CP VIOLATION and BARYOGENESIS

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CP violation ($\not{C}\not{P}$) in the laboratory observed so far
in the mixing and weak decays of K mesons (1964) and B mesons (2001)

These CP phenomena occur in $|\Delta F| = 2$ & $|\Delta F| = 1$ transitions;
can be explained by Kobayashi-Maskawa mechanism,
i.e., by a phase δ_{KM} in the couplings of the charged weak quark current

Long-standing question (since Sakharov (1967)):

Is $\not{C}\not{P}$ observed in the lab $\longrightarrow$ matter $-$ $\overline{\text{matter}}$ asymmetry of universe?

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \times 10^{-10}$$

More specifically:

Does $\arg \epsilon_K \simeq 43^\circ$ i.e., sign $\delta_{KM} > 0$ $\longrightarrow$ matter rather than antimatter in universe?

Modern version:

Can SMs of particle physics and cosmology explain η?

State of the art $\longrightarrow$ conclusion: NO!

CONTENTS

- The baryon asymmetry (BAU) η
- Sakharov conditions for dynamical generation of η
- $\not{B}$ in the standard model (SM) of particle physics
- Scenario 1: Baryogenesis at the electroweak phase transition (EWBG)

  Why the SM fails
  EWBG in some SM extensions (2 Higgs doublet, SUSY extensions)
  Is the SM $\not{C}\not{P}$ relevant?

- Scenario 2: Baryogenesis via leptogenesis
  through decay of ultra-heavy Majorana neutrinos
- Conclusions

Some reviews:

- W. Bernreuther, "CP violation and baryogenesis," Lect. Notes Phys. **591** (2002) 237 [hep-ph/0205279].
- M. Dine and A. Kusenko, "The origin of the matter-antimatter asymmetry," Rev. Mod. Phys. **76** (2004) 1 [hep-ph/0303065].
- J. M. Cline, "Baryogenesis", hep-ph/0609145.
- W. Buchmüller, R. D. Peccei and T. Yanagida, "Leptogenesis as the origin of matter," Ann. Rev. Nucl. Part. Sci. **55** (2005) 311 [hep-ph/0502169].
- A. Strumia, "Baryogenesis via leptogenesis", hep-ph/0608347.

The baryon asymmetry (BAU) $\eta \sim 10^{-10}$

Observations $\longrightarrow$ NO primordial antimatter in observable part of universe

• cosmic rays contain some fraction of $\bar{p}$: $n_{\bar{p}}/n_p \sim 10^{-4}$
consistent with secondary production

$$p \longrightarrow \mathrm{ISM}; \quad \mathrm{e.g.} \quad p + p \longrightarrow 3p + \bar{p}$$

• no evidence for $\overline{\mathrm{D}}$, $\overline{\mathrm{He}}$, ... found

• if large domains of matter and $\overline{\mathrm{matter}}$ would exist (e.g., galaxies and $\overline{\mathrm{galaxies}}$)
$\longrightarrow$ annihilation at boundaries:

$$p\bar{p} \longrightarrow (5 - 6)\pi\,, \qquad \pi^0 \longrightarrow 2\gamma\,, \quad \mathrm{peak} \sim 150\mathrm{MeV}$$

no anomaly in γ ray background observed

Conclusion: universe consists only of matter on scales $\lesssim 10^2 - 10^3\,\mathrm{Mpc}$
Cohen et al. (1998), ...

Determination of density $n_B - n_{\bar{B}} \simeq n_B$:

compare with number of γ's in microwave background:

$$n_\gamma = \frac{2\zeta(3)}{\pi^2} T^3 \simeq 420/\mathrm{cm}^3$$

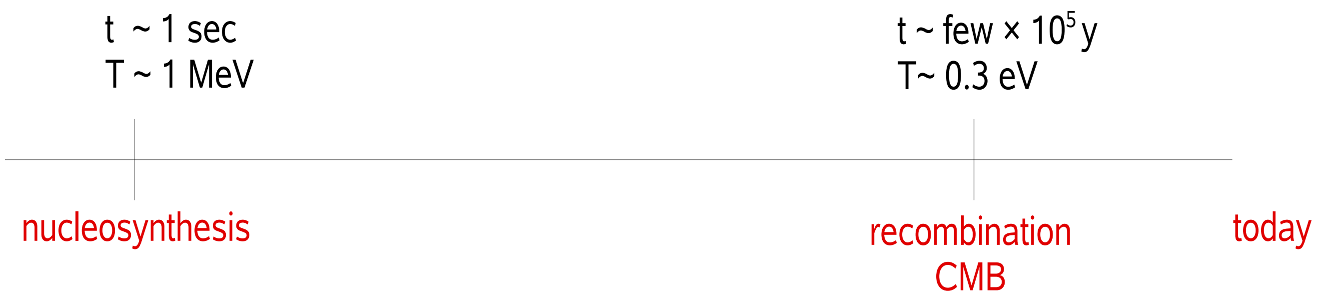
Most precise determinations of $\eta = \frac{n_B}{n_\gamma}$ come from

• Theory of primordial nucleosynthesis: present abundances of D, $^3\mathrm{He}$, $^4\mathrm{He}$, (Li) calculated in terms of input parameter η

$$\text{data} \quad \longrightarrow \quad 3.4 \times 10^{-10} < \eta < 6.9 \times 10^{-10}$$

• WMAP (2003): measurement of cosmic microwave background

$$\text{fits to data} \longrightarrow \Omega_b \longrightarrow \eta = (6.15 \pm 0.25) \times 10^{-10}$$



For models of baryogenesis a more useful quantity is

$$Y_B \equiv \frac{n_B}{s} \qquad \text{where s } = \text{ entropy density of universe}$$

remains constant during isentropic expansion

value today: $s \simeq 7 n_\gamma$

$$\longrightarrow Y_B = \frac{n_B}{s} \simeq \frac{1}{7}\eta \simeq 10^{-10}$$

In old days of bing bang model, $\eta \sim 10^{-10}$ was accepted as one of the fundamental cosmological input parameters.

Attitude changed with Sakharov's 1967 paper:

Within big bang model + model of particle physics interactions $\eta \neq 0$ can be explained, i.e., generated dynamically

if

- $\not{B}$ interactions
- $\not{C}$ and $\not{C}\mathrm{P}$ interactions
- departure from thermal equilibrium $\not{\mathrm{T}}\mathrm{E}$ ("arrow of time")

Which (experimentally testable) theories/models yield right order of magnitude of η ?

$\eta_{initial} = 0$ natural in view of inflation

- Requirement of $\not{B}$ obivous

- $\not{C}$ and $\not{C}\not{P}$:

baryon number operator $\hat{B} = \frac{1}{3}\sum_q \int d^3x\, q^\dagger q \;\; \rightarrow \;\; -\hat{B}$ under C and CP

$\longrightarrow \;\; \langle \hat{B} \rangle = 0$ if C and/or CP invariance holds

- $\not{T}\not{E}$:

if CPT invariance holds $\longrightarrow$ mass $m_A = m_{\bar{A}}$ for any particle A

$\longrightarrow$ equilibrium distributions in phase space

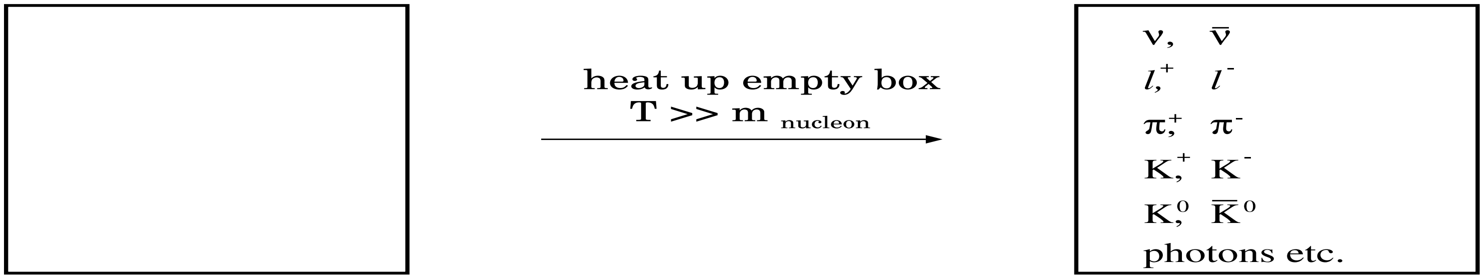
$$f_A^{eq}(\mathbf{p}) \;=\; \mathbf{f_{\bar{A}}^{eq}}(\mathbf{p})$$

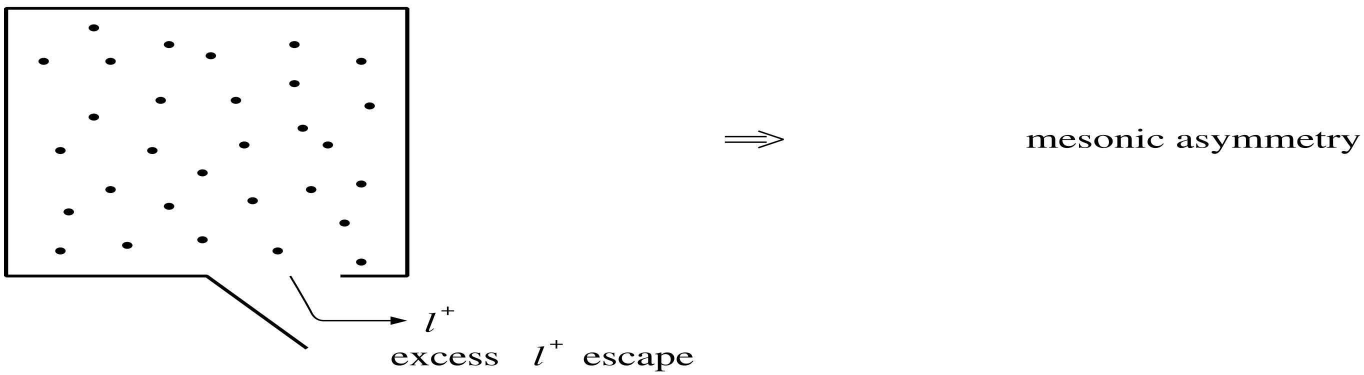
$\longrightarrow$ in thermal equilibrium

$$N_A \;=\; \int \frac{d^3p}{(2\pi)^3}\, f_A^{eq} \;=\; N_{\bar{A}}$$

(Note: in general, the Sakharov conditions are sufficient, not necessary.
E.g., give up CPT invariance)

Gedanken-Experiment to illustrate 2 of the 3 Sakharov conditions





equal # of K^0 and $\bar{K}^0$, CPV in semileptonic decay $K_L \longrightarrow \pi^{\mp}\ell^{\pm}\nu \longrightarrow N(\pi^-) > N(\pi^+)$.
As long as system is in thermal equilibrium $\longrightarrow$ CPV in reactions like
$\pi^-\ell^+ \leftrightarrow \pi^+\pi^-\bar{\nu}_\ell$ and $\pi^+\ell^- \leftrightarrow \pi^+\pi^-\nu_\ell$ will wash out temporary excess of π^-.

If thermal instability, excess ℓ^+ can escape,
inverse reactions with ℓ^+ "blocked" $\longrightarrow$ mesonic asymmetry $N(\pi^-) - N(\pi^+) > 0$

$\not{B}$ in the standard model (SM) of particle physics

The SMs of cosmology and particle physics have, in principle, all the ingredients:

- $\not{T}\not{E}$ from expansion of universe
- $\not{C}$ and $\not{C}\not{P}$ due to SM weak interactions
- $\not{B}$ also by the SM weak interactions: tiny effect in the laboratory, but large in early universe

	q	$\bar{q}$	ℓ^-, ν_ℓ	ℓ^+, $\bar{\nu}_\ell$
B	1/3	-1/3	0	0
L	0	0	1	-1

No hint of $\not{B}$ or $\not{L}$ in the laboratory
Corresponds to circumstance that

$$\mathcal{L}_{SM}^{class} = \mathcal{L}_{QCD} + \mathcal{L}_{SU(2)_L \times U(1)_Y}$$

has 2 global symmetries: $U(1)_B$ and $U(1)_L$
i.e., 2 classically conserved charges: B and L number

However, B and L symmetry explicitly broken at quantum level
by "large" gauge field fluctuations $W^a_\mu \sim 1/g_W$

Results : 't Hooft (1976)

- B, L violated, but

B - L conserved in SM

- in SM, all reactions

$$i\ (L_i, B_i) \longrightarrow f\ (L_f, B_f)$$

obey the selection rule

$$\Delta B \ = \ \Delta L \ = \ n_{gen}\, Q_{CS}$$

where $n_{gen} = 3$, and $Q_{CS} = 0, \pm 1, \pm 2, \ldots$

I.e., if B violated then $|\Delta B| = |\Delta L|$ at least 3 (no proton decay!)

$\not{B}+\not{L}$ transitions involve

9 left-handed quarks q_L (3 color states for each generation)
3 left-handed leptons $\ell_L,\ \nu_L$ (one per generation)
respectively $q_L,\ \ell_L,\ \nu_L\ \longrightarrow\ \bar{q}_R,\ \bar{\ell}_R,\ \bar{\nu}_R$

't Hooft (1976):

SM prediction for present lab. energies $E_{cm} \lesssim$ a few TeV
(we are in heat bath $T \simeq 0$):

$B\!\!\!/$ and $L\!\!\!/$ reactions with $\Delta(B-L)=0$, for instance, $\Delta B = \Delta L = \mp 3$:

$$u_L + d_L \longrightarrow \bar{d}_R + 2\bar{s}_R + \bar{c}_R + \bar{t}_R + 2\bar{b}_R + \bar{\nu}_e + \bar{\nu}_\mu + \bar{\nu}_\tau \,,$$
$$\bar{u}_R + \bar{d}_R \longrightarrow d_L + 2s_l + c_L + t_L + 2b_L + \nu_e + \nu_\mu + \nu_\tau \,,$$

but cross section exponentially suppressed for above kinematic situation!

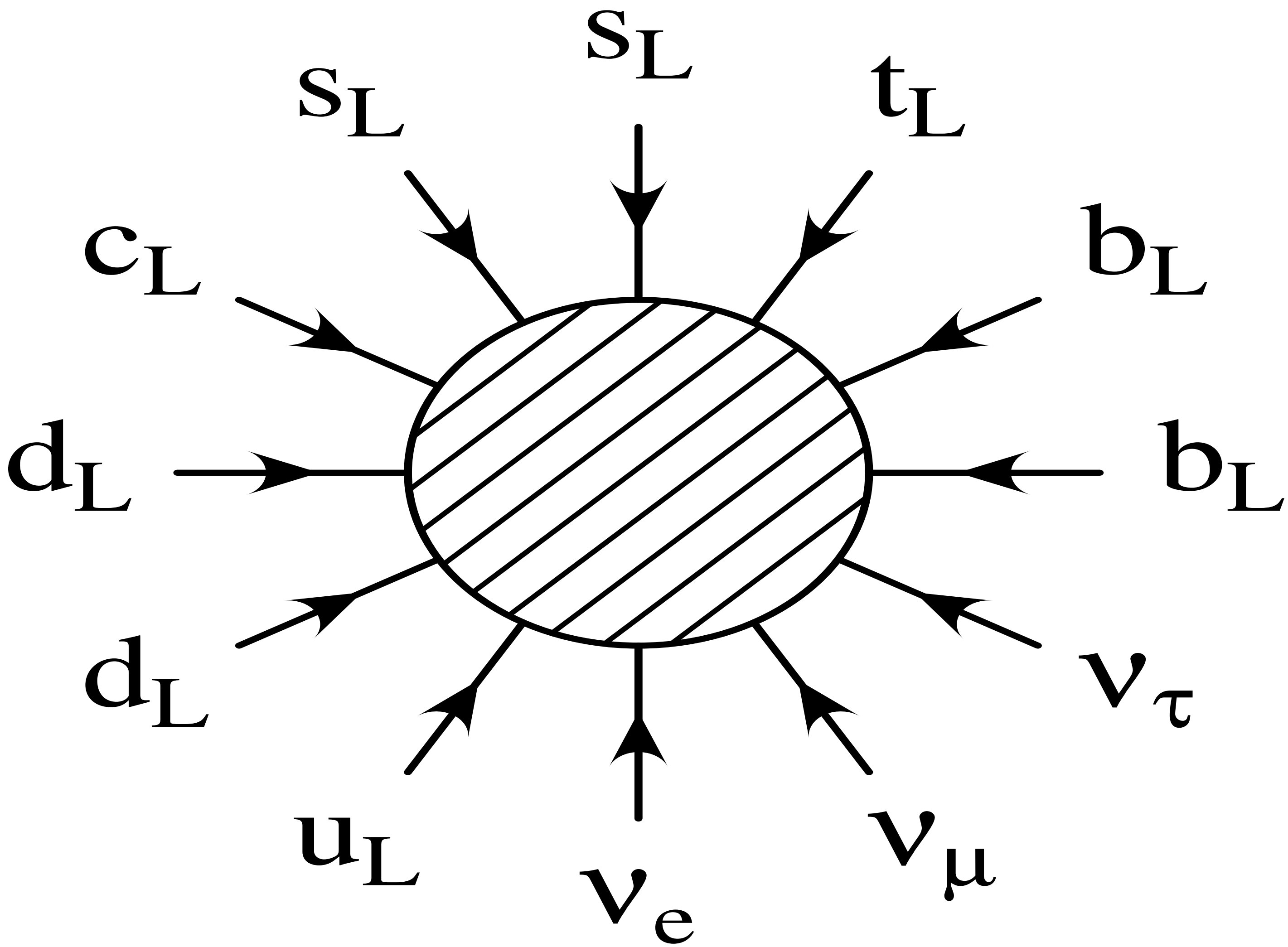
$$(\mathrm{Amp})_{\mathrm{B+L}} \sim \exp\left(-2\pi/\alpha_W\right)$$
$$\hat{\sigma}_{\mathrm{B+L}} \sim 10^{-129}\,\mathrm{pb} \quad \mathrm{at}\ \sqrt{\hat{s}} \sim 10\,\mathrm{TeV}\,.$$

Total inclusive $B\!\!\!/ + L\!\!\!/$ cross section, which involves reactions

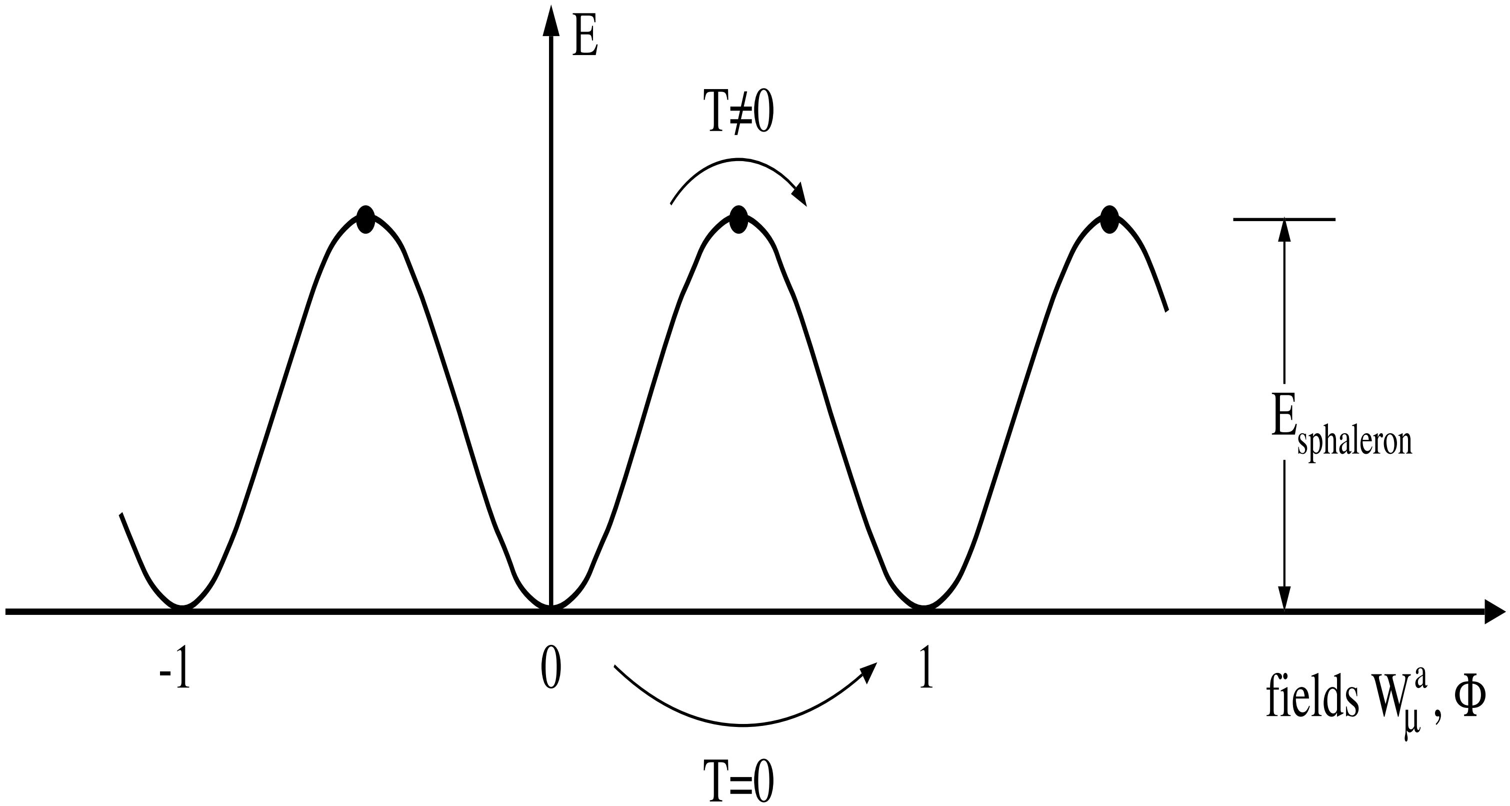
$$qq \longrightarrow 7\bar{q} + 3\bar{\ell} + n_H\,H + n_W\,W$$

could be substantially larger at $\hat{s} \gg 10\mathrm{TeV}$ (Ringwald; Espinoza (1990))

One of the $\not{B} + \not{L}$ amplitudes in SM



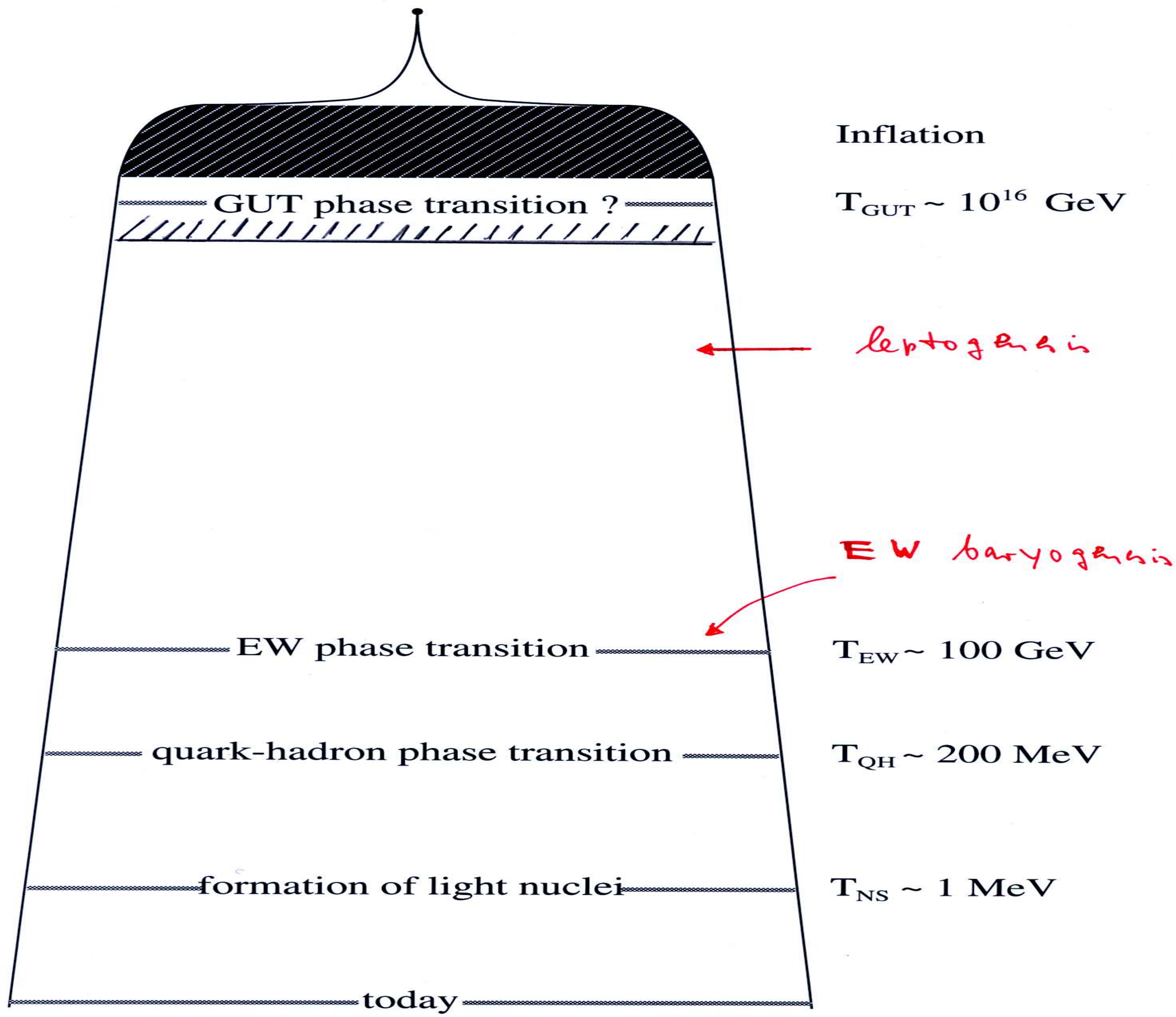
Periodic vacuum structure of SM



sphaleron = Higgs + W_μ^a field configuration which sits on top of energy barrier

Klinkhamer, Manton (1984)

Carton of the history of the universe



$\not{B} + \not{L}$ reaction rates at $T \neq 0$ (Kuzmin, Rubakov, Shaposhnikov 1985)

- $T < T_{EW} \sim 100$ GeV: EW gauge symmetry broken

$\not{B} + \not{L}$ reaction rate (sphaleron-induced processes):

$$\Gamma_{\rm B+L} \;=\; \kappa T \left(\frac{\alpha_W}{4\pi}\right)^4 \exp\left[-(4\pi f/g_W)(v_T/T)\right]$$

where $v_T = \sqrt{2}\langle 0|\Phi|0\rangle_T <$ 246 GeV $= v_{T=0}$

- in unbroken phase $T > T_{EW}$: $\not{B} + \not{L}$ reactions unsuppressed

$$\Gamma_{\rm B+L} \;=\; \kappa' \alpha_W^5 T \;\simeq\; 10^{20} \frac{T}{100 {\rm GeV}} \; [{\rm sec}^{-1}]$$

(Moore et al.; Bödeker et al., 2000)
Compare with expansion rate of universe
in radiation dominated era, $H = 1.66\sqrt{g_{eff}}\, T^2/M_{Planck}$, $\quad g_{eff} \sim 100$

$\longrightarrow$ $\not{B} + \not{L}$ **SM reactions are in thermal equilibrium ($\Gamma_{\rm B+L} > H$) for**

$$\mathbf{T_{EW} \sim 100\,{\rm GeV} \;<\; T \;<\; 10^{12}\,{\rm GeV}}$$

important constraint for baryogenesis scenarios above T_{EW} !

Scenario 1: Baryogenesis at EW phase transition

Suppose there is only SM physics at $T < T_{inflation}$.

Assuming $\eta_{initial} = 0$, how to explain $\eta \sim 10^{-10}$?

early universe @ $T > T_{EW}$: plasma of massless SM particles.

For $\mathbf{T_{EW} \sim 100\,GeV \ < \ T \ < \ 10^{12}\,GeV}$

$\not{B}$ reaction rates $\quad \Gamma_{\mathrm{B+L}} \ > \ H$

i.e., any temporary excess of B, L washed out by inverse reactions

$$\longrightarrow \qquad \langle \hat{\mathbf{B}} \rangle_{\mathbf{T}} \ = \ \mathbf{0}$$

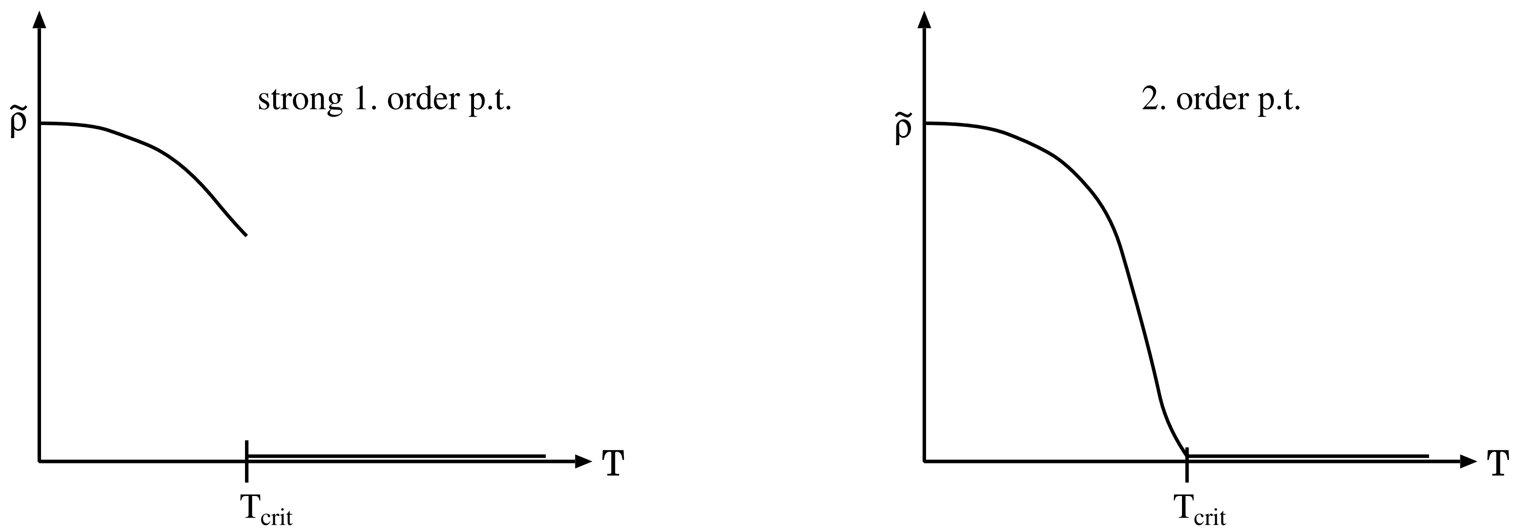
sizeable $\not{T}\!\not{E}$ required !

plausible instance: electroweak phase transition

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

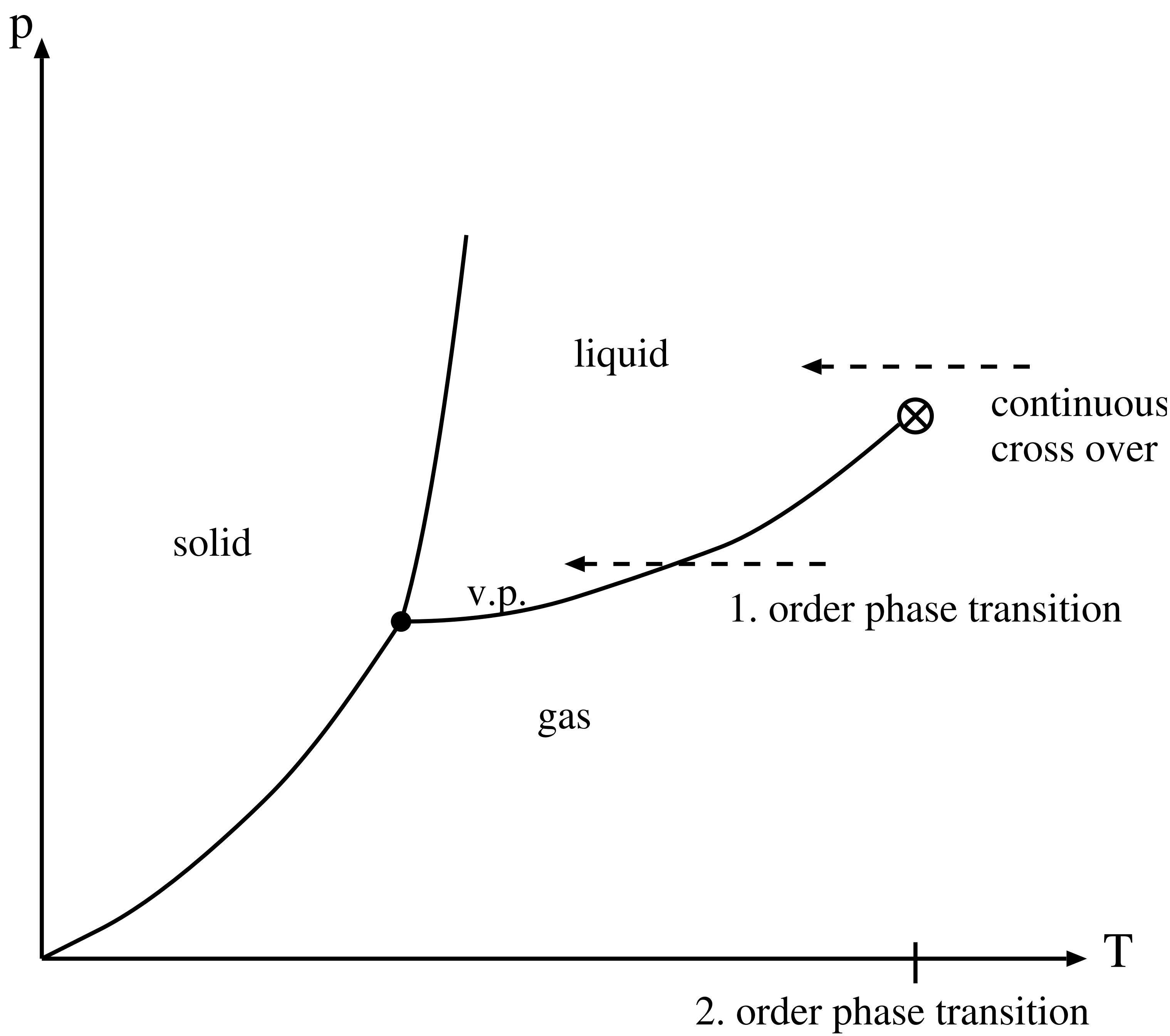
EW gauge symmetry broken at $T_c = T_{EW}$ by some spin 0 condensate,
in SM by $\langle 0|\Phi_{SM}|0\rangle_T \neq 0$.

Phase transition must be **strongly 1. order**
i.e., "order parameter" $v_T = \langle 0|\Phi|0\rangle_T/\sqrt{2}$ must have a sizeable jump at T_c

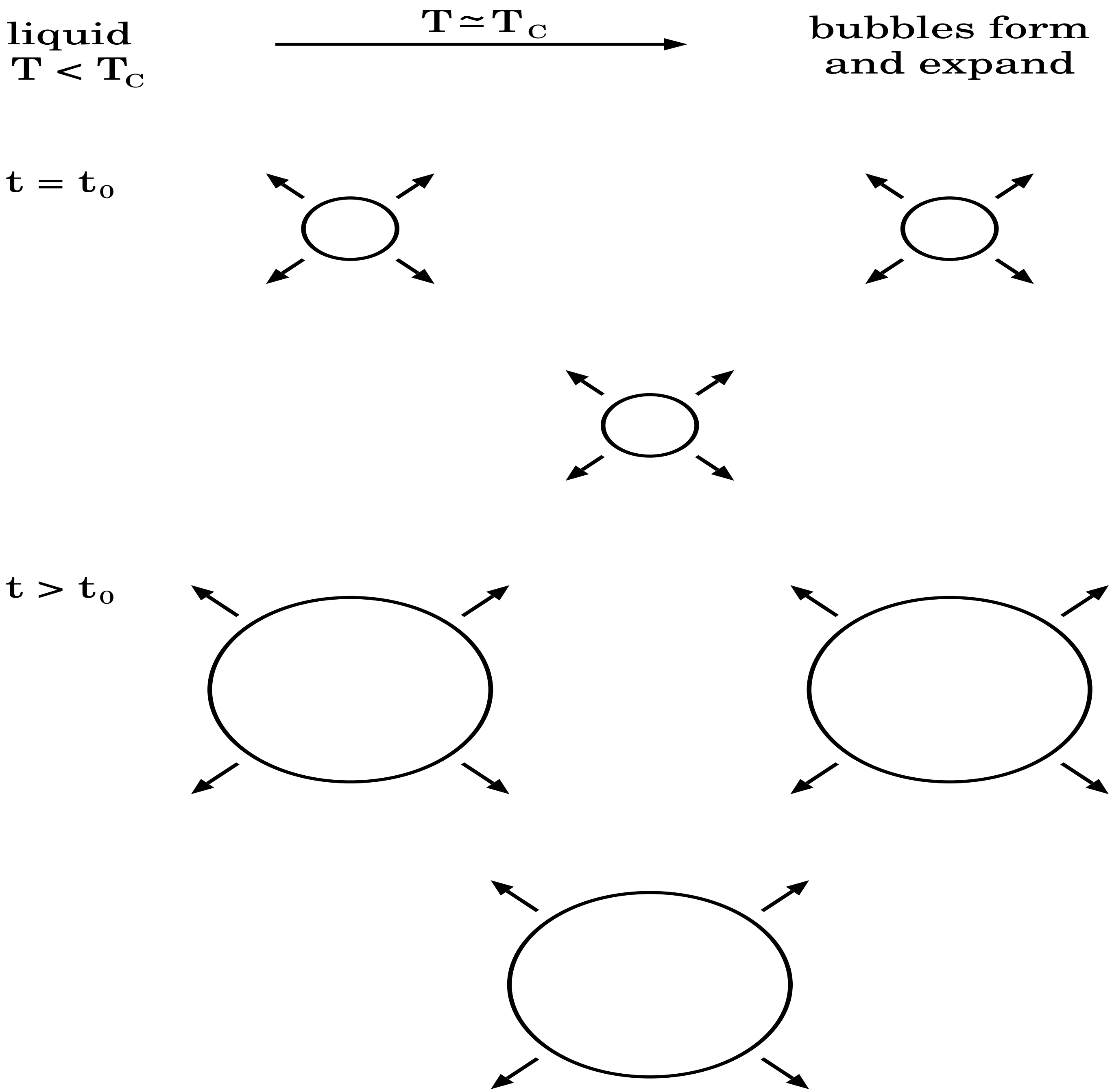


That's what is needed
in order to block the $\not{B}$ reactions
in the region(s) of space where the VEV $v_T \neq 0$

Example from houshold physics: The phase diagram of water



Dynamics of a 1. order phase transition

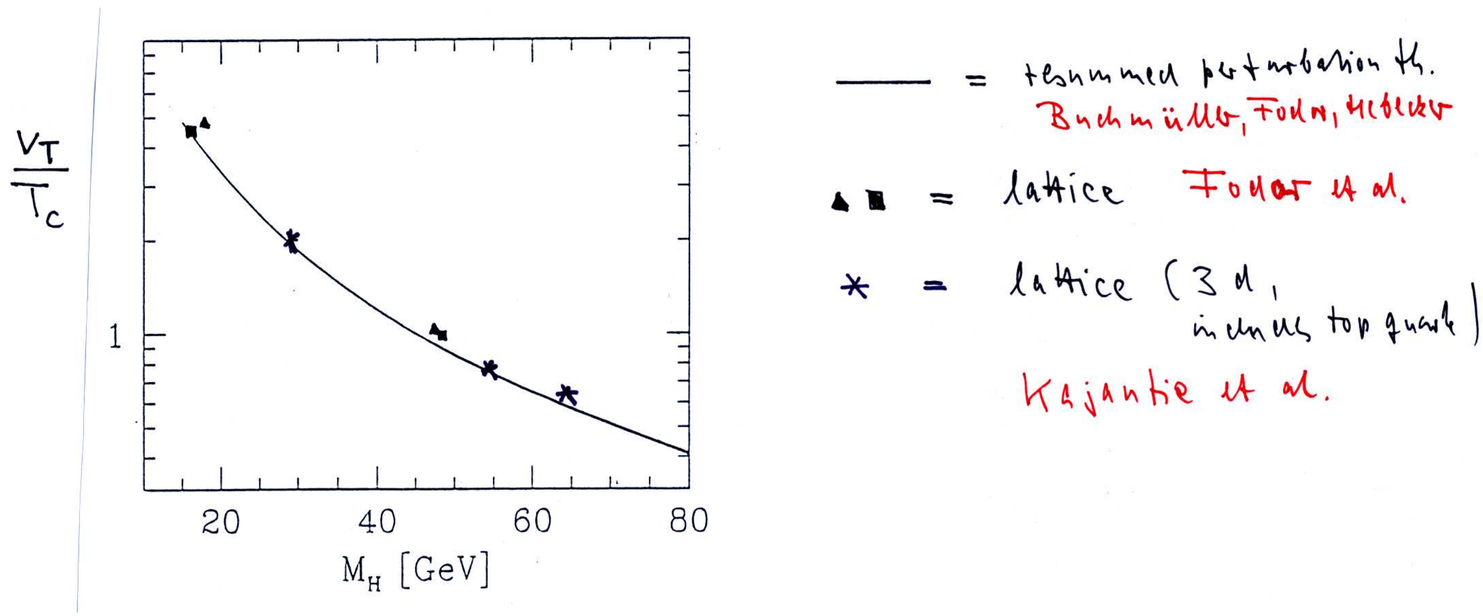


Condition for strength of phase transition:

jump $\frac{\Delta v_{T_c}}{T_c} \gtrsim 1$ required
in oder to suppress $\not{B}$ sphaleron reactions in broken phase for $T \leq T_c$:

$$\Gamma_{\mathrm{B+L}} = \kappa T \left(\frac{\alpha_W}{4\pi}\right)^4 \exp\left[-(4\pi f/g_W)(v_T/T)\right]$$

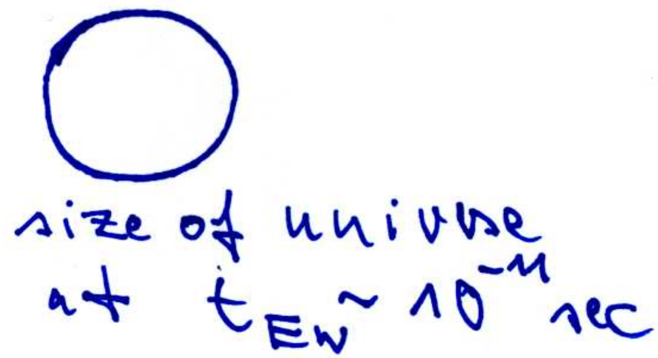
Results for SM SU(2) gauge-Higgs field theory



lattice calculations $\longrightarrow$ **smooth crossover for $m_H > 73$ GeV**

In view of LEP result $m_H^{SM} > 114$ GeV $\longrightarrow$

- **smooth crossover from symmetric phase ($T > T_{EW}$) $\rightarrow$ broken phase ($T < T_{EW}$)**



$$\frac{\Gamma_{\mathrm{B+L}}}{H}\Big|_{T=T_{EW}} \sim 10^{10}$$

- at $T = T_{EW}$:

$\not{B}$ **reactions rapid everywhere, i.e., in thermal equilibrium**
and, for $T \rightarrow 0$, $\Gamma_{\mathrm{B+L}} \rightarrow 0$ adiabatically.

Conclusion:

$\langle \hat{B} \rangle_T = 0$, also for $T \rightarrow 0$
SM cannot explain BAU η

irrespective of role of KM $\not{C}\mathrm{P}$

Some SM extensions

non-SUSY extensions:

- $\Phi \longrightarrow \Phi$ + singlet φ
- $\Phi \longrightarrow$ 2 doublets Φ_1, Φ_2

  i.e., Higgs potential $V_{SM}(\Phi) \longrightarrow V(\Phi, \varphi)$ or $V(\Phi_1, \Phi_2)$

SUSY extensions:

- minimal (MSSM), contains 2 Higgs doublets
- next-to-minimal (NMSSM), contains 2 Higgs doublets + 1 singlet

For certain phenomenologically acceptable parameter regions
$\longrightarrow$ **strong 1. order EW phase transition occurs in these models**

In MSSM: only if

lightest Higgs boson $m_{H_1} < 120$ GeV

and 1 stop particle $(\tilde{t}_R)$: $m_{\tilde{t}_R} < 170$ GeV

(Carena et al., Cline et al., ...)

testable at Tevatron, LHC

New $\not{C}\not{P}$ interactions

Examples: • Higgs sector $\not{C}\not{P}$, e.g. 2 Higgs doublet extension of SM
explicit $\not{C}\not{P}$ in Higgs potential $V(\Phi_1, \Phi_2)$ $\longrightarrow$

$$< 0|\phi_1^0|0 > = v_1 e^{i\xi_1}/\sqrt{2}\,, \qquad < 0|\phi_2^0|0 > = v_2 e^{i\xi_2}/\sqrt{2}\,,$$

$\longrightarrow$ neutral Higgs bosons H_j, $(j = 1, 2, 3)$ no longer CP eigenstates
i.e., couple both to scalar and pseudoscalar quark and lepton currents

$$\mathcal{L}_H = -\sum_\psi \left(c_\psi \frac{m_\psi}{v} \bar{\psi}_L \psi_R H \; - \; c_\psi^* \frac{m_\psi}{v} \bar{\psi}_R \psi_L H \right)$$

At nonzero temperature – here $T \sim T_{EW}$: assume EW phase transition is 1.order.
In the broken phase

$$< 0|\phi_1^0|0 >_T = \rho_1(z)\, e^{i\theta(z)}/\sqrt{2}\,, \qquad < 0|\phi_2^0|0 >_T = \rho_2(z)\; e^{i\omega(z)}/\sqrt{2}\,.$$

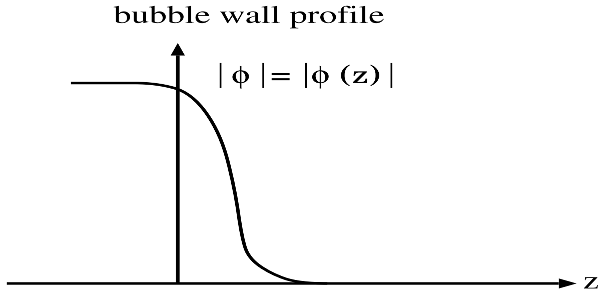
Then

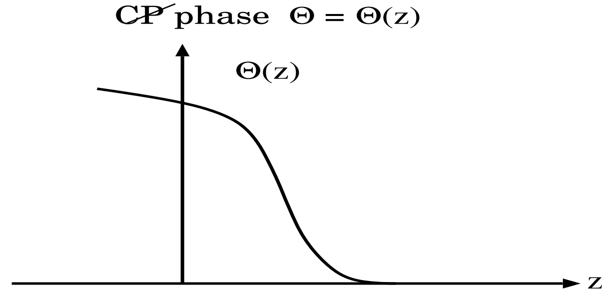
$$\mathcal{L}_{Yuk} \; = \; -h_\psi \bar{\psi}_L \psi_R \phi_1^0 \; + \; h.c. \; = \; -m_\psi(z) \bar{\psi}_L \psi_R \; - \; m_\psi^*(z) \bar{\psi}_R \psi_L \; + \; \ldots \;,$$

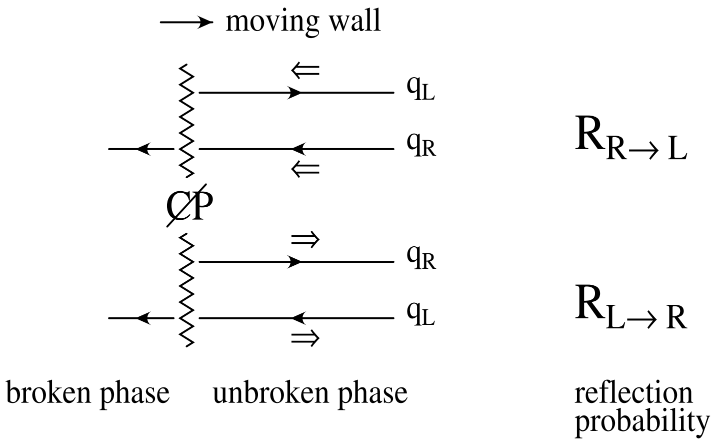
where (analogously for $< \phi_2^0 >$)

$$m_\psi(z) = h_\psi \rho_1(z)\; e^{i\theta(z)}/\sqrt{2}$$

$$\mathcal{L}_\psi \; = \; \bar{\psi}_L i\gamma^\mu \partial_\mu \psi_L + \bar{\psi}_R i\gamma^\mu \partial_\mu \psi_R - m_\psi(z) \bar{\psi}_L \psi_R \; - \; m_\psi^*(z) \bar{\psi}_R \psi_L \,.$$







likewise for $\bar{q}_L \longrightarrow \bar{q}_R,\ \bar{q}_R \longrightarrow \bar{q}_L$ (here: L,R = particle helicities)

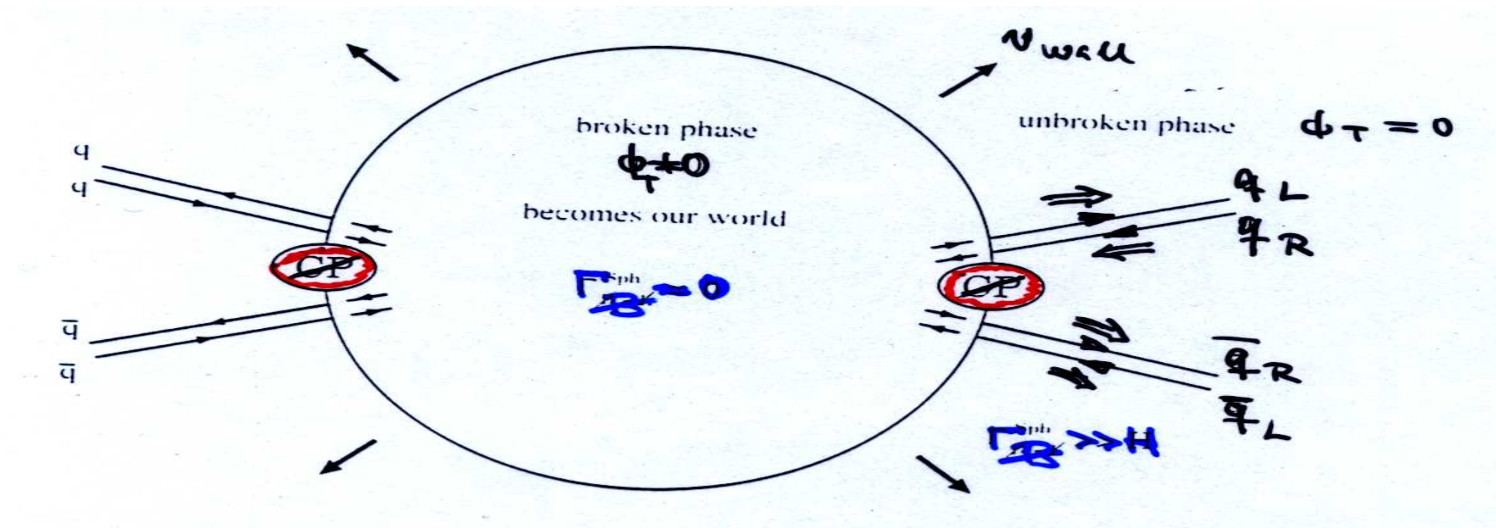
$$\begin{aligned} \text{CP violation :} \quad & \mathcal{R}_{\bar{L}\to\bar{R}} \neq \mathcal{R}_{R\to L} \quad \text{and} \quad \mathcal{R}_{\bar{R}\to\bar{L}} \neq \mathcal{R}_{L\to R} \\ \text{CPT invariance :} \quad & \mathcal{R}_{\bar{L}\to\bar{R}} = \mathcal{R}_{L\to R} \quad \text{and} \quad \mathcal{R}_{\bar{R}\to\bar{L}} = \mathcal{R}_{R\to L} \end{aligned} \tag{1}$$

$$\longrightarrow \quad \text{flux}(\bar{q}_R) - \text{flux}(q_L) \ = \ \text{flux}(q_R) - \text{flux}(\bar{q}_L)$$

i.e., no net quark number yet

The EW baryogenesis scenario for models with strong 1. order p.t.

Cohen, Kaplan, Nelson (1991)



- $\not{CP}$ in bubble wall $\longrightarrow$ asymmetry in reflection probability

  $\Delta \mathcal{R}_{CP} = \mathcal{R}_{\bar{L}\to\bar{R}} - \mathcal{R}_{R\to L} \neq 0$, analogous for transmission probability

- $\not{T}\not{E}$ by expanding Higgs bubble: $v_{wall} \neq 0$

  $\longrightarrow$ non-zero injected chiral flux into unbroken phase

  $J_L = \text{flux}(\bar{q}_R) - \text{flux}(q_L) \neq 0$

- in region with VEV $\phi_T = 0$: $\not{B} + \not{L}$ reactions rapid; both $\not{C}$ and $\not{B}$

e.g., $\bar{t}_R + \bar{b}_R \to 7 q_L + 3\nu_L$

$t_L + b_L \to 7\bar{q}_R + 3\bar{\nu}_R$

- $\not{T}\not{E}$: expanding Higgs bubble blocks $\not{B} + \not{L}$ wash-out reactions

$\longrightarrow \langle \hat{B} \rangle_T \neq 0$ frozen. If $\text{sign} J_L > 0 \longrightarrow n_q - n_{\bar{q}} > 0$

• EW baryogenesis in MSSM:

constrained MSSM version: several new CP phases:

• complex mass parameter $\mu \leftrightarrow$ mixing of the 2 Higgs superfields
• SUSY breaking terms:
  complex gaugino masses $\tilde{m}_i$
  complex trilinear coulings $A \leftrightarrow$ mixing of sfermions and Higgs doublets

here, the principal mechanism considered is the chargino reflection/transmission at bubble wall
charginos $= \tilde{W}^{\pm}_{L,R},\ \tilde{h}^{\pm}_{L,R}$

$\not{C}\not{P}$ phase $\varphi_\mu = \arg(\mu) - \arg(\tilde{m}_2) \longrightarrow$ chiral asymmetry in $\tilde{W}$ and $\tilde{h}$
decays and scatterings transfer CP asymmetry to quarks & leptons
via vertices like $\tilde{h}^+_L \to t_L + \tilde{b}^*$, $\tilde{h}^-_R \to \bar{t}_R + \tilde{b}$.

$\not{B}$ sphaleron processes affect $L\ (R)$ (anti)quarks $\longrightarrow$ non-zero quark number

Results:

- 2 Higgs doublet extensions:

Joyce, Prokopec, Turok; Cline et al., Huber et al., ...

$$\frac{n_B}{s} \sim 10^{-12} \frac{\boldsymbol{\Delta}\theta}{v_{wall}}$$

requires $\boldsymbol{\Delta}\theta \sim \mathcal{O}(1)$ $\longrightarrow$ electron and neutron EDMs close to exp. upper bounds

- MSSM:

of relevance here: $\not{C}\not{P}$ phase φ_μ in Higgs-chargino interactions

$$\frac{n_B}{s} \sim f \times 10^{-10} \sin \varphi_\mu$$

Considerable spread in predictions of f, resp. in required magnitude of CP phase:
$\varphi_\mu \sim 0.1 - \mathcal{O}(1)$

Carena et al., Cline et al., Prokopec et al., ...

severe constraints from exp. upper bounds on electron and neutron EDM.

- NMSSM:

model can accomodate 1. order phase transition and $n_B/s \sim 10^{-10}$

Huber, Schmidt; ...

Is the SM $C\!\!\!/P$ relevant?

If $\quad \mathcal{L}_{cc} = -\frac{g_W}{\sqrt{2}} J^{\mu}_{quark} W^{+}_{\mu} + h.c.$, i.e., KM phase δ_{KM} were the only source of $C\!\!\!/P$

resulting CP asymmetry $\Delta\mathcal{R}_{CP}$ at EW phase transition probably much too small !

$$\text{naively :} \qquad \Delta\mathcal{R}_{CP} \sim \frac{d_{CP}}{T^{12}_{EW}} \sim 10^{-19}$$

where

$$d_{CP} \;=\; \prod_{\substack{i>j \\ u,c,t}} (m_i^2 - m_j^2) \prod_{\substack{i>j \\ d,s,b}} (m_i^2 - m_j^2) \quad \mathrm{Im}(\mathbf{V_{ud}V_{cb}V^*_{ub}V^*_{cd}}),$$

$$\mathrm{Im}(\mathbf{V_{ud}V_{cb}V^*_{ub}V^*_{cd}}) \simeq \mathbf{10^{-5}} \sin\delta_{\mathbf{KM}}$$

$$\longrightarrow \mathbf{n_B/s} \sim \mathbf{10^{-26}}$$

Detailed investigations: Gavela et al. (1994); Huet, Sather (1995)
But not fool-proof, $\Delta\mathcal{R}_{CP}$ may be enhanced. Farrar, Shaposhnikov (1995)

Conclusion on EW baryogenesis

scenario is testable, i.e., falsifiable, in particular at LHC!

requires

• new particles with masses of $\mathcal{O}(100\,\mathrm{GeV})$ - $\mathcal{O}(1\,\mathrm{TeV})$
in particular more than 1 type of Higgs boson H

• and new $\not{C}\not{P}$ interactions

New $\not{C}\not{P}$ interactions:

$\longrightarrow$ non-zero electric dipole moments (EDM), in particular of electron and neutron
present exp. upper bounds:

$$|d_e| < 1.6 \times 10^{-27}\,\mathrm{e\,cm}\,, \qquad |d_n| < 3 \times 10^{-26}\,\mathrm{e\,cm}$$

$\longrightarrow$ $\not{C}\not{P}$ in $H \to \tau^+\tau^-,\ t\bar{t},\ \ldots$

$\longrightarrow$ new $\not{C}\not{P}$ in B meson decays (could be vey small)

Scenario 2: Baryogenesis via leptogenesis

Mechanism:
Out-of-equilibrium decay of superheavy Majorana neutrinos at $T \gg T_{EW}$

$\not{L}$ decay $\longrightarrow L \neq 0 \quad \xrightarrow{\text{SM sphalerons (conserve B} - \text{L)}} \quad B \neq 0$

proposed by Fukugita, Yanagida (1978) now: $>$ 400 papers on SPIRES

attractive scenario in view of fact that observed light ν_i are **massive** $\&$ **non-degenerate**

Light neutrinos ν: either Dirac or Majorana particles

must be clarified by experiment

If ν = Dirac $\longrightarrow \nu \neq \bar{\nu}$

Theoretical description: introduce ν_{Ri} $(i = e, \mu, \tau)$, $SU(2)_L \times U(1)_Y$ singlets
gauge-invariant coupling to SM particles only via

$$\mathcal{L}_{Yukawa} = -\sum_{ij} h_{ij}\, \bar{\nu}_{Ri} L_j \cdot \Phi + \text{h.c.}$$

$L_i = (\nu_L, \ell_L)_i, \quad \Phi = (-H^0, H^+)$
Generation of ν masses via Higgs VEV $< \phi^0 > \neq 0$
in complete analogy to $I_W = +1/2$ quarks

transform from weak basis to mass basis for ν and ℓ.
In complete analogy to quark sector: lepton flavor mixing and $\not{C}\not{P}$,
described by unitary 3×3 matrix U_D `(MNS matrix)`
U_D has 4 observable parameters: 3 angles and 1 CP phase
$\longrightarrow$

- ν oscillations
- $\not{C}\not{P}$, e.g. $\text{prob}(\nu_e \to \nu_\mu) \neq \text{prob}(\bar{\nu}_\mu \to \bar{\nu}_e)$
- but no ν-less 2 β decay: ${}^{76}Ge \nrightarrow {}^{76}Se + 2e^-$

lepton number = conserved (but not flepton flavor nr.)

Some basics about Majorana fields/particles

$$\psi^c \stackrel{!}{=} \psi \quad \longrightarrow \quad \begin{cases} \psi_1 \; = \; \psi_L \; + \; \psi_L^c \\ \psi_2 \; = \; \psi_R \; + \; \psi_R^c \end{cases}$$

field ψ_L annihilates fermion state $|\psi_L>$, ψ_L^c annihilates $|\bar{\psi}_R>$, ...

Mass terms: Dirac mass term: constructed with chiral fields ψ_L and ψ_R :

$$\mathcal{L}_D - m_D \bar{\psi}_R \psi_L \; + \; \text{h.c.} \; ,$$

Majorana mass terms: constuctible with ψ_L (or ψ_R) alone:

$$\mathcal{L}_M^{(1)} \; = \; -\frac{m_1}{2} \bar{\psi}_1 \psi_1 \; = \; -\frac{m_1}{2} \overline{\psi_L^c} \psi_L \; + \; \text{h.c.} \; , \tag{2}$$

$$\mathcal{L}_M^{(2)} \; = \; -\frac{m_2}{2} \bar{\psi}_2 \psi_2 \; = \; -\frac{m_2}{2} \overline{\psi_R^c} \psi_R \; + \; \text{h.c.} \; ,$$

`(have used that` $\bar{\psi}_A \psi_A = \overline{\psi_A^c} \psi_A^c = 0$ `for A=L,R)`
Majorana mass terms violate the "ψ-number" by 2 units, $|\Delta \mathrm{L}_\psi| = 2$.
For instance $< \bar{\psi}_R | \overline{\psi_L^c} \psi_L | \psi_L > \neq 0$,
i.e., the first term in $\mathcal{L}_M^{(1)}$ flips a left-handed $|\psi_L>$ into a right-handed $|\bar{\psi}_R>$.
Because ψ-number is not conserved when Majorana mass terms are present, distinction between ψ particle and antiparticle looses its meaning
If neutrino = Majorana, then "ν" and "$\bar{\nu}$" are the 2 helicity states of single particle ν^M

Now to model building: "See-saw mechanism"

1 flavor only
in addition to $\nu_L \quad (I_W = +1/2)$ introduce $\nu_R \quad (I_W = 0)$
and assume that, in addition to Dirac mass term, also a Majorana mass term for ν_R is present (o.k. with $SU(2)_L \times U(1)_Y$ gauge symmetry)

$$-\mathcal{L}_{D+M} = m_D \, \bar{\nu}_R \nu_L + \frac{M}{2} \overline{\nu_R^c} \nu_R + \text{ h.c.} \tag{3}$$

$$= \frac{1}{2} (\bar{\psi}_1, \bar{\psi}_2) \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \, ,$$

where

$$\psi_1 = \nu_L + \nu_L^c \, , \quad \psi_2 = \nu_R + \nu_R^c$$

are Majorana fields.
Diagonalize mass matrix **assuming** $M >> m_D$: $\longrightarrow$

$$-\mathcal{L}_{D+M} = \frac{m_\nu}{2} \bar{\nu} \nu + \frac{m_N}{2} \bar{N} N \, , \tag{4}$$

where the mass eigenfields

$$\nu \simeq \psi_1 \, , \quad N \simeq \psi_2 \, , \tag{5}$$

and

$$m_\nu \simeq \frac{m_D^2}{M} << m_D \, , \qquad m_N \simeq M \, .$$

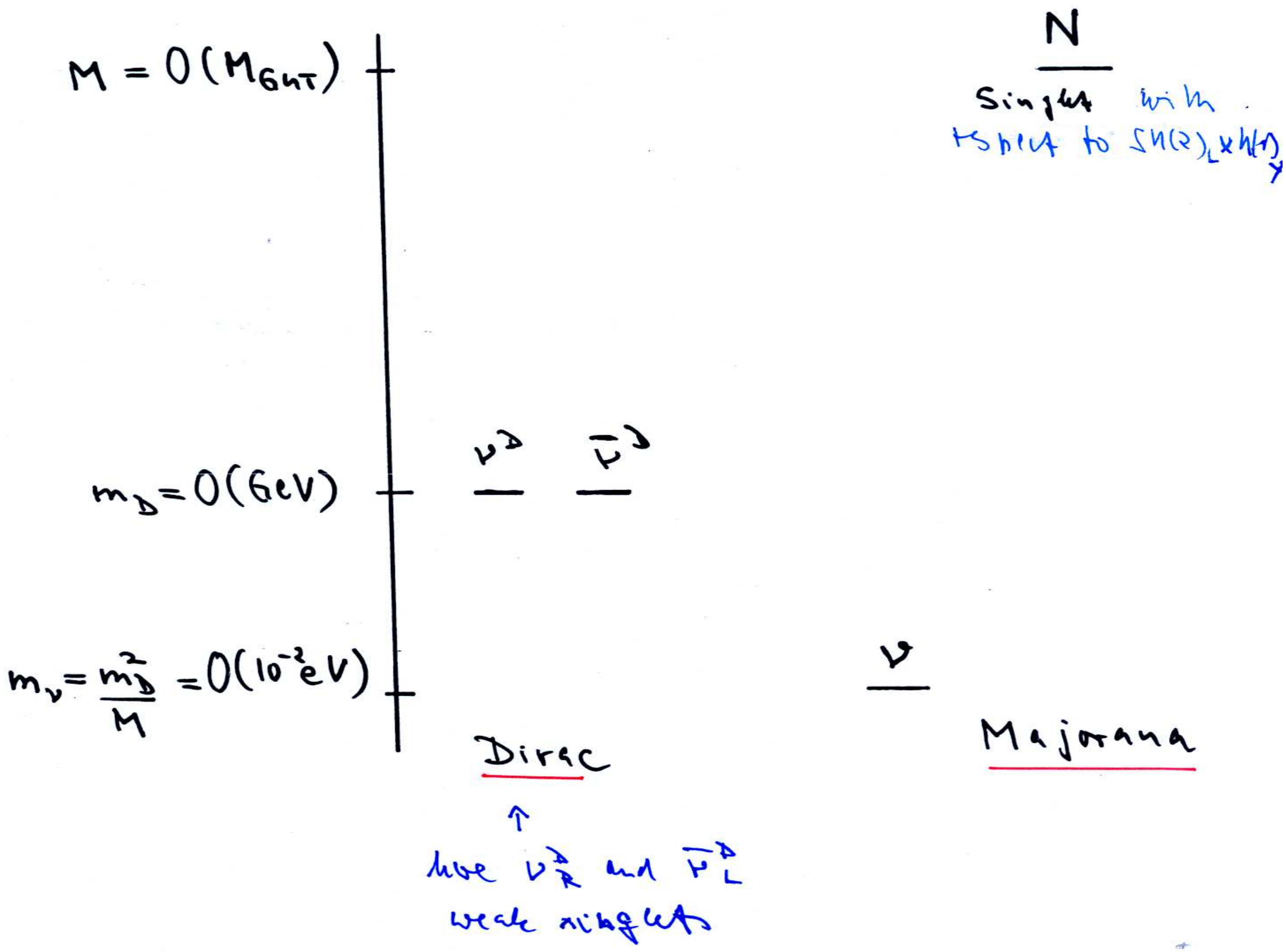
For $M >> m_D$ the neutrino mass eigenstates consist of

very light Majorana $|\nu>$ (weak doublet, 2 helicity states)

and

very heavy Majorana $|N>$ (weak singlet, 2 helicity states)

Introducing a very large Majorana mass term for ν_R explains $m_\nu \ll m_{q,\ell}$



Case of 3 lepton generations

consider SM fields + 3 heavy right-handed neutrinos, weak singlets, with Majorana mass terms.
$N_j = \nu_{Rj} \; + \; \nu^c_{Rj} \; (j = 1, 2, 3)$ = heavy Majorana fields in mass basis
Coupling of the N_j to SM fields:

$$\mathcal{L} \;=\; .... \;-\; \sum_{ij} \; L_i \cdot \Phi h_{ij} \, N_j \;\; - \sum_j \frac{M_j}{2} \bar{N}_j N_j \;+\; \text{ h.c.}$$

$L_i = (\nu_i, \; \ell_i)$ (i = flavor), $\quad \Phi = (-H^0, \; H^+)$,

Transform from weak basis to mass basis for light ν and ℓ.
$\longrightarrow$ charged current interactions that determine ν phenomenology

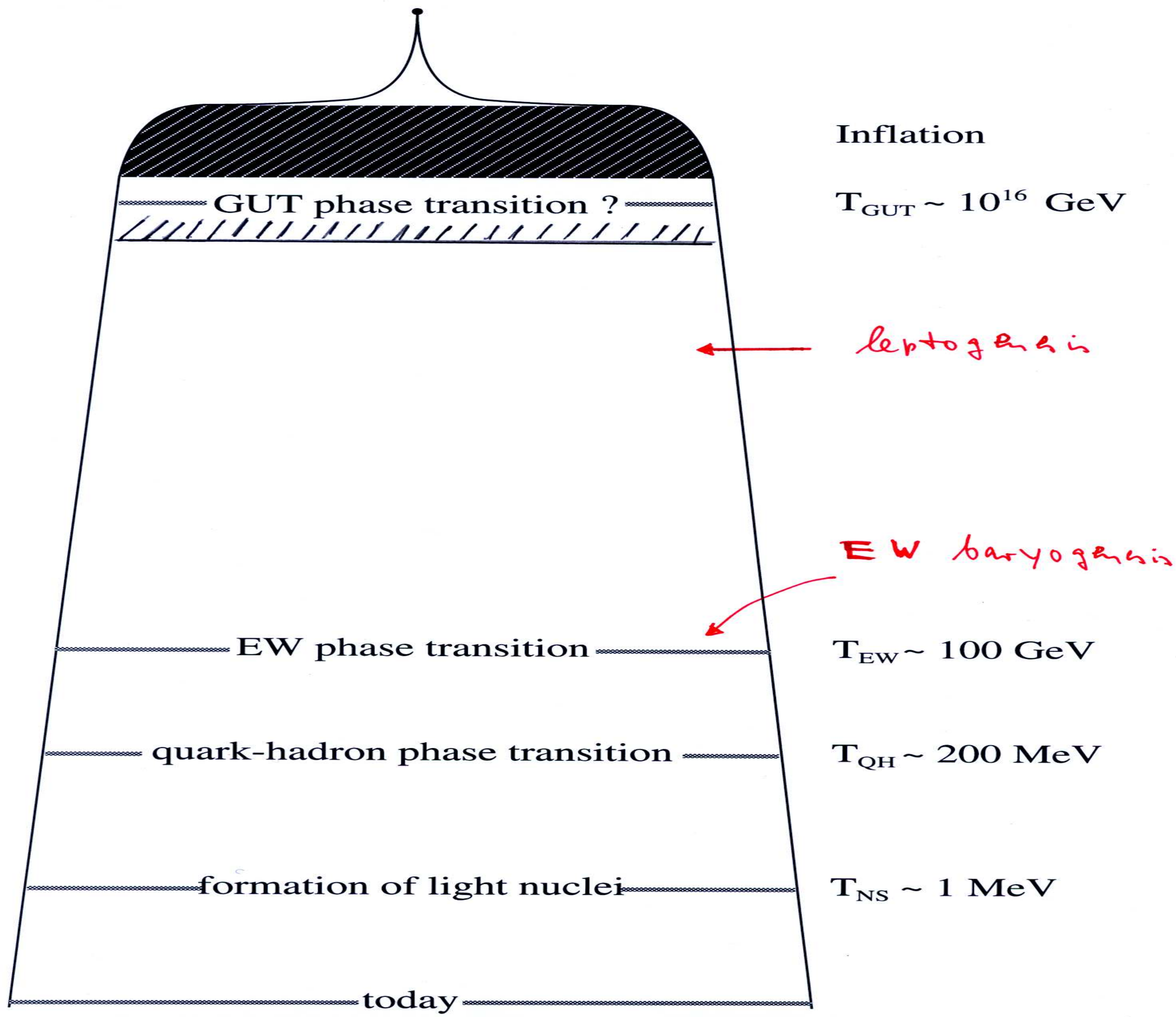
$$\mathcal{L}^{lept}_{cc} = -\frac{g_w}{\sqrt{2}} \bar{\ell}_{mL} \gamma^{\mu} U_{mj} \nu_j W^-_{\mu} \; + \; h.c.$$

$\nu_j = \nu_{Lj} \; + \; \nu^c_{Lj}$ = Majorana
MNS matrix U now depends on 3 angles and 1 + 2 additional CP phases

$\longrightarrow$

- ν oscillations
- $\not{C}\!\!\!\not{P}$, e.g. $\text{prob}(\nu_e \rightarrow \nu_\mu) \neq \text{prob}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  but independent of Majorana CP phases
- **lepton number violation: ν-less 2 β decay, e.g.,** ${}^{76}Ge \rightarrow {}^{76}Se + 2e^-$

Now to leptogenesis - da capo:



Basics of leptogenesis scenario:

early universe at $T \gg T_{EW}$

Simplest model:
assume SM particles + very heavy N_1, N_2, N_3 with masses M_j $\quad (SU(2)_L \times U(1)_Y$ singlets)

N_j couple to e, ν, τ, ν_i, and Higgs bosons

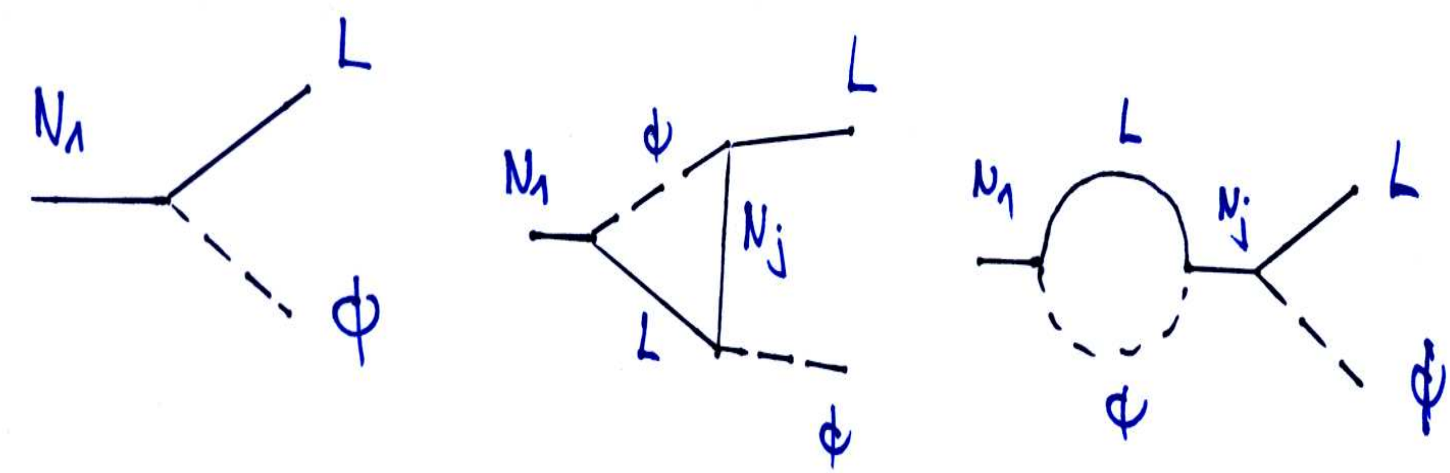
$$\mathcal{L}_{Yukawa} = - \sum_{ij} \Phi \cdot L_i h_{ij} N_j + \text{h.c.}$$

$L_i = (\nu_i, \ell_i)$ (i = flavor), $\quad \Phi = (-H^0, H^+)$,
h_{ij} complex coupling matrix, $\quad \not{C}$ and $\not{C}\text{P}$

assume mass hierachy $M_1 < M_2, M_3$
consider temperatures $T \sim M_1$

$$\not{L}: \quad \text{e.g. in decays } N_1 \longrightarrow \begin{array}{ll} \ell^- + H^+, & \Delta L = +1 \\ \ell^+ + H^-, & \Delta L = -1 \end{array}$$

$\not{C}\not{P}$ in $\mathcal{L}_{Yukawa}$ generates lepton-antilepton asymmetry in $N_1 \to L_i\Phi,\ \bar{L}_i\bar{\Phi}$



here L = charged lepton or light neutrino, $\Phi = H^0$ or H^+

CP asymmetry in N_1 decays in "one-flavor" approximation
(relevant if lepton flavors are indistinguishable in particle plasma)

$$\epsilon_1 \equiv \frac{\sum_i \left[\Gamma(N_1 \to L_i\Phi) - \Gamma(N_1 \to \overline{L_i\Phi})\right]}{\sum_i \left[\Gamma + \Gamma\right]} = -\frac{3M_1}{8\pi^2 v^2} \frac{\mathrm{Im} \sum_j m_j^2 R_{1j}^2}{\sum_j m_j |R_{1j}|^2}$$

where m_j are masses of light ν_j

- $\epsilon_1 \neq 0 \quad \leftrightarrow \quad \nu_j$ non-degenerate

- in one-flavor approx.: $\not{C}\not{P}$ relevant for leptogenesis $\not\leftrightarrow$ $\not{C}\not{P}$ in ν mixing matrix

R is complex orthogonal matrix related to Yukawa matrix h by

$$h = \frac{1}{v}\sqrt{M}\, R\, \sqrt{m}\, U^\dagger$$

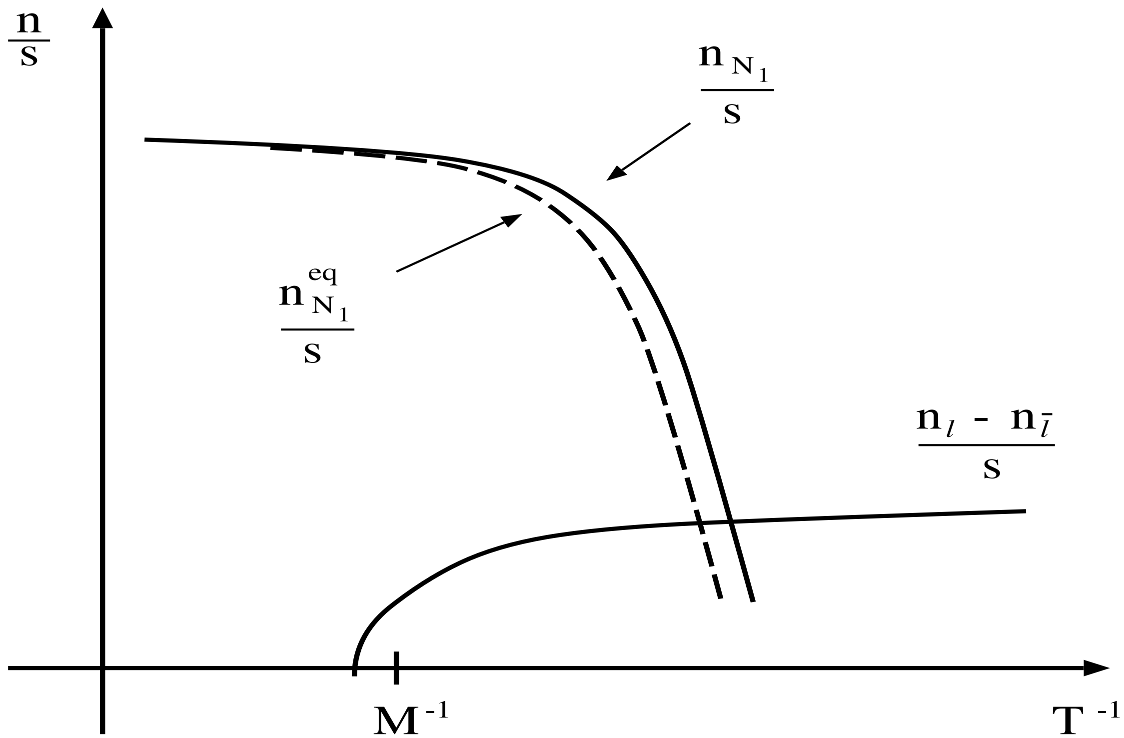
where $M = \mathrm{diag}(M_1, M_2, M_3)$, $m = \mathrm{diag}(m_1, m_2, m_3)$,
and U is ν mixing matrix (MNS matrix) (Casas, Ibarra (2001))

The relevant couplings in ϵ_1 arise from product

$$hh^\dagger = \frac{1}{v^2}\sqrt{M}\, R\, m\, R^\dagger\, \sqrt{M}$$

which does not depend on the CP phases of U

~~TE~~ : N_1 (singlet): only very weakly coupled to “heat bath”
N_1 decouple if
decay rate Γ_{N_1} < expansion rate $H(T)$ (rule of thumb)
then “inverse decays” $L_i\Phi,\ \bar{L}_i\bar{\Phi} \longrightarrow N_1$ & wash-out reactions “blocked”
more precisely: density distribution n_{N_1} determined with Boltzmann eq.
taking into acount decays, inverse decays, and scatterings, e.g.,
$H^+H^+ \leftrightarrow \ell^+\ell^+ \ldots (|\Delta L| = 2) \quad N_1\,\ell \leftrightarrow t\,q, \ldots (|\Delta L| = 1), \quad \ldots.$



Result: Excess of N_1 particles with respect to equilibrium distribution $n_{N_1}^{eq} \sim e^{-M_1/T}$
$\longrightarrow$ generation of non-zero lepton nr. density

$$\left.\begin{array}{l}\text{Thus } \langle\hat{\mathsf{L}}\rangle_{\mathsf{T}} \neq 0,\ \langle\hat{\mathsf{B}}\rangle_{\mathsf{T}} = 0 \\ \text{i.e., } \langle\hat{\mathsf{B}} - \hat{\mathsf{L}}\rangle_{\mathsf{T}} \neq 0\end{array}\right\} \xrightarrow{\not{B} + \not{L} \quad \text{SM reactions}} \left\{\begin{array}{l}\text{do not wash out} \\ \langle\hat{B} - \hat{L}\rangle_T \neq 0\end{array}\right.$$

$\not{B} + \not{L}$ SM reactions convert $n_L \neq 0$ into $n_B \neq 0$ at $T > T_{EW}$
e.g. by

$$\begin{aligned}\mu_R^+ + \tau_R^+ &\longrightarrow 9\, q_L + e_L^- \qquad (\Delta B = 3) \\ \mu_R^- + \tau_R^- &\longrightarrow 9\, \bar{q}_R + e_R^+ \qquad (\Delta B = -3)\end{aligned} \tag{6}$$

Formula: (Khlebnikov,Shaposhnikov;...)

$$\frac{n_B}{s} = c\,\frac{n_L}{s}\,, \quad c \text{ model} - \text{dependent},\ c_{SM} = -\frac{28}{61}$$

i.e., $n_L = n_{lepton} - n_{\overline{lepton}} < 0 \quad \longrightarrow \quad n_B = \frac{1}{3}(n_q - n_{\bar{q}}) > 0$

One may write:

$$n_L = \eta \, \epsilon_1 \, n_\gamma$$

where efficiency factor η typically 0.1 - 0.01 (from solution of Boltzmann eqs.)
and n_γ is photon # density

Entropy density for $T > T_{EW}$: (only SM particles):

$$s = 1.8 \times g_{\rm eff} \, n_\gamma = 1.8 \times 118 \, n_\gamma$$

Then

$$\frac{n_B}{s} = c \, \eta \, \frac{\epsilon_1 n_\gamma}{1.8 \, g_{\rm eff} \, n_\gamma} \simeq -2 \times 10^{-3} \, \eta \, \epsilon_1$$

Today's value $n_B/s \sim 10^{-10}$ requires $\not{C}\not{P}$ asymmetry $|\epsilon_1| \gtrsim 10^{-7}$

All factors above are model-dependent
likewise: leptogenesis $\leftrightarrow$ light ν masses and mixings

General conclusion:
Leptogenesis with Majorana neutrinos works
for light ν masses compatible with oscillation data
typically: $M_1 \gtrsim 10^{10}$ GeV

Taking lepton flavor into account:
Abada et al., Nardi et al. (2006)

one-flavor approx. holds rigorosly only if ALL lepton interactions are out-of-eq. with respect to exp. rate H
holds for $T \sim M_1 \gtrsim 10^{11}$ GeV
For $M_1 \lesssim 10^9$ GeV the τ and μ Yukawa couplings induce scattering rates $> H$
$\longrightarrow$ **lepton flavors are distinguishable**

$$\epsilon_1 \longrightarrow \epsilon_1^i \propto \Gamma(N_1 \to L_i \Phi) - \Gamma(N_1 \to \overline{L_i \Phi})$$

and

$$\frac{n_B}{s} = \frac{c}{g_{eff}} \sum_i \eta_i \, \epsilon_1^i$$

This adds many uncertainties.

- Larger CP asymmetries possible
- Now: $\not{C}\not{P}$ phases in light ν mixing matrix $U \to$ non-zero ϵ_1^i

Summary

- BAU cannot be explained in SM:

  SM predicts the EW phase transition to be a smooth cross-over phenomenon (lack of $\not{T}\!E$)

  State-of-the-art: KM $\not{C}P$ irrelevant for baryogenesis scenarios

At present: 2 popular scenarios:

- EW baryogenesis at $T_{EW} \sim 100$ GeV

* works only in SM extensions with sufficiently strong 1. order EW p.t.

  For minimal SUSY, some "window" still open

  Constraints for MSSM: $m_{H_1} < 120$ GeV, $m_{\tilde{t}_R} < 170$ GeV

* new $\not{C}P$ required

Scenario is testable (falsifiable) in the lab.:

find new particles at colliders / find new $\not{C}P$

- Leptogenesis by heavy Majorana neutrinos at $T \gg T_{EW}$

attractive scenario – but direct tests (seem) impossible

Nevertheless: future experimental findings on

  ν-less 2β decay

  lepton flavor violation

  masses of light ν

  search for $\not{C}P$ in $\nu_i \longrightarrow \nu_j$ oscillations

will have a bearing on this scenario