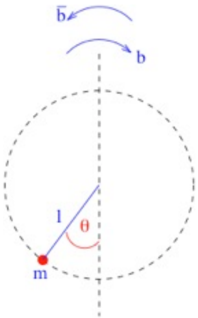

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- Define $\chi \equiv \theta/2$, $\omega \equiv g/l$, $\alpha \equiv \hbar\omega/4mgl \ll 1$.
- Schrödinger equation:

$$\frac{\hbar\omega}{2}\left(-\alpha\frac{d^2}{d\chi^2} + \frac{1}{\alpha}\sin^2\chi\right)\psi_n(\chi) = E_n\psi_n(\chi)$$

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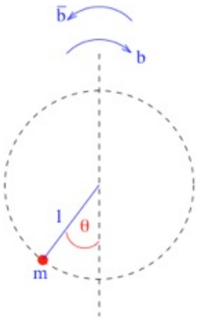

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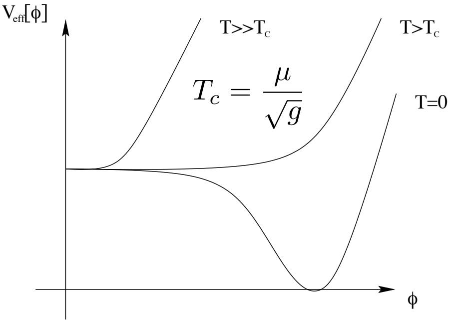
- Perturbative approach: $\sin^2\chi = \chi^2 - \frac{\chi^4}{3} + \cdots$
- First term: Harmonic oscillator.
- Approach valid for energies $\ll$ barrier height.
- Periodicity lost in perturbative approximation (analogous to the perturbative regime of the SM).

Departure from Equilibrium

- SM Higgs sector has also interesting behavior at finite temperature.
- Without Yukawa interactions,

$$V_{\text{eff}}(\phi, T) = \frac{1}{2}(gT^2 - \mu^2)\phi^2 + \frac{\lambda}{4}\phi^4$$

- Phase transition at $T_c = \mu/\sqrt{g}$.



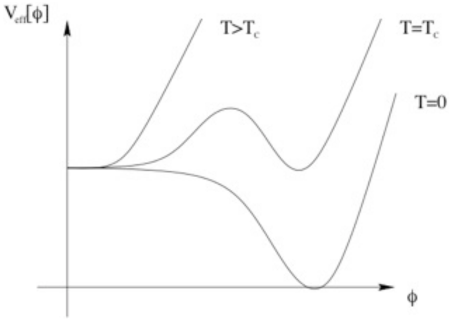
- PT is continuous (2nd order), as the field calmly rolls down the effective potential to its non-zero minimum as T drops below T_c.
- Insufficient for baryogenesis.

Departure from Equilibrium

- Including Yukawa couplings yields a more interesting possibility.

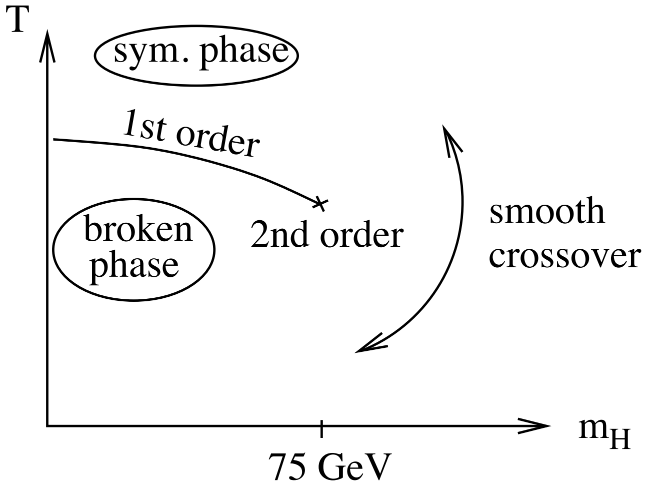
$$V_{\text{eff}}^{(1)}(\phi, T) = \left(\frac{3}{32}g^2 + \frac{\lambda}{4} + \frac{m_t^2}{4v^2}\right)(T^2 - T_c^2)\phi^2 - \frac{3}{32\pi}g^2 T\phi^3 + \frac{\lambda}{4}\phi^4$$

$$T_c = m_H\left(\frac{3}{8}g^2 + \lambda - \frac{9}{256\pi^2}g^6 + \frac{m_t^2}{v^2}\right)^{-1/2}$$



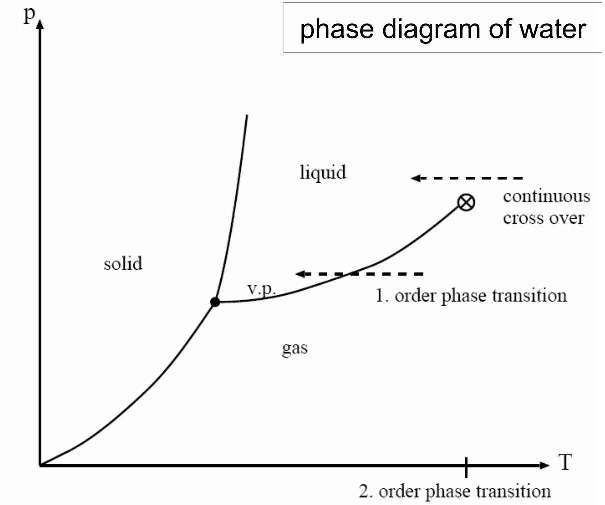
- If the cubic term is large enough, a strongly 1st order phase transition occurs.

SM Phase Diagram

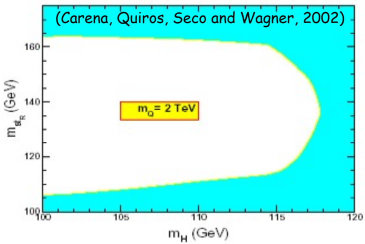


- 1st order PT not possible in the SM for the observed $m_H = 125$ GeV.
- **Rules out SM baryogenesis.**

Classical Analogy



MSSM Baryogenesis



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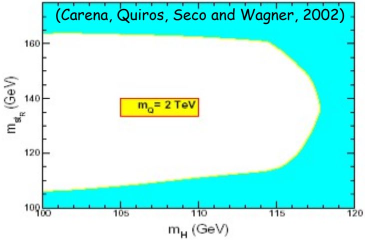
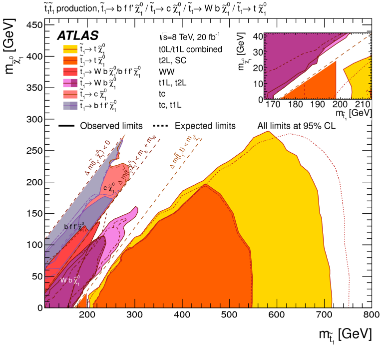
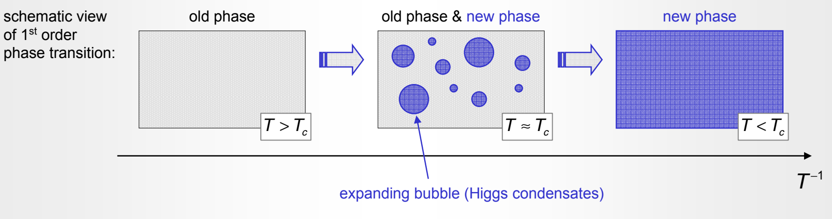




Why 1st Order?

- Discontinuous change of v_T leads to condensation of Higgs field at $T \sim T_c$.



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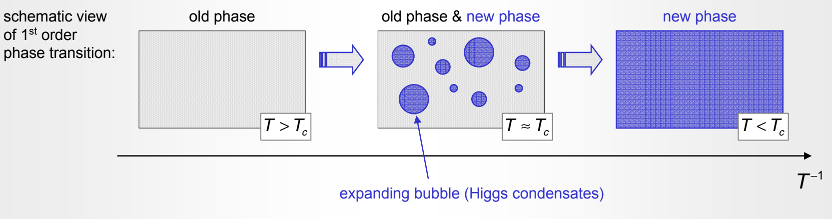
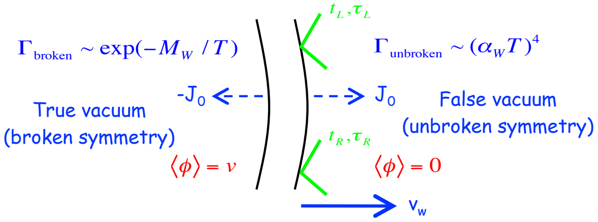


- Asymmetric reflection and transmission of chiral fermions through the bubble wall.
- *CP* violation at the boundary due to gradient in the Higgs phase.
- If the PT is strong enough, overcomes washout and excess *B* is frozen in.



SM *CP* Violation

- Through the CKM quark mixing matrix V_{CKM}.
- 1 *CP* phase for $n_f = 3$.
- Relevant quantity for us:

$$J = \det[m_u^2, m_d^2] = (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)K$$

where

$$K = \mathrm{Im}[V_{ii} V_{jj} V_{ij}^* V_{ji}^*] \qquad (\text{with } i \neq j)$$

- Strength of *CP* violation can be estimated by calculating the dimensionless quantity

$$\frac{J}{v_{\mathrm{EW}}^{12}} \sim 10^{-18}$$

- Too small to account for the observed BAU $\eta \sim 10^{-10}$.

(see M. Bona's lecture)

Summary

- CKM *CP* violation is too small (by $\sim$ 10 orders of magnitude).
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Requires New Physics!

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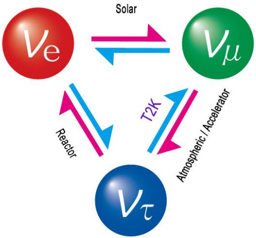
Requires New Physics!

- New sources of *CP* violation.
- Another mechanism for departure from equilibrium (in addition to EWPT) or modify the EWPT itself.
- Many interesting ideas, some of which are testable down to the EW scale and below.
- We will focus on one interesting scenario: Leptogenesis.

Connection to Neutrino Mass



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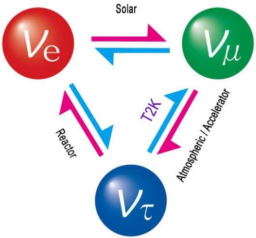
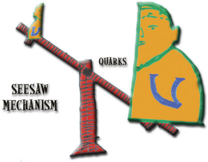
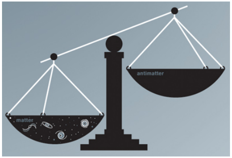


Seesaw Mechanism: a common link between neutrino mass and baryon asymmetry.





[Fukugita, Yanagida (Phys. Lett. B '86)]