Dynamical Generation of the Matter-Antimatter Asymmetry of the Universe – an Overview

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At present only a few facts point to physics beyond the Standard Model (SM) of particle physics:

smallness of neutrino masses ($m_\nu < 1$ eV)

dark matter

matter - antimatter asymmetry, more precisely: baryon asymmetry of universe, quantified by

$$\eta \equiv \frac{\mathbf{n_{baryon} - n_{\overline{baryon}}}}{\mathbf{n_{photon}}} \simeq \mathbf{6 \times 10^{-10}}$$

Contents of these lectures:
* why SM fails to explain η
* some (presently) popular BSM scenarios that succeed

CONTENTS

- Some basics of cosmology
- 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

  Status of EWBG in some SM extensions (2 Higgs doublet, SUSY extensions)

  Is the SM $\not{C}\!\not{P}$ relevant?

- Scenario 2: Baryogenesis via leptogenesis

  A) Thermal leptogenesis (ultra-heavy Majorana neutrinos)

  B) Low scale leptogenesis

- 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].
- S. Davidson, E. Nardi and Y. Nir, “Leptogenesis,” Phys. Rept. **466** (2008) 105 [arXiv:0802.2962 [hep-ph]].
- W. Buchmüller, “Baryogenesis, Dark Matter and the Maximal Temperature of the Early Universe,” arXiv:1212.3554 [hep-ph].
- M. Drewes, “News on Right Handed Neutrinos”, arXiv:1303.6912 [hep-ph].

Textbooks:

- E. W. Kolb and M. S. Turner, “The Early Universe” (1993)
- K. Zuber, “Neutrino Physics” (2012)

Some basics of cosmology: standard big-bang model (SCM)

Units

$$\hbar = c = k_{\mathrm{Boltzmann}} = 1$$

$\Rightarrow$ [energy] = [mass] = [temperature] = [length]$^{-1}$ = [time]$^{-1}$

1 GeV $\simeq 10^{13}$ K

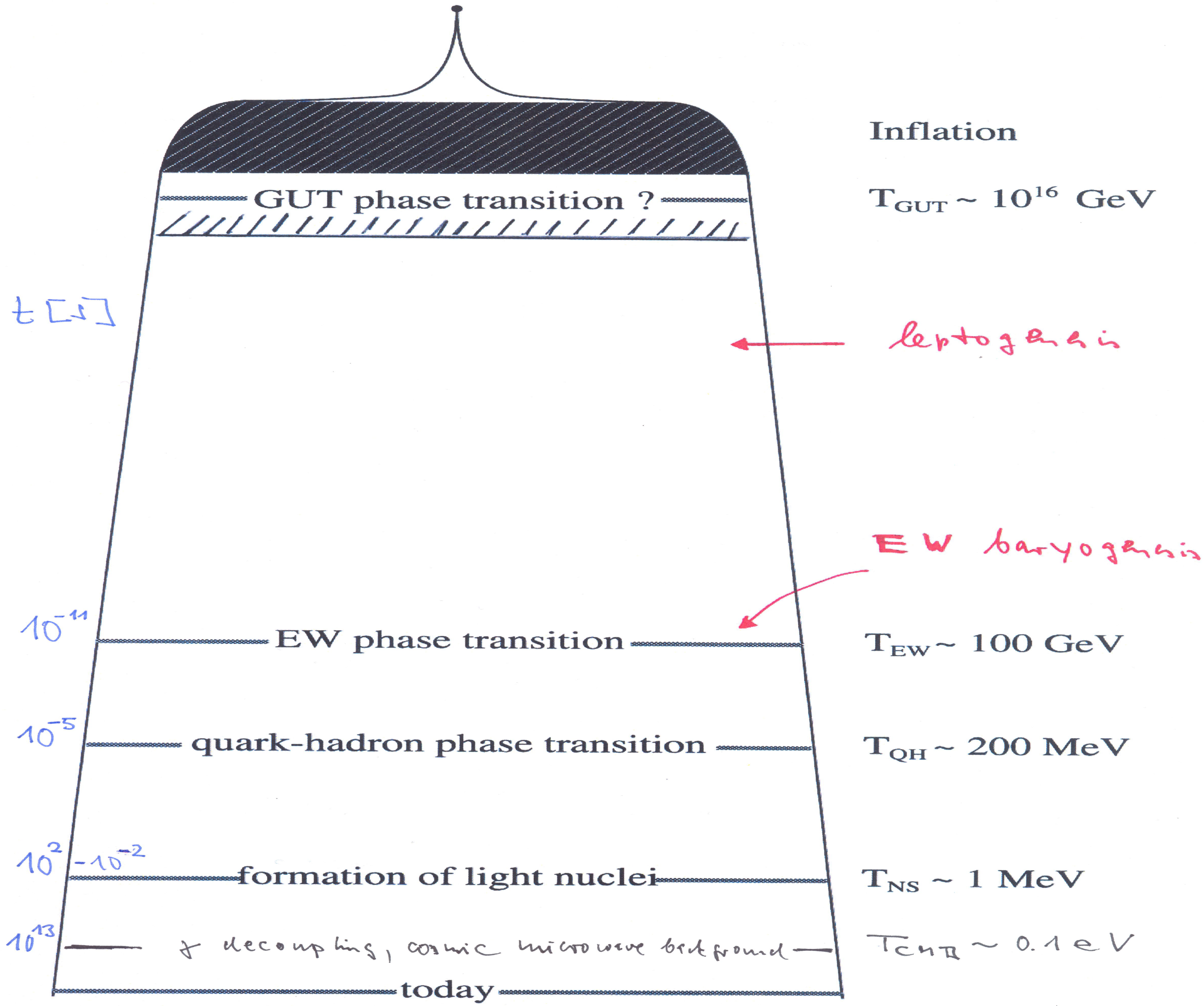
1 (GeV)$^{-1}$ $\simeq 6 \times 10^{-25}$ sec

1 parsec $\simeq 3.2$ light years

Standard Cosmological Model (SCM): age of universe $\sim 2 \times 10^{10}$ years

present extension of "visible" universe: $H_0^{-1} \sim 10$ G parsec

Cartoon of history of the universe



From observations:

"visible" universe $\sim$ spatially homogeneous $\&$ isotropic on very large scales

$\Rightarrow$ ART metric for such a space: **Robertson-Walker metric**

$$ds^2 = dt^2 - R^2(t)\left\{\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right\}$$

coordinates t, r, θ, ϕ

space of constant +, -, 0 curvature: $k = 1, -1, 0$

$R(t) =$ **scale factor,** **[R] = [length]**

Dynamics of universe governed by Einstein eqns.

$$G_{\mu\nu} = 8\pi G_N T_{\mu\nu} + \Lambda g_{\mu\nu}\,, \qquad (1)$$

G_N = Newton's constant, $T_{\mu\nu}$ = energy-momentum tensor of univ., Λ = cosmological constant

symmetries of RW metric $\Rightarrow$ $T_{\mu\nu}$ diagonal and $T_{11} = T_{22} = T_{33}$

simplest model for matter/energy distribution on large scales: perfect fluid

$$T^{\mu\nu} = \mathrm{diag}(\rho, p, p, p) \qquad (1a)$$

$\rho(t)$ = total energy density, $p(t)$ = isotropic pressure

RW metric and (1a) into (1) $\Rightarrow$ Friedmann eqn. (from 00 component of (1))

$$H^2 \equiv \frac{\dot{R}^2}{R^2} = \frac{8\pi G_N}{3}\rho - \frac{k}{R} + \frac{\Lambda}{3}, \qquad (2)$$

$H(t)$ = Hubble parameter at time t = expansion rate of universe

Energy conservation (= covariant conservation of $T_{\mu\nu}$)

$$\Rightarrow \quad d(\rho R^3) = -p d(R^3) \qquad (3)$$

= 1. law of thermodynamics: $dU = dA = -pdV$
Use equation of state:

$$p = w\rho\,, \qquad w \simeq \text{const (see below)} \qquad (4)$$

Integrate (3), using (4) $\Rightarrow$ $\rho \propto \mathbf{R^{-3(1+w)}}$

$$\begin{array}{lll} \text{Vacuum dominance}, p = -\rho & \Rightarrow & \rho = \text{const.} \\ \text{Radiation dominance}, p = \frac{1}{3}\rho & \Rightarrow & \rho \propto \mathbf{R^{-4}} \\ \text{Nonrel. matter dominance}, p = 0 & \Rightarrow & \rho \propto \mathbf{R^{-3}} \end{array}$$

Use this in Friedmann eqn. to solve for $R(t)$: $\Rightarrow$

$$R(t) \propto e^{at} \quad \text{in vacuum dominated epoch,}$$

$$R(t) \propto t^{1/2} \quad \text{in radiation d.e.,} \qquad R(t) \propto t^{2/3} \quad \text{in matter d.e.}$$

Side note: $T^{\mu\nu}$ for relativistic particles moving at random:

$$T^{\mu 0} = p^\mu \quad \text{(4-momentum), where} \quad E^2 = \vec{p}^2 + m^2 \simeq E^2 \,,$$

$$T^{\mu i} = p^\mu \dot{x}^i \,.$$

Use $\vec{p}/E = \vec{v}$

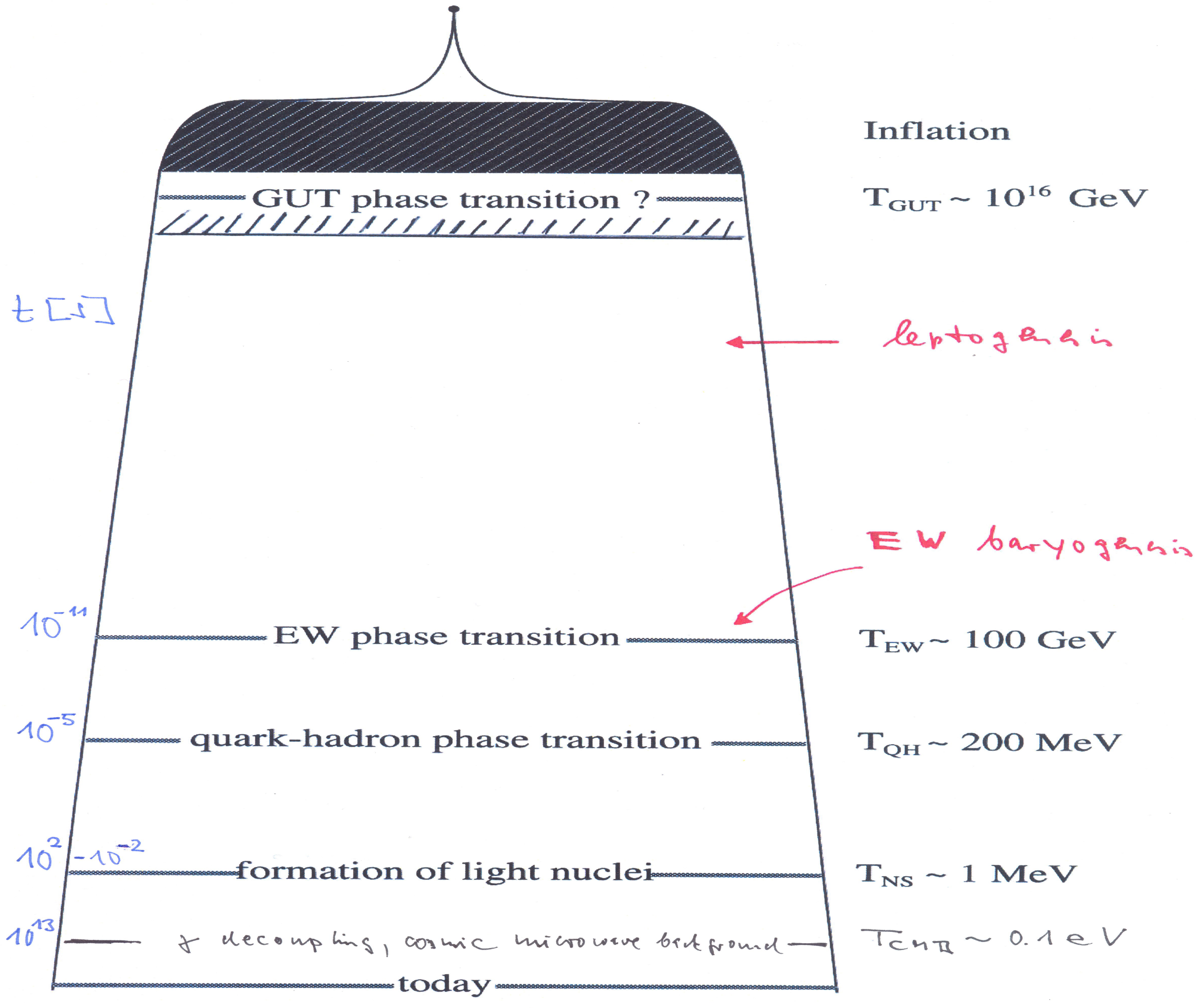
$$\Rightarrow \quad p^j = E\dot{x}^j$$

$$\Rightarrow \quad T^{ij} = \frac{p^i p^j}{E}$$

Average over angles

$$\Rightarrow \quad T^{ij}_{av.} = \frac{1}{3}\frac{|\vec{p}|^2}{E}\delta_{ij} \simeq \frac{E}{3}\delta_{ij}$$

holds for massless and relativistic massive particles


Inflation
GUT phase transition ?
$T_{GUT} \sim 10^{16}$ GeV
t [s]
leptogenesis
EW baryogenesis
10^{-11}
EW phase transition
$T_{EW} \sim 100$ GeV
10^{-5}
quark-hadron phase transition
$T_{QH} \sim 200$ MeV
$10^{2}-10^{-2}$
formation of light nuclei
$T_{NS} \sim 1$ MeV
10^{13}
γ decoupling, cosmic microwave background
$T_{CMB} \sim 0.1$ eV
today

Equilibrium thermodynamics:

After inflation, early universe $\approx$ gas gas of relativistic particles, are most of the time in equilibrium.

Species A distributed in $\vec{p}$-space according to

$$f_A(\vec{p}) = \frac{1}{e^{(E_A-\mu_A)/T} \mp 1}$$

bosons: -1 ,   fermions: $+1$, $\mu_A =$ chemical potential of species A

(Grand canonical ensemble adequate because particles are created/destroyed.)

If species A, B, C are in (chemical) equilibrium $\Rightarrow$ their μ's are related

$$A + B \leftrightarrow C \quad \Rightarrow \quad \mu_A + \mu_B = \mu_C \,.$$

number density $\quad n_A = g_A \int d\tilde{p}\ f_A(\vec{p})\,, \qquad d\tilde{p} \equiv \frac{d^3p}{(2\pi)^3}$

energy density $\quad \rho_A = g_A \int d\tilde{p}\ E(\vec{p}) f_A(\vec{p})\,,$

isotropic pressure $\quad p_A = g_A \int d\tilde{p}\ \frac{|\vec{p}|^2}{3E} f_A(\vec{p})\,,$

entropy density $\quad s_A = \frac{\rho_A + p_A}{T}\,.$

g_A : # of internal degrees of freedom of A

e.g., electron: $g_e = 2$,   neutrino ν_L: $g_{\nu_L} = 1$

Integrate these equations (drop index A).

For relativistic particles, i.e., for $T \gg m$, and for $T \gg \mu$:

$$n \simeq a_X \; g \; T^3 \, ,$$
$$\rho \simeq b_X \; g \; T^4 \, ,$$
$$p \simeq \tfrac{\rho}{3} \, , \qquad \text{equation of state}$$

constants a_X, b_X, $X =$ boson, fermion.

For nonrelativistic bosons or fermions, i.e., for $m \gg T$:

$$n \simeq g \left(\tfrac{mT}{2\pi}\right)^{3/2} e^{-(m-\mu)/T} \, ,$$
$$\rho \simeq n \cdot m \, ,$$
$$p \simeq nT \ll \rho \, , \qquad \text{i.e., eqn. of state } p = 0.$$

Total energy density and pressure of all species in terms of photon temperature T:
Sum over all species A;
take into account that species A may have thermal distribution with $T_A \neq T$.

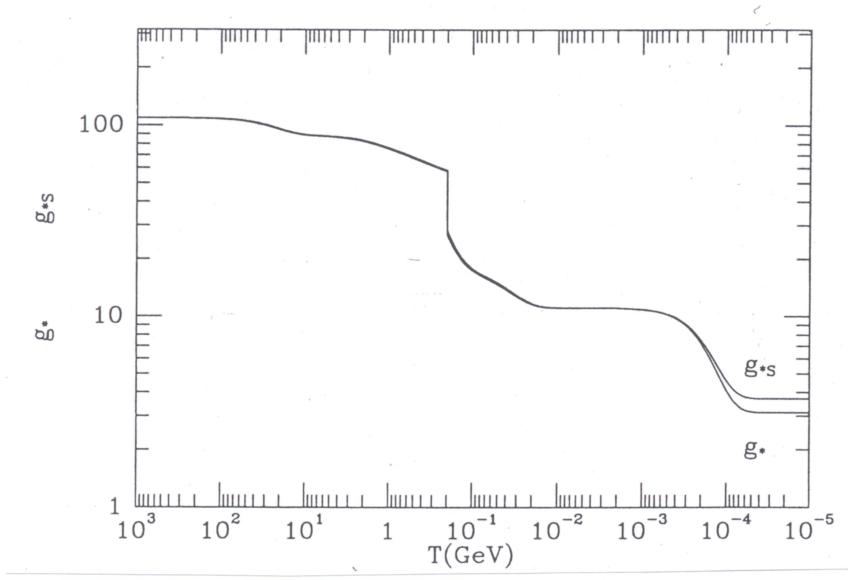
Total number g_* of effectively massless degrees of freedom ($m_i \ll T$) in the 3-generation standard model

Because ρ_j, p_j of non-rel. species are exponentially suppressed with respect to rel. species

$$\Rightarrow \quad \rho = \rho_{rel} = \frac{\pi^2}{30}\, g_*\, T^4\,, \qquad p_{rel} = \frac{\rho_{rel}}{3}$$

where T is photon temperature and

$$g_* = \sum_{i=\mathrm{boson}} g_i \left(\frac{T_i}{T}\right)^4 + \frac{7}{8} \sum_{i=\mathrm{fermion}} g_i \left(\frac{T_i}{T}\right)^4 \qquad \text{for } m_i \ll T.$$



from book of Kolb, Turner

Early universe in radiation-dom. epoch: For most of the time

reaction rates of most particles j: $\Gamma_j \gg$ expansion rate H

$\Rightarrow$ particles j $\sim$ thermal equilibrium $\Rightarrow$ entropy = const.

Consider entropy density

$$s = \frac{S}{V} = \frac{\rho + p}{T} \overset{\text{dominated by rel. particles}}{=} \frac{2\pi^2}{45}\, g_{*S}\, T^3$$

where $g_{*S} = g_*$ most of the time (see the figure)

$$\text{entropy S = const.} \quad \Rightarrow \quad s \propto R^{-3} \quad \Rightarrow \quad g_{*S}\, T^3 R^3 = \text{const.} \qquad (*)$$

$$(*) \quad \Rightarrow \quad \mathbf{T} \propto \mathbf{R}^{-1}$$

Furthermore, number N of some species

$$N \equiv R^3 n \propto \frac{n}{s}$$

$\Rightarrow$ n/s **is not changing if this species is not produced/destroyed!**

That's why one considers, for dynamical explanations (see below),

$$\mathbf{\frac{n_B}{s} \equiv \frac{n_{baryon} - n_{\overline{baryon}}}{s}} \quad \text{rather than} \quad \eta \equiv \frac{n_B}{n_\gamma}$$

These quantities are related by

$$\eta = 1.8 \; g_{*S} \; \frac{n_B}{s}$$

$g_{*S} =$ const only after time of e^+e^- annihilation.
From then on

$$\eta \simeq \mathbf{7} \; \mathbf{\frac{n_B}{s}} \, .$$

Departures from thermal equilibrium

Departures from TE occured of course during history of universe – otherwise, present state of the universe would be a system of 2.75 K.

Examples:	ν decoupling, decoupling of γ background, primordial nucleosynthesis,
more or less speculative:	inflation, 1. order phase transitions in early universe, baryogenesis, decoupling of WIMPs,...

Particles that fall out of equilibrium:
Particle species A: compare its interaction rate Γ_A with expansion rate H:

$$\Gamma_A = \sigma(A + \text{ target } \to X)\, n_{\text{target}}\, |\vec{v}|\,, \qquad [\Gamma_A] = \text{sec}^{-1}$$

expansion rate in radiation dominated epoch:

$$\text{Friedman eqn.} \quad \Rightarrow \quad H = \sqrt{\frac{8\pi G_N}{3}\rho} = 1.66\,\sqrt{g_*}\,\frac{T^2}{M_{Pl}}$$

Useful rule of thumb:

Reactions of A are rapid enough to maintain thermal equilibrium if

$$\Gamma_A \gtrsim H\,.$$

If $\Gamma_A < H$ then A out of equilibrium

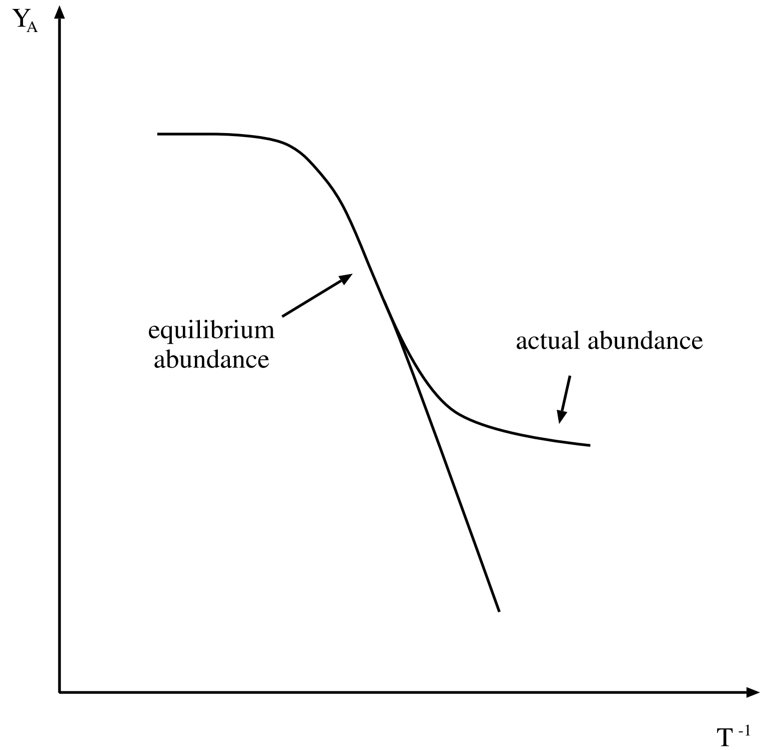
Precise method: Compute time evolution of particle distribution $f_A(\vec{p})$
by integrating Boltzmann eqn(s).

$$\dot{n}_A + 3\,\frac{\dot{R}}{R}\,n_A = \int d\phi\; C[f]$$

and compare with equilibrium distribution
Collision term $C[f]$ is determined by matrix element(s) $|\mathcal{M}|^2$
of most important reaction(s) of A:

$$A + a + b + ... \rightarrow i + j + ...$$

Example: "Freeze out" of massive, non-relativistic particle species A:



$Y_A = n_A/s$ as function of inverse temperature

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

Searches for anti-nuclei in space $\rightarrow$ NO primordial antimatter found

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

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

• No evidence for $\overline{\mathrm{D}}$, $\overline{\mathrm{He}}$, ... found
e.g. $N(\overline{\mathrm{He}})/N(\mathrm{He}) < 10^{-6}$, `BESS collab. (2002)`

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

$$p\bar{p} \rightarrow (4 \ - \ 5)\pi \,, \qquad \pi^0 \rightarrow 2\gamma \,, \quad \mathrm{peak} \sim 140\mathrm{MeV}$$

no anomaly in γ ray background observed

Conclusion: universe consists only of matter on scales $\lesssim$a few $\times 10^2 - 10^3\,\mathrm{Mpc}$
`Cohen, DeRujula, Glashow (1998), ...`

No mechanism is known that would separate matter from $\overline{\mathrm{matter}}$ on such large scales.

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

compare with number of γ's in microwave background:

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

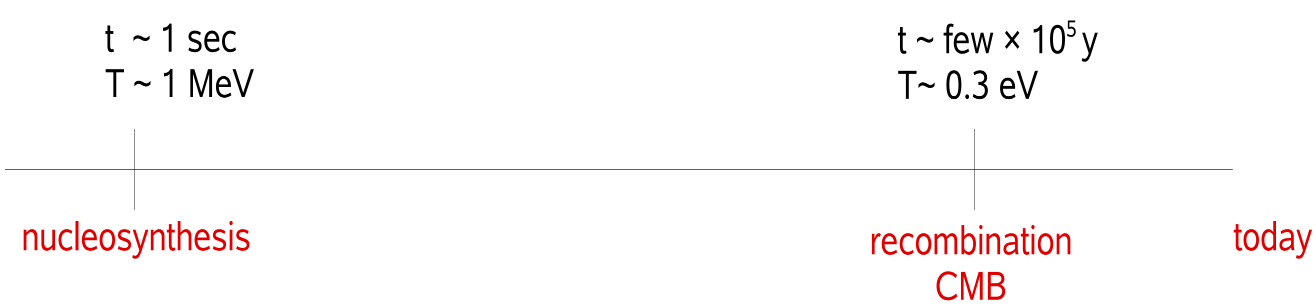
Most precise determinations of $\eta = \frac{n_B}{n_\gamma}$ come from

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

$$\text{data} \quad \longrightarrow \quad \eta = (5.80 \pm 0.27) \times 10^{-10} \qquad [1008.4765]$$

- WMAP (2003): measurement of cosmic microwave background

$$\text{fits to data} \longrightarrow \Omega_b \longrightarrow \eta = (6.21 \pm 0.12) \times 10^{-10} \qquad [1212.5266]$$



For models of baryogenesis a more useful quantity is (see above)

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

remains constant during isentropic expansion

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

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

Can order of magnitude of η be understood in SCM ? – **NO !**

Start with $\eta = 0$ – B-symmetric universe, no $\not{B}$ interactions
Compute (anti)nucleon $N, \bar{N}$ densities
Equilibrium numbers of non-relativistic $N, \bar{N}$:

$$\frac{n_B}{n_\gamma} \simeq \frac{n_{\bar{B}}}{n_\gamma} \simeq \left(\frac{m_N}{T}\right)^{3/2} e^{-m_N/T} \qquad (*)$$

Number of $N, \bar{N}$ decreases when universe cools off

and as long as $\Gamma_{annihil.} = n_B \langle \sigma_{annihil.} v \rangle \gtrsim H$

$\sigma_{annihil.} \sim 1/m_\pi^2 \quad \Rightarrow \quad \Gamma_{annihil.} = H$ at $T \simeq 20$ MeV, freeze out

insert into (*) $\Rightarrow \quad \frac{n_B}{n_\gamma} \simeq \frac{n_{\bar{B}}}{n_\gamma} \simeq 10^{-18}$

$N, \bar{N}$ **densities 8 orders of magnitude off!**

Requiring $\frac{n_B}{n_\gamma} \overset{!}{=} 6 \times 10^{-10} \quad \Rightarrow \quad T \simeq 38$ MeV

Thus, to prevent $N\bar{N}$ annihilation, some **unknown mechanism**
would have to operate at $T \gtrsim 38$ MeV and separate N and $\bar{N}$

What do these numbers tell us?

In principle, universe could be matter-$\overline{\mathrm{matter}}$ symmetric,
but, from observations $\Rightarrow$ $\overline{\mathrm{matter}}$ must be segregated **today** at mass scales $> 10^{14} M_\odot$

On the other hand, to avoid complete $N\bar{N}$ annihilation in early universe,
some **unknown mechanism** must have been at work at $T \gtrsim 38$ MeV to separate N from $\bar{N}$.
However, horizon at that time contained only $10^{-7} M_\odot$.

Thus, **causality** precludes separation of $N,\ \bar{N}$ of the required order of magnitude!

**Most reasonable conclusion: At early times, i.e. $T \gtrsim 38$ MeV,
universe possessed a baryon asymmetry**

****

Imposing $n_B/s \sim \eta/7 \simeq 10^{-10}$ as initial condition?

- at $t_{universe} = 0$: makes no sense in view of inflation

- after inflation: very unnatural

The Sakharov conditions

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

Attitude changed, however, 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 $\not{C}P$ interactions
- departure from thermal equilibrium $T\not{E}$ ("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 $\not{C}P$:

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

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

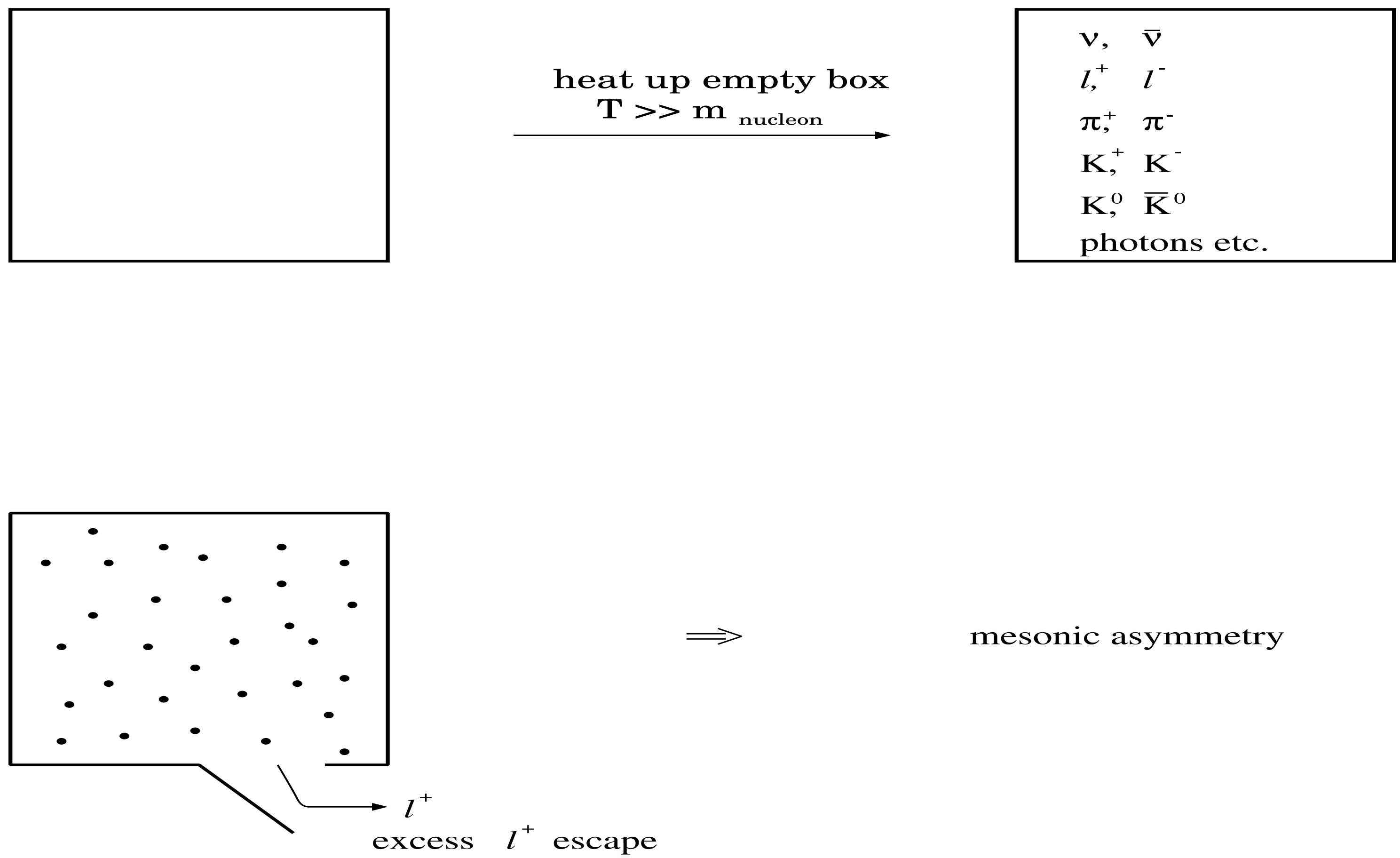
$\longrightarrow$ in thermal equilibrium

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

holds also in quantum theory.

Notice: in general, the Sakharov conditions are sufficient, not necessary.
If CPT invariance is given up $\Rightarrow$ requirement of, e.g., $\not{B}$ can be avoided

Gedanken-Experiment to illustrate 2 of the 3 Sakharov conditions



equal # of K^0 and $\bar{K}^0$, CPV in semileptonic decay $K_L \to \pi^{\mp}\ell^{\pm}\nu \to N(\pi^-) > N(\pi^+)$.
As long as system is in thermal equilibrium $\to$ 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" $\to$ 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 $\not{C}\!P$ due to SM weak interactions

- $\not{B}$ also by the SM weak interactions – **non-perturbative effect!**

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 $U(1)_L$
Noether theorem $\Rightarrow$ 2 classically conserved charges: B and L number

Currents J_μ^B, J_μ^L, conserved classically (= tree level)

$$\partial^\mu J_\mu^B = \frac{1}{3}\partial^\mu \sum_q \bar{q}\gamma_\mu q = 0\,, \qquad \partial^\mu J_\mu^L = \partial^\mu \sum_\ell \bar{\ell}\gamma_\mu \ell = 0\,.$$

associated charge operators

$$\hat{B} = \int d^3x\; J_0^B\,, \quad \hat{L} = \int d^3x\; J_0^L \quad \text{t-independent at classical level}$$

However, these symmetries are broken at **quantum level!**

$$\text{Recall} \qquad \bar{f}\gamma_\mu f = \bar{f}_L\gamma_\mu f_L + \bar{f}_R\gamma_\mu f_R\,, \qquad f = q, \ell\,.$$

Clash between gauge and chiral symmetries:
chiral U(1) currents **are not conserved** at quantum level.
Adler-Bell-Jackiw anomaly

$$\partial^\mu \bar{q}_L\gamma_\mu q_L = -\frac{g^2 c_L}{32\pi^2}\underbrace{F_{\mu\nu}\tilde{F}^{\mu\nu}}_{\vec{E}\cdot\vec{B}}, \qquad \partial^\mu \bar{q}_R\gamma_\mu q_R = +\frac{g^2 c_R}{32\pi^2}\,F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$c_L = c_R$ in QCD, no anomaly in vector current $\bar{q}\gamma_\mu q$.
BUT, gauge fields $W_\mu^\pm$, W_μ^3, B_μ of SU(2)$_L\times$U(1)$_Y$ gauge theory
couple differently to f_L and f_R

$$\Rightarrow \quad \partial^\mu J_\mu^B = \partial^\mu J_\mu^L = \frac{n_f}{32\pi^2}\left(-g_W^2 W_{\mu\nu}^a \tilde{W}^{\mu\nu a} + g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right) \qquad (*)$$

$n_f = 3$ generations, abelian anomaly $B_{\mu\nu}\tilde{B}^{\mu\nu}$ irrelevant for the following

$$(*) \quad \Rightarrow \quad \partial^\mu (J^B_\mu - J^L_\mu) = 0$$
$$\Rightarrow \quad B - L \textbf{ conserved in SM}$$

but not B, L separately!

How does $\not B + \not L$ come about?

Right-hand side of (*) is a total divergence,

$$\partial^\mu J^B_\mu = \partial^\mu J^L_\mu = n_f \partial^\mu K_\mu \qquad (**)$$

$$\int d^3x dt\, \partial_\mu K^\mu \stackrel{\text{Gauß}}{=} N_{CS}(t_f) - N_{CS}(t_i) \equiv \Delta N_{CS} \,,$$

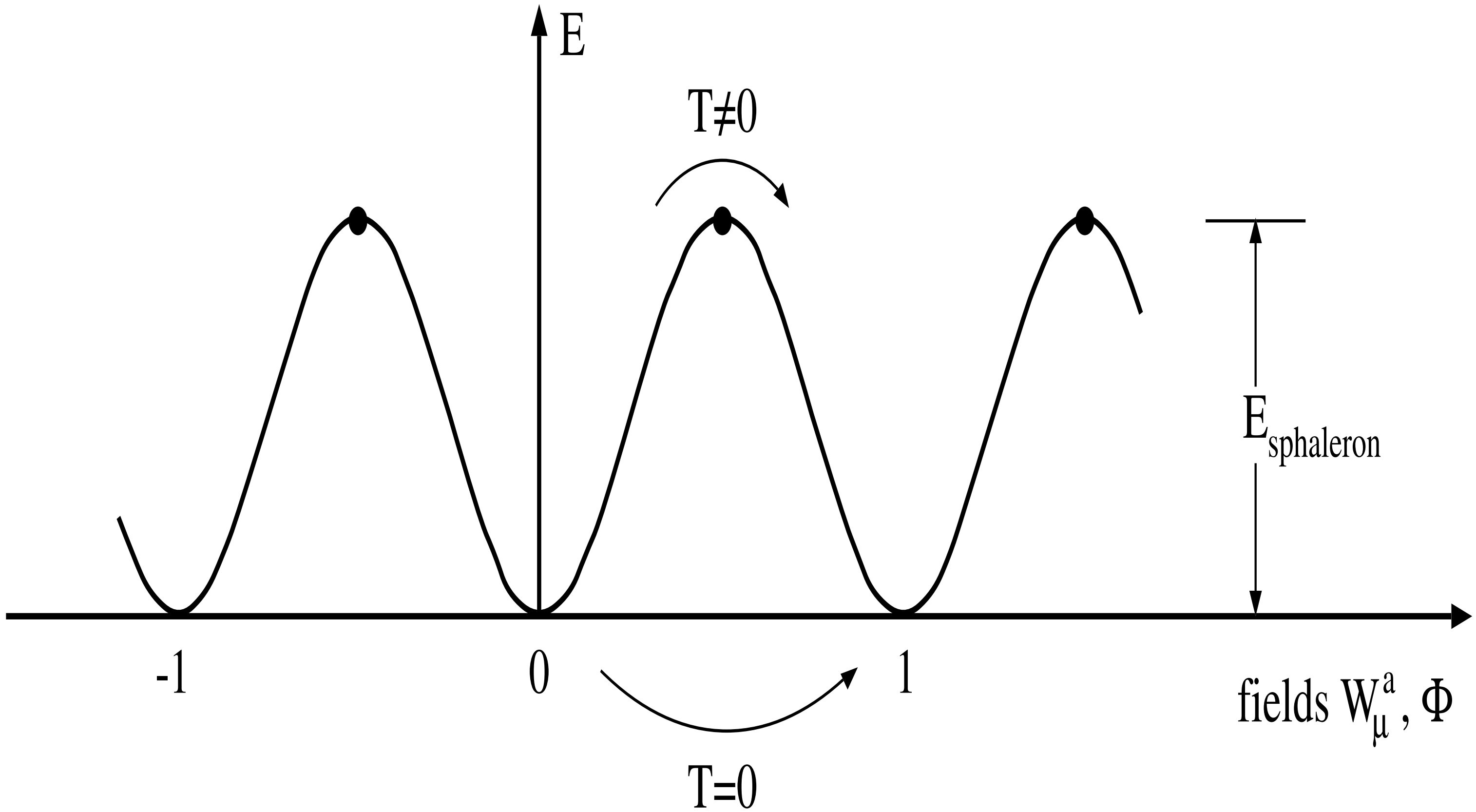
where Chern-Simons number (in gauge $W^a_0 = 0$)

$$N_{CS}(t) \;=\; \frac{g_w^3}{96\pi^2} \int d^3x\, \epsilon_{ijk} \epsilon^{abc} W^{ai} W^{bj} W^{ck}$$

integral assigns a **topological charge** to a classical $SU(2)_L$ gauge field.

Non-trivial vacuum structure of SM, i.e. $SU(2)_L$ gauge theory

energy functional E[field] at temperature $T = 0$



infinite number of 'n-vacua',
vacuum gauge field configurations have topolocial charges $\Delta N_{CS} = 0, \pm 1, \pm 2, \ldots$
True vacuum $=$ coherent superposition of the n-vacua

Back to anomaly in B and L current:

$$\text{Define} \qquad \Delta \hat{B} \equiv \hat{B}(t_f) - \hat{B}(t_i), \qquad \text{likewise } \Delta \hat{L}$$

Integrate anomaly eqn. (*) and use (**)

$$\Rightarrow \quad \mathbf{\Delta \hat{B} = \Delta \hat{L} = n_f \Delta N_{CS}} \qquad (***)$$

Interpretation:

- Perturbation theory $\leftrightarrow$ small gauge field qauntum fluctuations around $W^a_\mu = 0$
  $\Rightarrow$ r.h. side of (***) is zero, B and L conserved

- "Large" non-abelian gauge gauge fields $W^a_\mu \sim 1/g_W$ with $\Delta N_{CS} = \pm 1, \pm 2, \ldots$. exist [(anti)instantons]
  they induce, at quantum level, $\not{B} + \not{L}$ transitions 't Hooft (1976)

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

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

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

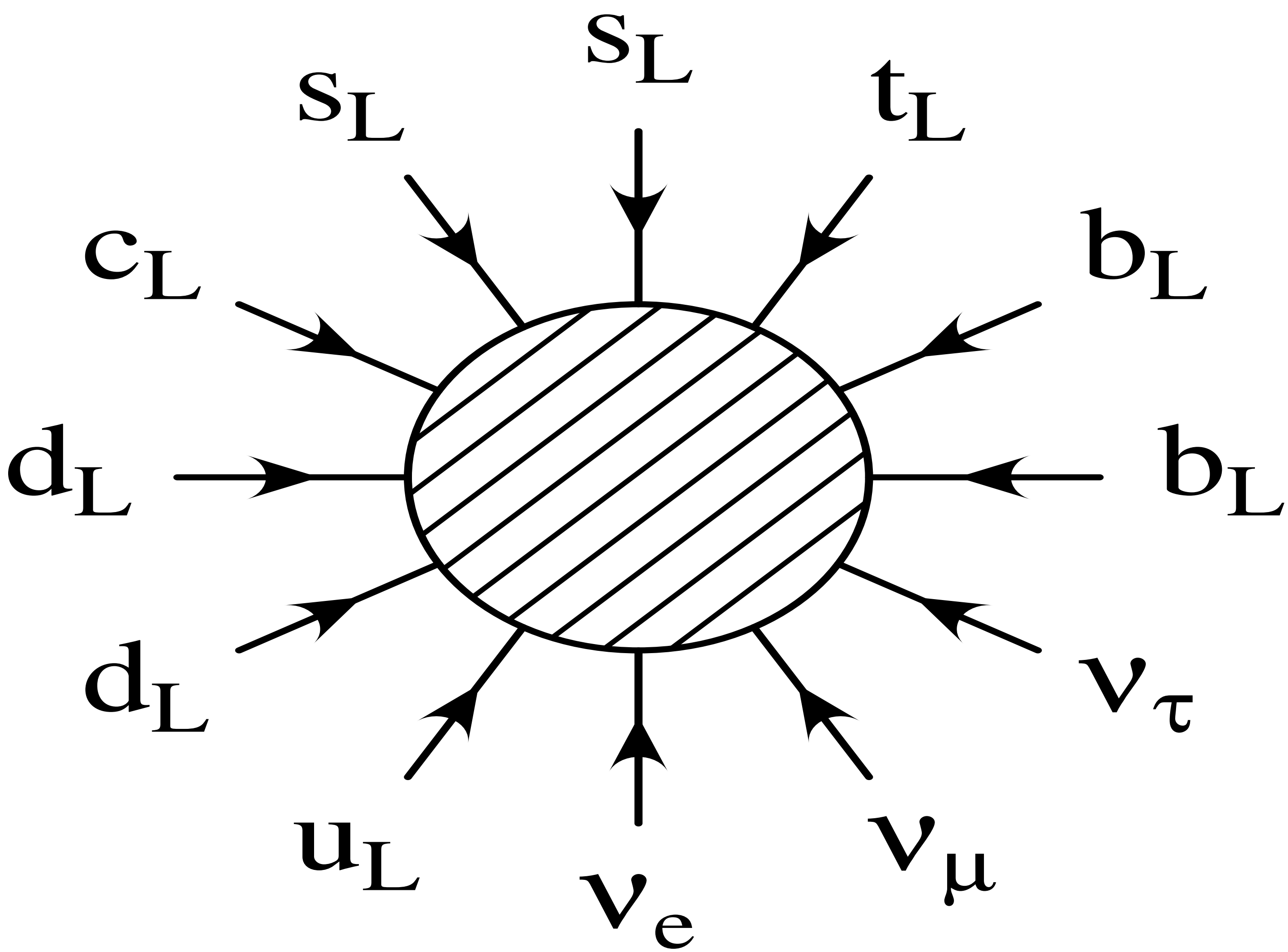
where $n_{gen} = 3$, and $\Delta N_{CS} = 0, \pm 1, \pm 2, \ldots$

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

Precisely: $\not{B}+\not{L}$ 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 $q_L,\ \ell_L,\ \nu_L \longrightarrow \bar{q}_R,\ \bar{\ell}_R,\ \bar{\nu}_R$

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



arrow $\leftrightarrow$ flow of fermionic quantum number 't Hooft (1976):

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

$\not{B}$ and $\not{L}$ reactions with, for instance, $\Delta B = \Delta L = \mp 3$ – and $\Delta(B - L) = 0$:

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

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 $\not{B} + \not{L}$ cross section, which involves reactions

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

could be substantially larger at $\hat{s} \gg 10$ TeV and $n_H, n_W \gg 1$

`Ringwald;  Espinoza (1990)`

Situation changes, when SM is coupled to heat bath of temperature $T \neq 0$:
For large T, $\not{B} + \not{L}$ processes are no longer suppressed!

Reason: ground states with different N_{CS} are separated by potential barrier

$$E_{sphaleron}(T) = \frac{4\pi}{g_W}\, v_T \; f\left(\frac{\lambda}{g_W}\right)$$

$v_T = \sqrt{2}\langle 0|\Phi|0\rangle_T$ Higgs v.e.v. at $T \neq 0$, $\quad f \sim 2$
$E_{sphaleron}$ is energy of "sphaleron" $=$ gauge $+$ Higgs field configuration,
(unstable) solution of classical field eqns. (`Klinkhamer, Manton (1984)`) with

$$\Delta N_{CS}(\text{sphaleron}) = \frac{1}{2} + (\text{integer})$$

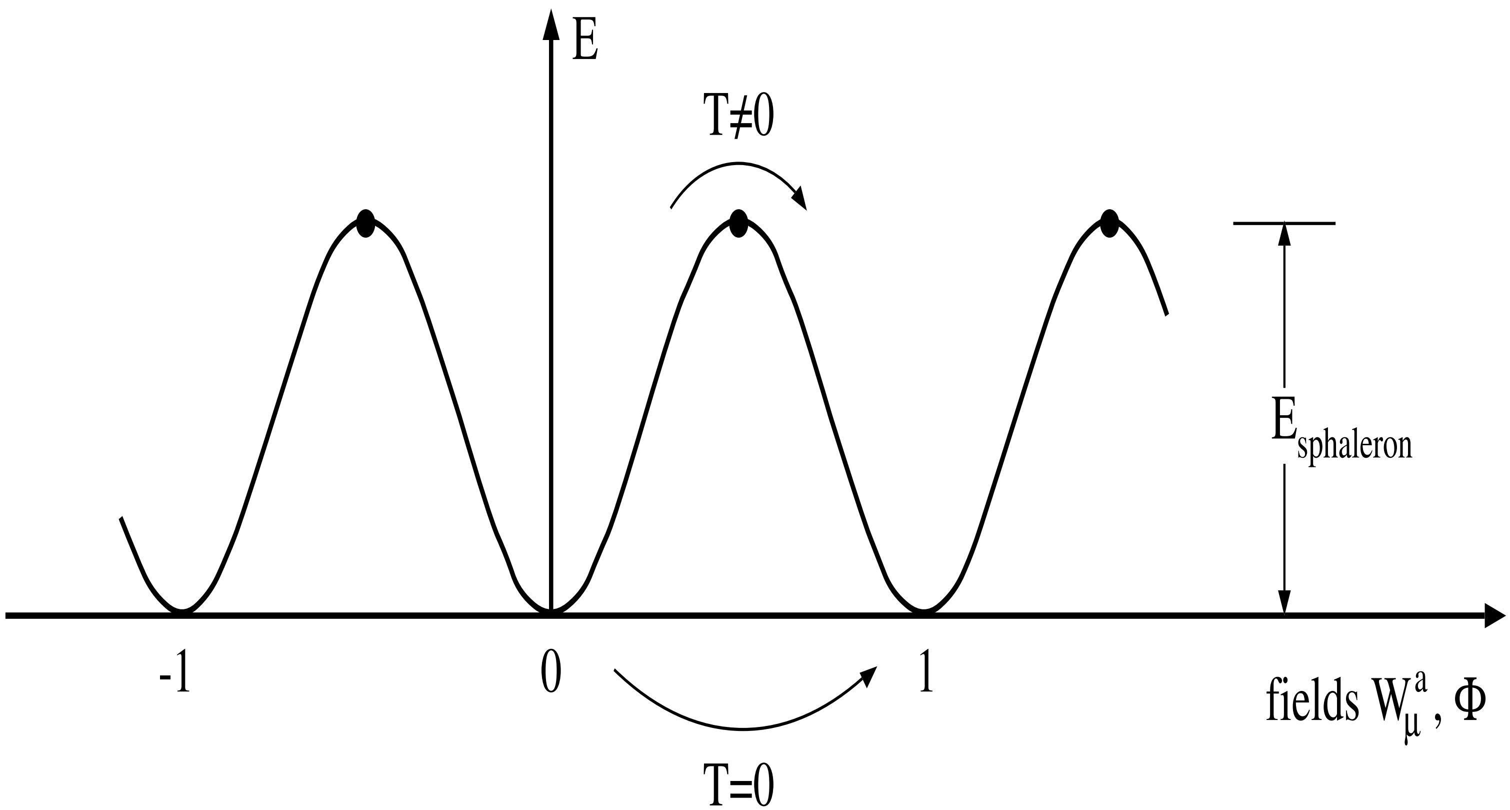
expect that

- $\not{B} + \not{L}$ processes $\propto e^{-E_{sphaleron}(T)/T}$ if energy of thermal excitations $<$ barrier
- $\not{B} + \not{L}$ processes above barrier

Here we note that (see below)

$T < T_{EW} \sim 100$ GeV	$T > T_{EW}$
EW gauge symmetry broken	EW gauge symmetry restored

Periodic vacuum structure of standard EW theory



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

Klinkhamer, Manton (1984)

$\not{B} + \not{L}$ 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):

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

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

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

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

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

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

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

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

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

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

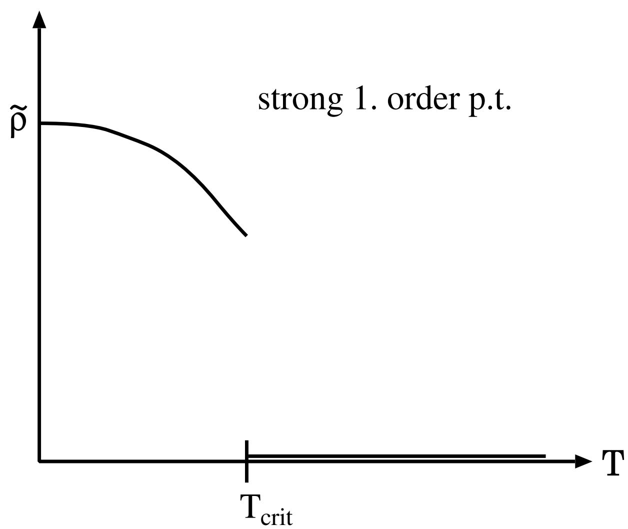
sizeable $\not{T}\not{E}$ required !

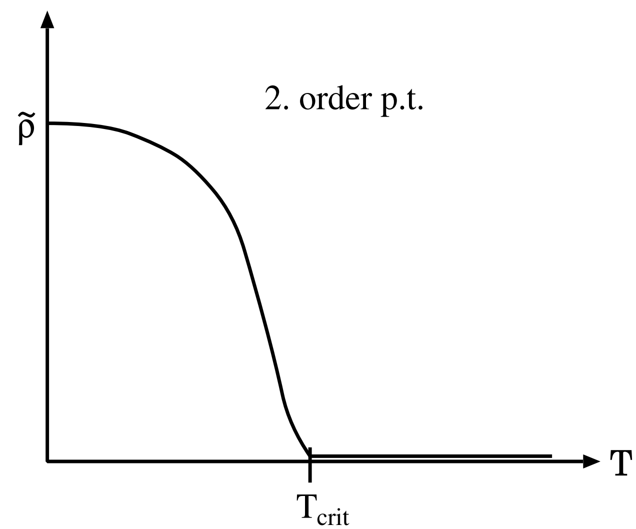
plausible instance: electroweak phase transition

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

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

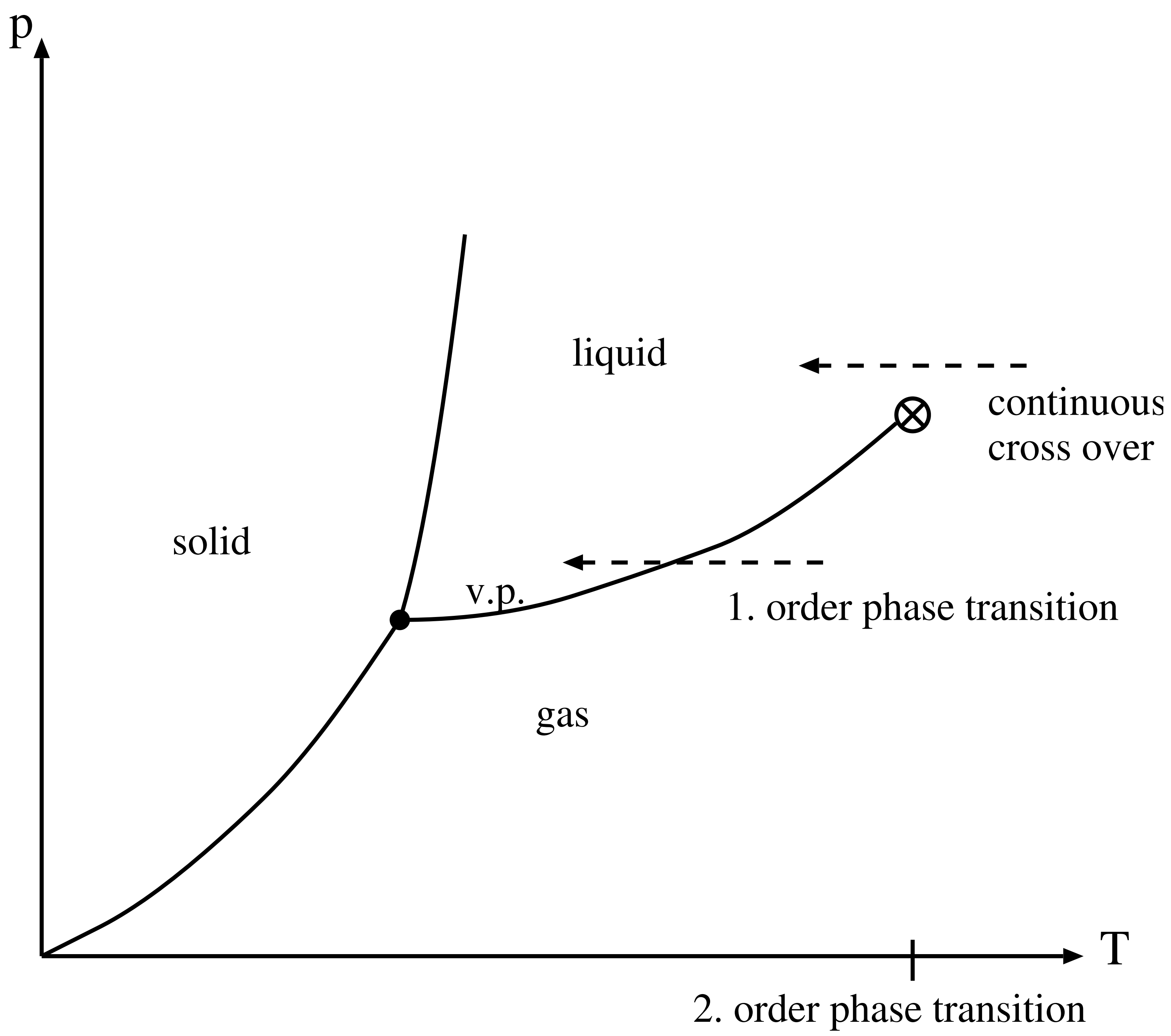
Phase transition must be **strongly 1. order**
i.e., "order parameter" $v_T = \langle 0|\Phi|0\rangle_T/\sqrt{2}$ must have a sizeable jump at T_c



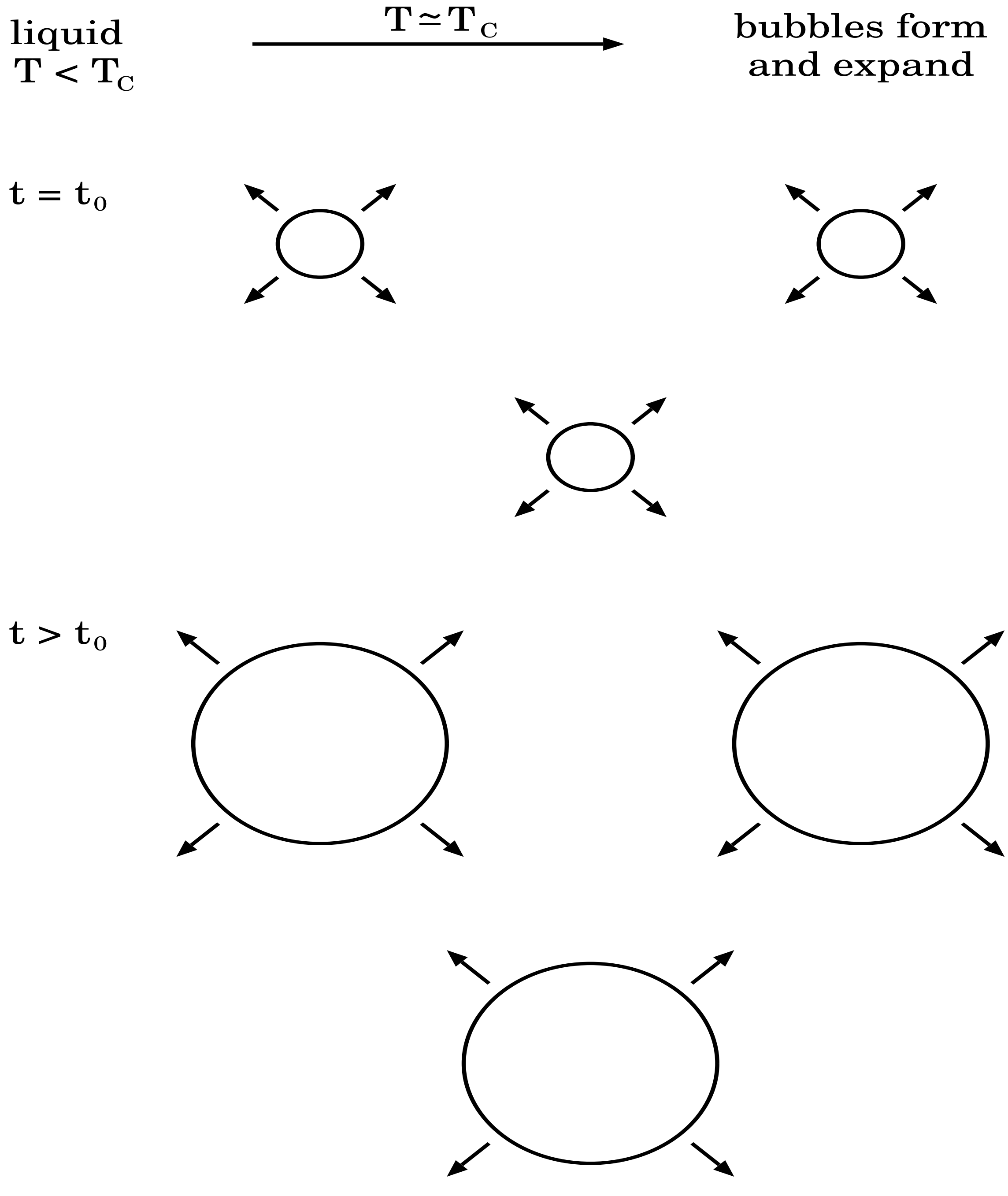


That's what is needed
in order to block the $\not{B}$ reactions
in the region(s) of space where the VEV $v_T \neq 0$

Example from houshold physics: The phase diagram of water



Dynamics of a 1. order phase transition



Why the SM fails

Thermostatics of a gauge field theory – well developed technology

compute free energy $F = -T \ln Z$ with the Euclidean functional integral

$$F(J,T) \; = \; -T \ln \left[\int_\beta \mathcal{D}[\text{fields}] \exp(- \int_\beta dx (\mathcal{L}_{EW} + J \cdot \Phi)) \right] ,$$

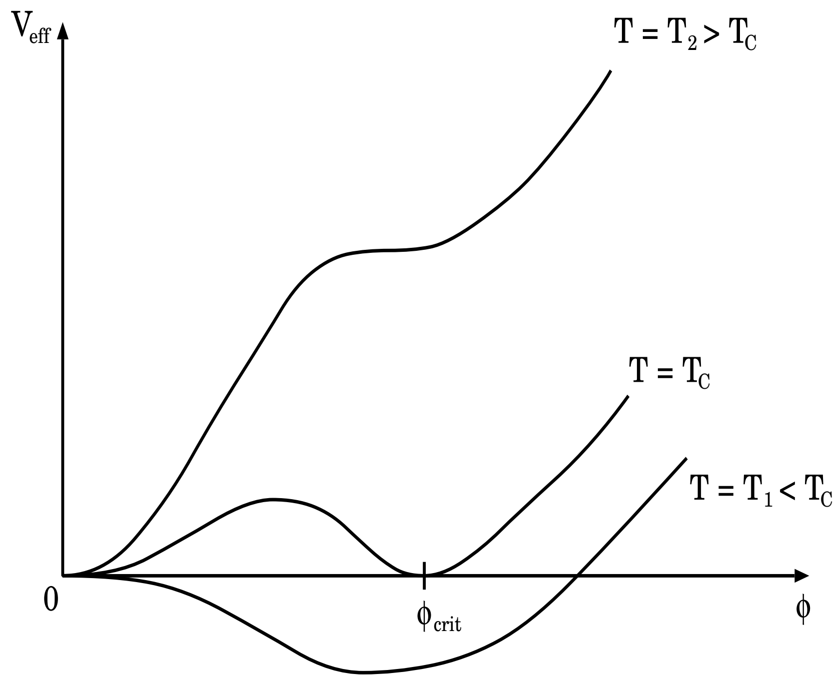
$\mathcal{L}_{EW}(\Phi, W_\mu^a, B_\mu, q, \ell)$ is electroweak SM Lagrangian, J is an auxiliary external field, $\beta = 1/T$.

$$F(J,T)/V \quad \longrightarrow \quad \text{effective potential } V_{eff}(\phi, T)$$

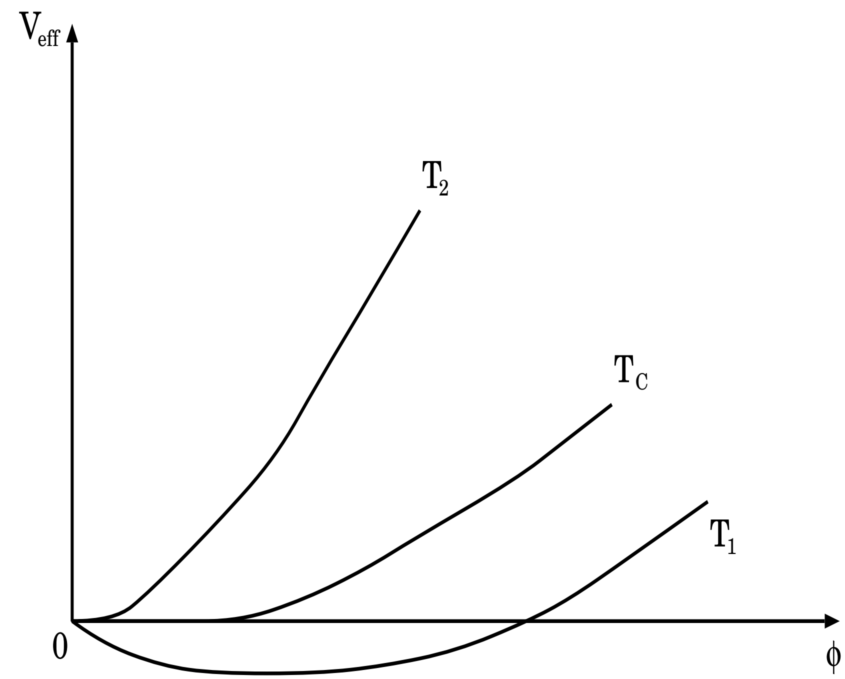
by Legendre transformation, where $\phi = \partial F / \partial J|_{J=0} =< \Phi >_T$.

v.e.v.(s) $< \Phi >_T$ from stationary point(s) $\partial V_{eff}(\phi, T)/\partial\phi = 0$.

V_{eff} in case of a 1. order phase transition



V_{eff} in case of a 2. order p.t.

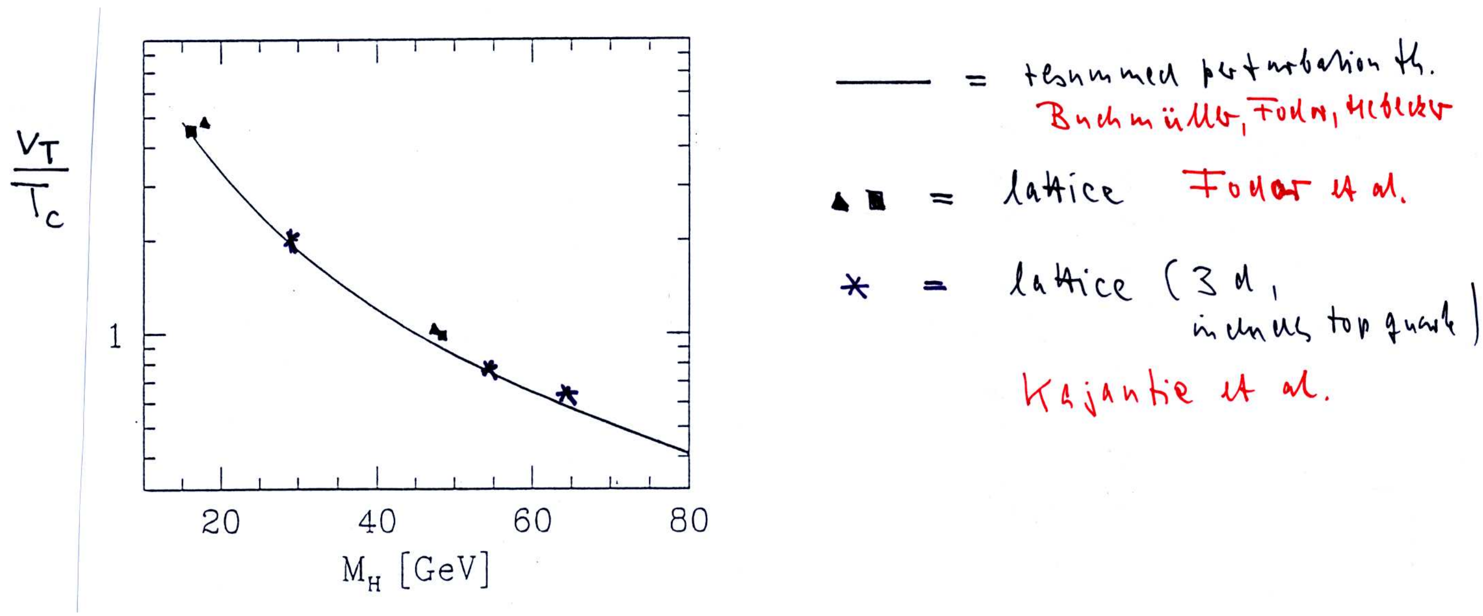


Condition for strength of phase transition:

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

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

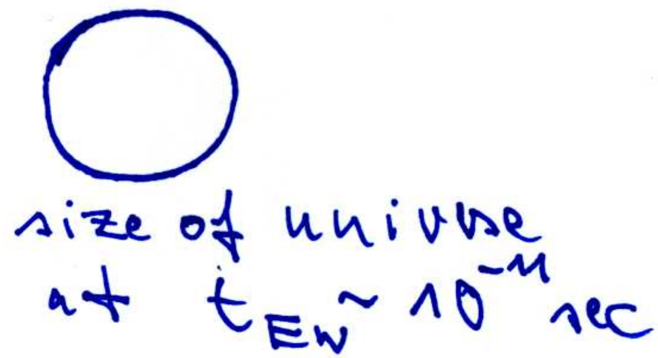
Results for SM SU(2) gauge-Higgs field theory



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

In view of LEP lower bound $m_H^{SM} > 114$ GeV and LHC result: $m_H = 126$ GeV $\quad \Rightarrow$

- **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 $\not{C}P$

Some SM extensions

non-SUSY extensions:

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

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

These models have phenomenologically acceptable parameter regions such that lightest Higgs boson $m_H = 126$ GeV and EW phase transition is 1. order

SUSY extensions:

- minimal (MSSM), contains 2 Higgs doublets

Strong 1. order EW phase transition in MSSM?

State-of-the-art before discovery of 126 GeV resonance at LHC:

yes, if

lightest Higgs boson $m_{H_1} <$ 120 - 125 GeV and 1 light stop $(\tilde{t}_R)$, $m_{\tilde{t}_R} <$ 120 GeV

(Carena et al. (1996), Cline et al. (1996), ...)

Recent reanalysis, in view of production cross section, etc., of 126 GeV Higgs resonance and negative SUSY searches at the LHC:
Carena et al. (2012)
conclude that 1. order p.t. in MSSM still possible in extreme scenario:

$$m_{\tilde{t}_R} < 110 \text{ GeV and } m_{\tilde{t}_L} > 50 \text{ TeV}$$

This scenario probably ruled out rather soon (?)

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

requirement of 1. order p.t. and lightest Higgs $m_H = 126$ GeV can be arranged.
(Huber, Schmidt (2001), ...)

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

Examples: • Higgs sector $\not{C}\!\!P$, e.g. 2 Higgs doublet extension of SM
explicit $\not{C}\!\!P$ 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

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

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

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

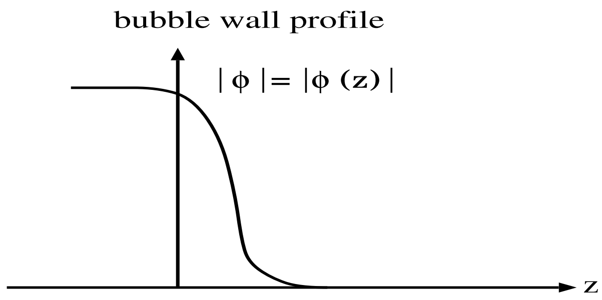
Then

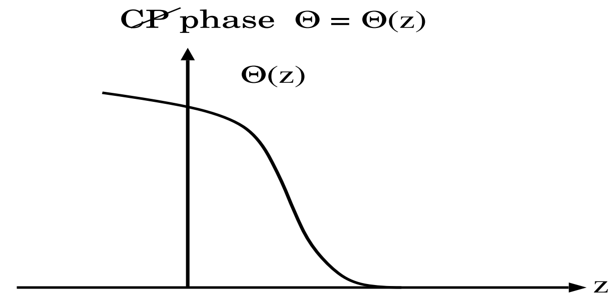
$$\mathcal{L}_1 \;=\; -h_\psi\bar{\psi}_L\psi_R\phi_1^0 \;+\; h.c. \;=\; -m_\psi(z)\bar{\psi}_L\psi_R \;-\; m_\psi^*(z)\bar{\psi}_R\psi_L \;+\; \ldots\,,$$

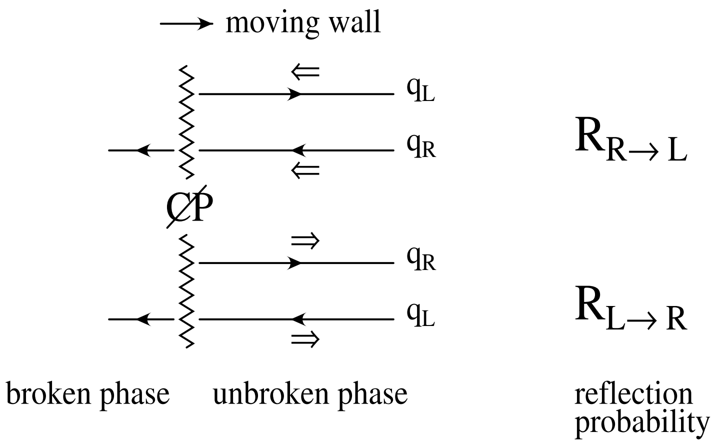
where (analogously for $< \phi_2^0 >$)

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

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





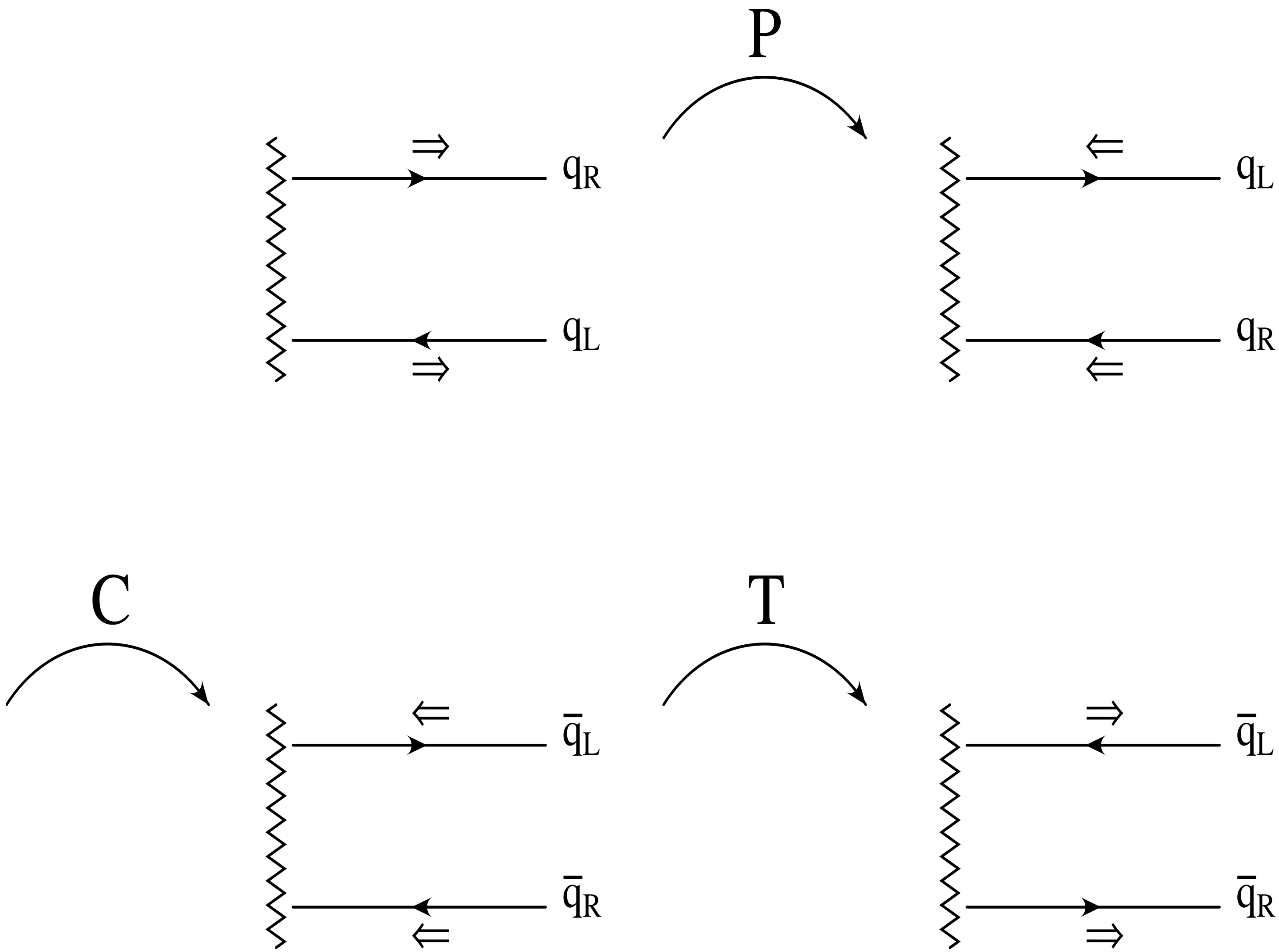


likewise for $\bar{q}_L \to \bar{q}_R,\ \bar{q}_R \to \bar{q}_L$ (here: L,R = particle helicities)

$$\begin{aligned} \text{CP violation}: \quad & \mathcal{R}_{\bar{L}\to\bar{R}} \neq \mathcal{R}_{R\to L} \quad \text{and} \quad \mathcal{R}_{\bar{R}\to\bar{L}} \neq \mathcal{R}_{L\to R} \\ \text{CPT invariance}: \quad & \mathcal{R}_{\bar{L}\to\bar{R}} = \mathcal{R}_{L\to R} \quad \text{and} \quad \mathcal{R}_{\bar{R}\to\bar{L}} = \mathcal{R}_{R\to L} \\ \longrightarrow \quad & \text{flux}(\bar{q}_R) - \text{flux}(q_L) \ = \ \text{flux}(q_R) - \text{flux}(\bar{q}_L) \end{aligned} \tag{1}$$

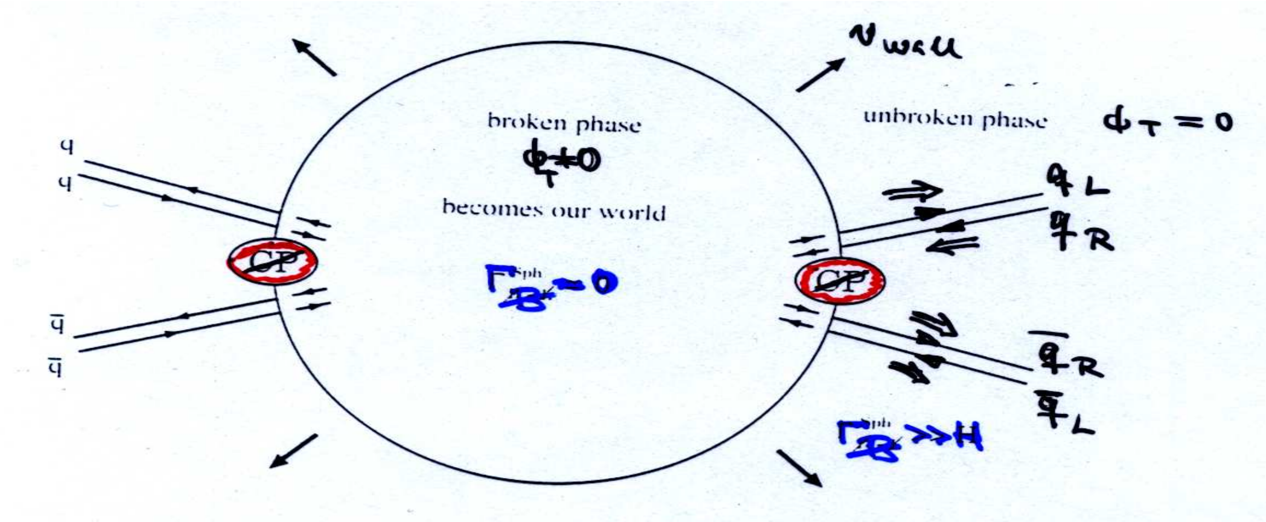
i.e., no net quark number yet

The reflection $q_L \to q_R$ and the P-, CP-, and CPT-transformed process



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

Cohen, Kaplan, Nelson (1991)



- $\not{C}\!\not{P}$ 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.,
$$\bar{t}_R + \bar{b}_R \to 7q_L + 3\nu_L$$
$$t_L + b_L \to 7\bar{q}_R + 3\bar{\nu}_R$$

- $\not{T}\!\not{E}$: 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 couplings $A \leftrightarrow$ 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 accommodate 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 !

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

where

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

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

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

Detailed investigations: Gavela et al. (1994); Huet, Sather (1995)

(But statement not fool-proof, $\Delta\mathcal{R}_{CP}$ may be enhanced. Farrar, Shaposhnikov (1995))

Side note:

In 4-generation SM,
the CP asymmetry $\Delta\mathcal{R}_{CP}$ at EW phase transition can be dramatically enhanced!
W.S. Hou (2008)

Assume 4th sequential quark generation t', b' with masses ~ 500 GeV

$$d_{CP}^{3gen} \quad \longrightarrow \quad d_{CP}^{4gen}$$, enhanced by 15 orders of magnitude!

However, existence of sequential 4th quark generation (almost) excluded

- by negative searches at LHC
- measured production cross section of 126 GeV resonance at LHC $\leftrightarrow$ SM predictions

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 (for 1. order p.t.)

- and new $\not{C}\!P$ interactions

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

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

$$|d_e| < 1.05 \times 10^{-27}\,\mathrm{e\,cm}\,, \qquad |d_n| < 2.9 \times 10^{-26}\,\mathrm{e\,cm}$$

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

$\longrightarrow$ new $\not{C}\!P$ in B and D meson decays

(For baryogenesis, flavour-diagonal $\not{C}\!P$ sufficient $\Rightarrow$ small efects in B & D decays)

Side note on recent parity-determination of 126 GeV resonance H by ATLAS and CMS:

Angular distributions in $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$
data $\Rightarrow$ spin $J_H = 0.$
From angular distribution of $H \to ZZ^* \to 4\ell$, ATLAS concludes $J^P = 0^+$ (scalar) favoured
However, this does not prove that H is a pure scalar!

Reason:

- the very fact that $H \to ZZ^*$ was observed with (SM-like) strength implies that H **cannot be a pure pseudoscalar,** $J^P = 0^-$, because
  * no tree-level coupling of pseudoscalar to ZZ or W^+W^-
  * these couplings must be induced by fermion loops ($\not{P}$ required)

  investigation in a number of BSM models $\Rightarrow$ induced couplings very small

  W.B., Gonzalez, Wiebusch (2010)

Conclusion: still an option that H is a CP mixture,
pseudoscalar component is not detectable in $H \to ZZ$

Unambiguous P and CP determinations possible in

$$H \to \tau^+\tau^- \to \text{1-prong}, \quad \text{3-prong}$$

W.B., Brandenburg (1993), Berge, W.B.,.. (2008,2009,2011)

Scenario 2: Baryogenesis via leptogenesis

Variant A: Thermal leptogenesis:

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

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

proposed by Fukugita, Yanagida (1978) since then: $\sim 10^3$ papers

Popular 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

$$\mathcal{L}_{Yukawa} = - \sum_{ij} \bar{L}_i h_{ij} \nu_{Rj} \tilde{\Phi} + \text{h.c.}$$

$L_i = (\nu_L, \ell_L)_i$, $\tilde{\Phi} \equiv i\sigma_2 \Phi^* = (\phi_0^*, -\phi_-)$
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 $\not{C}\!P$,
described by unitary 3×3 matrix U_D (PMNS matrix)
U_D has 4 observable parameters: 3 angles and 1 CP phase
$\longrightarrow$

- ν oscillations
- $\not{C}\!P$, 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 lepton flavor nr.)
ν = Dirac requires tiny Yukawa couplings h_{ij} – unsatisfactory

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)

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

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

where

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

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

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

where the mass eigenfields

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

and

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

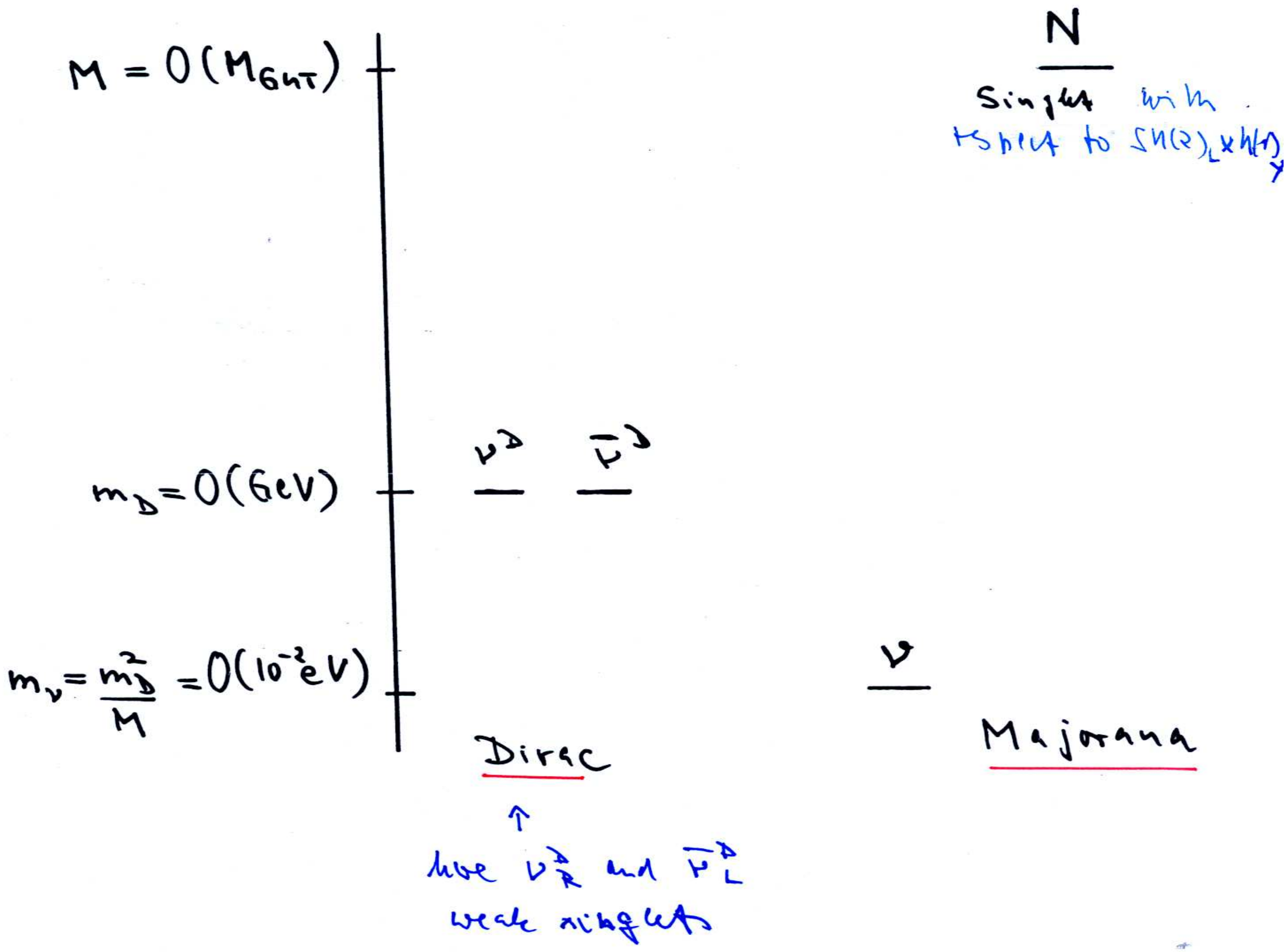
For $M >> m_D$ the neutrino mass eigenstates consist of

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

and very heavy Majorana $|N\rangle$ (weak singlet, 2 helicity states)

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

$M = \mathcal{O}(M_{GUT})$ suggested by GUTs



Case of 3 lepton generations

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

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

$L_i = (\nu_i, \ell_i)$ (i = flavor), $\quad \tilde{\Phi} = (\phi_0^*, -\phi_-)$,

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

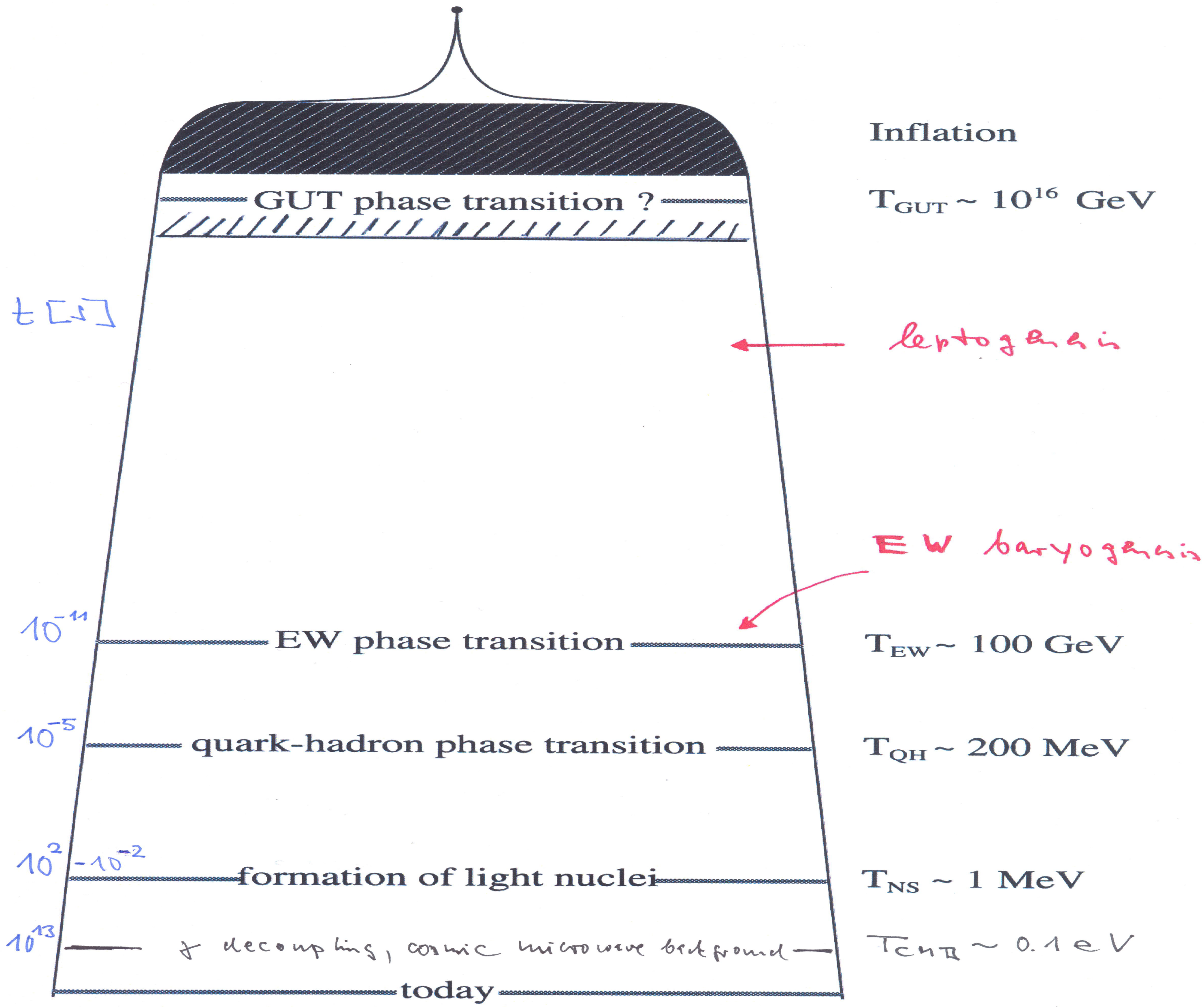
$$\mathcal{L}_{cc}^{lept} = -\frac{g_w}{\sqrt{2}} \bar{\ell}_{mL} \gamma^\mu U_{mn} \nu_n W_\mu^- + h.c.$$

$\nu_n = \nu_{Ln} + \nu_{Ln}^c$ = Majorana
PMNS matrix U now depends on 3 angles and 1 + 2 additional CP phases

$\Rightarrow$

- small ν masses by seesaw mechanism
- ν oscillations
- $\not{CP}$, e.g. $\text{prob}(\nu_e \to \nu_\mu) \neq \text{prob}(\bar{\nu}_\mu \to \bar{\nu}_e)$
- but Majorana CP phases do not enter here
- **lepton number violation: ν-less 2 β decay, e.g.,** $^{76}Ge \to {}^{76}Se + 2e^-$

Now to thermal leptogenesis - da capo:



Basics of thermal leptogenesis scenario: $M \gg T_{EW}$

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

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

N_j couple to e, ν, τ, ν_i, and Higgs bosons, i.e. to neutral & charged component of Φ

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

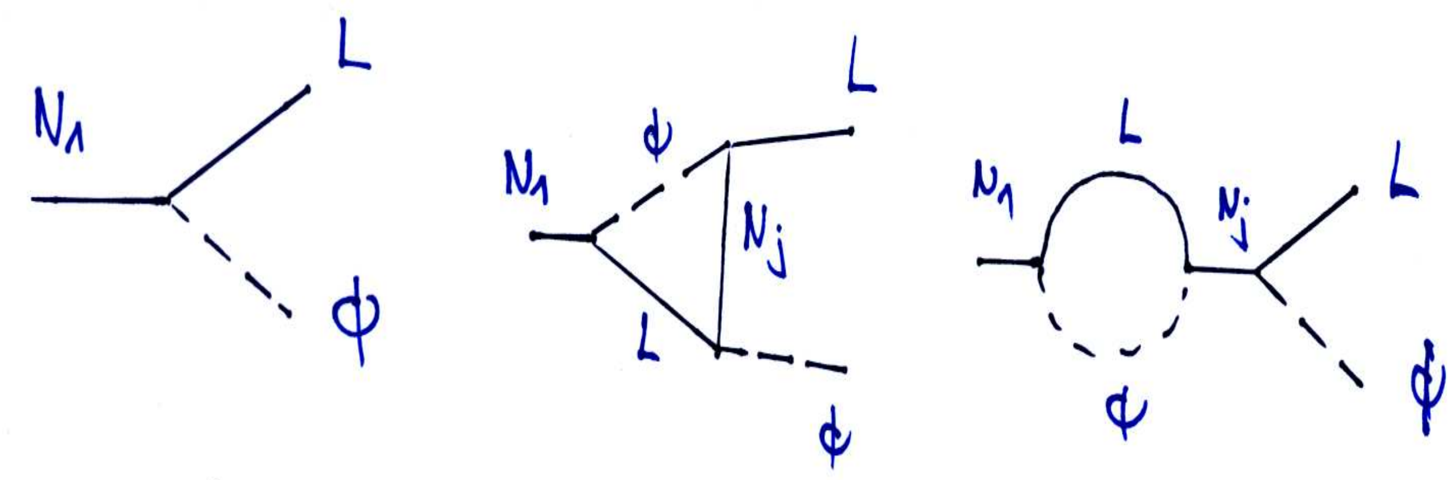
$L_i = (\nu_i, \ell_i)$ (i = flavor), $\tilde{\Phi} = (\phi_0^*, -\phi_-)$,
h_{ij} complex coupling matrix, $\not{C}$ and $\not{C}\text{P}$

N_i produced thermally: $q\bar{q} \to N_i \nu_j$, $\phi^\pm \to N_i \ell_j^\pm$, ... (hence the name *thermal l.g.)*

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

$$\not{L}: \quad \text{e.g. in decays N}_1 \longrightarrow \begin{array}{ll} \ell^- + \phi^+, & L_f = +1 \\ \ell^+ + \phi^-, & L_f = -1 \end{array}$$

$\not{CP}$ 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, $\Phi = \phi^0$ or $\phi^{\pm}$

CP asymmetry in N_1 decays in "one-flavor" approximation = treat all Yuk. coupl. equal (relevant if lepton flavors are indistinguishable in particle plasma)

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

where m_j are masses of light ν_j

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

- in one-flavor approx.: $\not{CP}$ relevant for leptogenesis $\not\leftrightarrow$ $\not{CP}$ 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 (PMNS 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

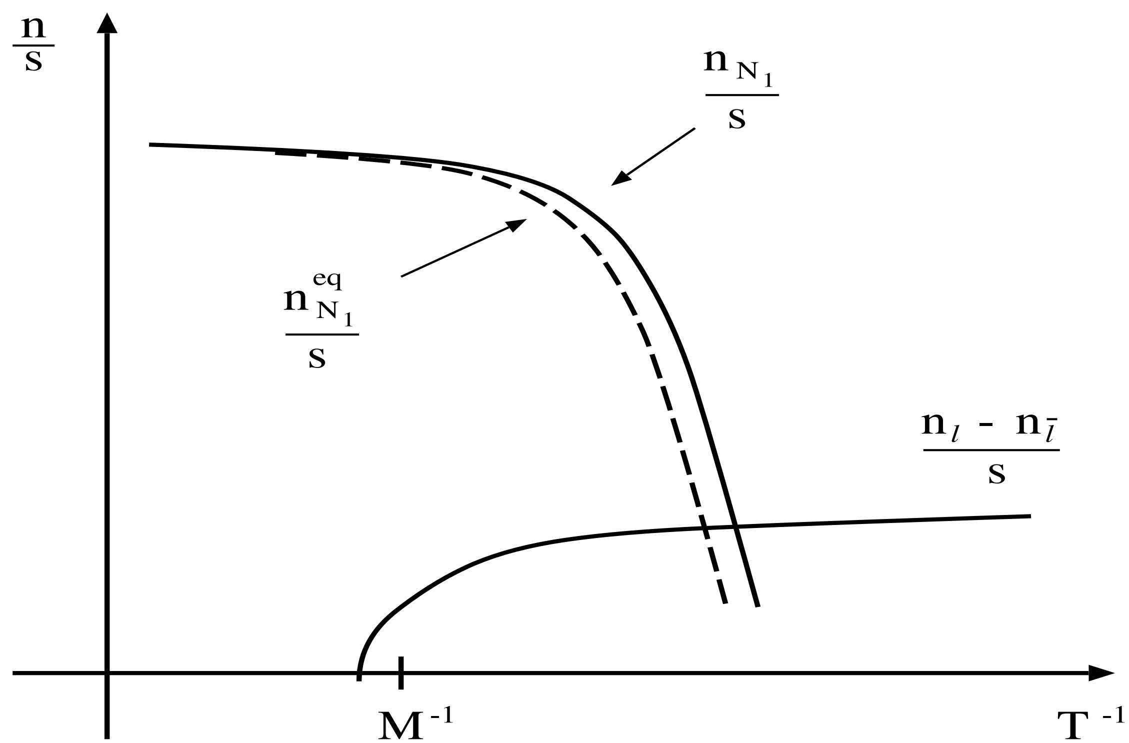
- There is a upper bound on the $\not{C}\!P$ asymmetry ϵ_1:

From orthogonalitiy of R, $\sum_j R_{1j}^2 = 1, \quad \Rightarrow$

$$|\epsilon_1| \leq \frac{3M_1}{8\pi v^2}(m_3 - m_1) = \frac{3M_1}{8\pi v^2}\frac{\Delta m_{atm}^2}{m_1 + m_3} = 10^{-6}\frac{M_1}{10^{10}\mathrm{GeV}}\frac{\sqrt{\Delta m_{atm}^2}}{m_1 + m_3}$$

with $\sqrt{\Delta m_{atm}^2} \simeq 0.05$ eV (Davison, Ibarra (2002))

$\not{T}E$: N_1 (singlet): only very weakly coupled to “heat bath”
N_1 decouple if
decay rate $\Gamma_{N_1} <$ expansion rate $H(T)$ (rule of thumb)
then “inverse decays” $L_i\Phi,\ \bar{L}_i\bar{\Phi} \to N_1$ & wash-out reactions “blocked”
more precisely: density distribution n_{N_1} determined with Boltzmann eq.
taking into account decays, inverse decays, and scatterings, e.g.,
$\phi^+\phi^+ \leftrightarrow \ell^+\ell^+ \ldots (|\Delta L| = 2) \quad N_1\,\ell \leftrightarrow t\,q, \ldots (|\Delta L| = 1), \quad \ldots.$



Buchmüller, Plümacher (2000)

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

$$\mu_R^+ + \tau_R^+ \to 9\, q_L + e_L^- \qquad (\Delta B = 3)$$
$$\mu_L^- + \tau_L^- \to 9\, \bar{q}_R + e_R^+ \qquad (\Delta B = -3)$$

Recall that $\not{B} + \not{L}$ sphaleron processes affect only f_L and $\bar{f}_R$

Formula: (Harvey, Turner (1990), Khlebnikov,Shaposhnikov (1996))

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

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 $\not{C}\!P$ 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 10^{-3} eV$\lesssim m_i \lesssim 0.1$ eV, compatible with oscillation data
and $M_1 \gtrsim 10^9 - 10^{10}$ GeV
cf., e.g., Buchmüller, arXiv:1212.3554

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 expansion rate H
holds only for $T \sim M_1 \gtrsim 10^{12}$ GeV
For $M_1 \lesssim 10^{11}\,(10^9)$ GeV the τ (μ) Yukawa couplings induce scattering rates $> H$
i.e., these flavors equilibrate earlier
$\longrightarrow$ **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 several uncertainties.

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

Flavor effects can reduce lower bound on M_1 by 1 - 2 orders of magnitude

Antusch et al., arXiv:0910.5972

Variant B: **Low scale leptogenesis:**

A number of leptogenesis scenarios were proposed
with singlet neutrinos (sterile neutrinos) with much smaller masses (TeV - GeV range)

Sketch here only *Neutrino Minimal Standard Model* (νMSM) Shaposhnikov et al. [hep-ph/0503065, ...]

Goal:
Explanation of η by minimal extension of SM, in accord with ν oscillations,
AND provide Dark Matter candidate

Extend SM by three SU(2)$_L\times$U(1)$_Y$ singlet neutrinos $\nu_{R,i}$:

$$\mathcal{L}_{\nu MSM} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \left(\bar{L}_L F \nu_R \tilde{\Phi} - \frac{1}{2} \overline{\nu_R^c} M \nu_R + \text{h.c.} \right)$$

where $L_L = (\nu_L, \ell_L)$, generation indices suppressed, $\tilde{\Phi} = (\phi_0^*, \; -\phi_-)$
M, F : 3×3 Majorana mass and Yukawa coupling matrices.
Block diagonalization of full 6×6 mass matrix

mass matrix of 'active' neutrinos: $m_\nu = -\theta M \theta^T$, $\theta = m_D M^{-1}$
mass matrix of sterile neutrinos: $M_N = M + \frac{1}{2}\left(\theta^\dagger \theta M + M^T \theta^T \theta^*\right)$

where $m_D = Fv$
3×3 matrix $\theta \leftrightarrow$ mixing of active ν and sterile N; suppressed ($|m_D| \ll |M|$)

active mass eigenstates ν_i, masses m_i: mainly mixings of SM neutrinos $\nu_{L,\alpha}$
sterile mass eigenstates N_I, masses M_I: mainly mixings of $\nu_{R,\alpha}$

This model assumes masses M_I below the EW scale ~ 100 GeV.

In order to obtain the right order of magnitude of light ν_i masses m_i
$\Rightarrow$ Yukawa couplings F must be tiny: $F = \sqrt{m_\nu M_N}/v < 10^{-6}$

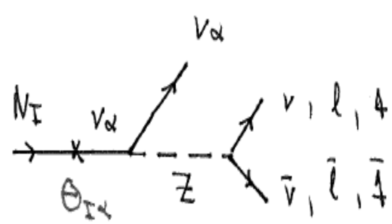
Scenario:

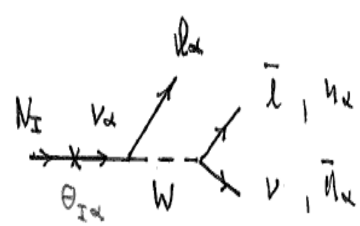
1) one sterile neutrino, N_1, much lighter than N_2, N_3, provides (warm) Dark Matter, plays no role in leptogenesis

2) the other two, N_2, N_3, generate BAU via leptogenesis and generate masses of light ν_i via seesaw mechanism

requirement 1) $\Rightarrow$ lifetime of $N_1 >$ age of universe

Main decay mode: $N_1 \to \nu_\alpha \bar{\nu}_\beta \nu_\beta$

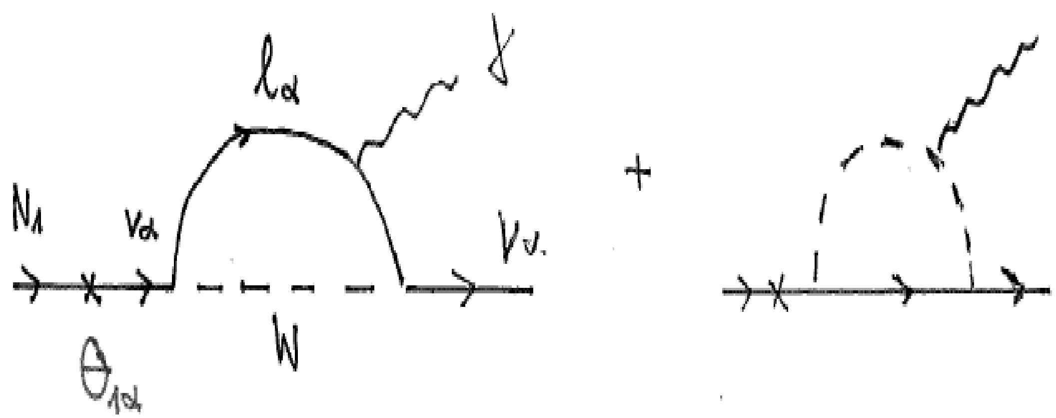




$$\tau_{N_1} = 10^{14}\text{years}\left(\frac{10\text{keV}}{M_1}\right)^5\left(\frac{10^{-8}}{\theta_{1\alpha}^2}\right)$$

Recall $\theta = vFM^{-1}$.

Radiative decay $N_1 \to \nu_\alpha \gamma$ subdominant,



but produces a γ signal at $E_\gamma = M_1/2$ in diffuse γ-ray background

$$\Gamma(N_1 \to \nu_\alpha \gamma) = \frac{9\alpha G_F^2}{1024\pi^4} \sin^2(2\theta_{1\alpha}) M_1^5 = 5.5 \times 10^{-22} \theta_{1\alpha}^2 \left[\frac{M_1}{\text{keV}}\right]^5 \; s^{-1}$$

Non-observation $\Rightarrow$ $\theta_{1\alpha}^2 \leq 1.8 \times 10^{-5} (\text{keV}/M_1)^5$

From these constraints

and reqiring to get the right order of magnitude of dark matter density $\Omega_{DM} \sim 0.25$

$\Rightarrow$ 1 keV $\lesssim M_1 \lesssim$ 50 keV [0901.0011]

Leptogenesis via sterile neutrinos N_2, N_3:

The N_I are produced thermally in early universe at $T > T_{EW} \sim 100$ GeV
$q\bar{q} \to N_I \nu_\alpha, \quad \phi^+ \ell_\alpha^-, \phi^0 \nu_\alpha \leftrightarrow N_I, \quad \phi^\pm \leftrightarrow N_I \ell_\alpha^\pm, \quad \phi^0 \leftrightarrow N_I \nu_\alpha, \quad N_I \leftrightarrow \nu_\alpha$ ....

Because of very small Yukawa couplings F, they are never in thermal equilibrium

Total lepton nr. is

$$L = L_L + L_R, \qquad L_L = \sum_{\alpha=\nu_L,\ell_L} L_{L,\alpha}, \qquad L_R = \sum_{I=N_{1,2,3}} L_{R,I} + \sum_{\alpha=\ell_R} L_{R,\alpha}$$

Interactions in $\mathcal{L}_{\nu MSM}$ violate lepton-flavour nr. L_α via F
violate total lepton nr. L via Majorana mass M,
but total $\not{L}$ suppressed if $M/T_{EW} \ll 1$

Due to interference of CP-even and -odd amplitudes at quantum level
Processes where $N_{2,3}$ scatter/decay/oscillate into ordinay leptons & antileptons
$\longrightarrow n(\ell_L) - n(\bar{\ell}_R) \neq 0$
I.e., through these processes **a non-zero L-chiral lepton nr. $L_L \neq 0$ is produced**
– even if $L = L_L + L_R \simeq 0$ i.e., $n(\ell_L) - n(\bar{\ell}_R) = -(n(\ell_R) - n(\bar{\ell}_L))$

Sphaleron processes affect only L-chiral leptons, i.e. "see" only L_L
Because $B - L$ is conserved $\Rightarrow$ convert L_L asymmetry into B-asymmetry at $T \gtrsim T_{EW}$

Result from numerical study of coupled Boltzmann eqns.

$$\frac{n_B}{s} = 2 \times 10^{-10} \delta_{\mathbf{CP}} \left(\frac{10^{-6}}{\Delta M_{23}^2 / M_3^2} \right)^{2/3} \left(\frac{M_3}{10\mathrm{GeV}} \right)^{5/3}$$

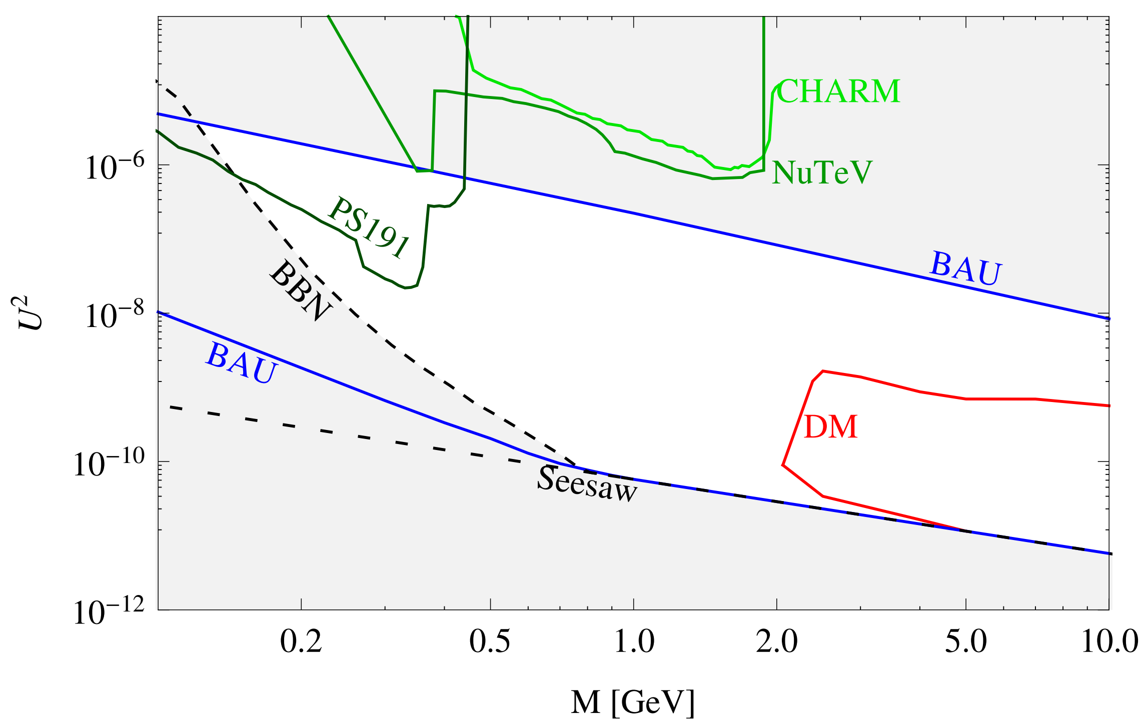
(Akasa, Shaposhnikov, 0505013)

$\delta_{\mathbf{CP}}$ = combination of N and ν mixing angles and $\not{C}\mathrm{P}$ phases, can be $\mathcal{O}(1)$

constraint: $\Delta M_{23}^2 \equiv |M_2^2 - M_3^2| \ll M_{2,3}^2$

i.e., N_2, N_3 must be almost degenerate

Constraints on masses $M_{2,3} \simeq M$ of $N_{2,3}$
and on active-sterile mixing $U^2 \equiv \mathrm{Tr}(\theta^\dagger \theta)$



Canetti, Drewes, Shaposhnikov, 1204.3902
Within the red line, η and Ω_{DM} can be explained

Predictions:

- As $M_1 = \mathcal{O}(\mathrm{keV}) \Rightarrow$ one of the active ν very light: $m_1 = \mathcal{O}(10^{-6}\mathrm{eV})$
- normal hierarchy: $m_2 \simeq 9 \times 10^{-3}$ eV, $m_3 \simeq 5 \times 10^{-2}$ eV
- inverted hierarchy: $m_{2,3} \simeq 5 \times 10^{-2}$ eV
- effective Majorana mass m_{ee} in ν-less double β decay:

  1.3 meV $\lesssim m_{ee} \lesssim$ 3.4 meV (normal) 13 meV $\lesssim m_{ee} \lesssim$ 50 meV (inverted)

The νMSM model can, in principle, be experimentally tested,
by searching for production & decay of $N_{2,3}$ in the lab.

- production cross section at LHC tiny,

  i.e., prediction: nothing new besides the Higgs boson will found there.
- $M_{2,3} < M_D$, $M_{2,3} < M_B$: missing energy signal in decays of D, B mesons

  luminosity of B factories not enough
- The case $M_{2,3} > M_B$ seems extremely difficult

  in principle: production of $N_{2,3}$ by high intensity beam dump exp.
  search for decays $N_{2,3} \to \mu^+\mu^-\nu$, $N_{2,3} \to \pi^0\nu$, ...

Summary

- **BAU cannot be explained in SM:**

  SM predicts the EW transition *symmetric* $\rightarrow$ *broken* to be a smooth cross-over phenomenon

  lack of $\not{T}E$

  3-generation KM $\not{C}P$ irrelevant for baryogenesis scenarios

We discussed here 2 popular scenarios:

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

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

  In minimal SUSY, 1. order p.t. only for 'extreme parameter scenario'

  Non-SUSY multi-Higgs extensions work, but where are the additional Higgses ?

* new $\not{C}P$ required

Scenario is testable (falsifiable) in the lab.:
find new particles at LHC / find new $\not{C}P$

- **Baryogenesis via Leptogenesis**

A) by ultra-heavy Majorana neutrinos, $M_N \gg T_{EW}$
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 $\nu_i \rightarrow \nu_j$ oscillations will have a bearing on this scenario
B) Low scale leptogenesis, νMSM:
attractive scenario – no new mass scale introduced; in principle testable