Lecture 4

The Violation of Symmetry between Matter and Antimatter

Andreas Höcker

CERN

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M.C. Escher

Lecture Themes

I. Introduction
- Antimatter
- Discrete Symmetries

II. The Phenomena of *CP* Violation
- Electric and weak dipole moments
- The strong *CP* problem
- The discovery of *CP* violation in the kaon system

III. *CP* Violation in the Standard Model
- The CKM matrix and the Unitarity Triangle
- *B* Factories
- *CP* violation in the *B*-meson system and a global CKM fit
- The Future at the LHC

IV. *CP* Violation and the Genesis of a Matter World
- Baryogenesis and *CP* violation
- Models for Baryogenesis

CP Violation and the Genesis of a Matter World

1. Has Antimatter Really Disappeared ?
2. Baryogenesis in the Early Universe
3. Baryogenesis through Electroweak Phase Transitions
4. Baryogenesis through Leptogenesis

astronomical units:

1 pc $\approx$ 3.2 light years

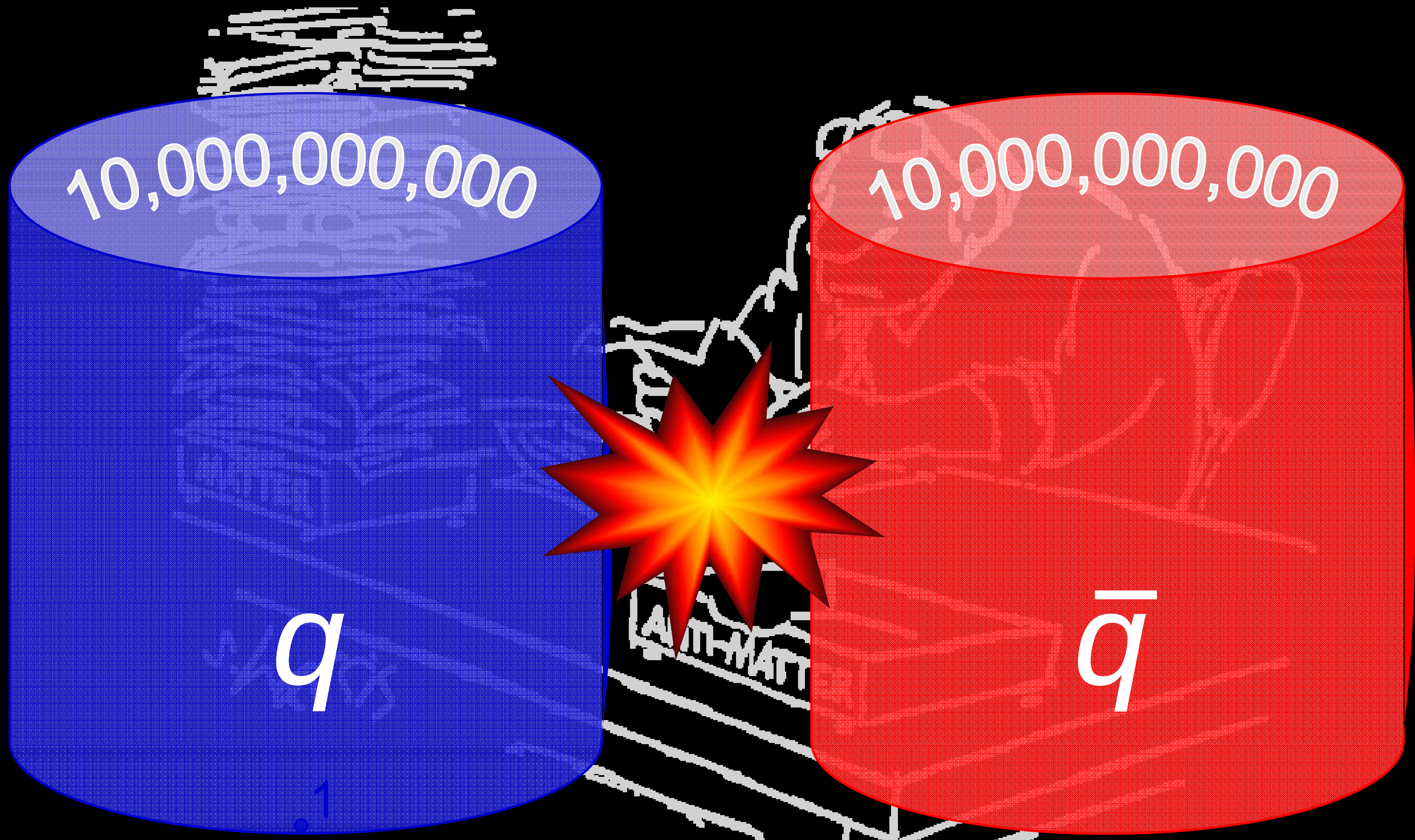
1 GeV $\approx$ 10^{13} K

1 GeV^{-1} $\approx$ 6×10^{-25} s

Prerequisites

- Antimatter ☑
- Matter-antimatter asymmetry ☑
- Expansion of the universe ☒
- Equilibrium thermodynamics ☒
- Higgs mechanism ☒
- *CP* violation in the quark sector: CKM matrix ☑

Matter-Antimatter Asymmetry



Current universe

Sakharov Conditions

([*])Bigi-Sanda, *CP* Violation, 2000

- The Universe is not empty* !
- The Universe is almost empty* !

$$\frac{\Delta n_{\text{baryon}}}{n_\gamma} = \frac{n_{\text{baryon}} - n_{\overline{\text{baryon}}}}{n_\gamma} \sim O\left(10^{-10}\right)$$

Sakharov conditions (1967) for Baryogenesis

1. Baryon number violation
2. *C* and *CP* violation
3. Departure from thermodynamic equilibrium (non-stationary system)

Expansion of the Universe

- Robertson-Walker space-time metric describes curvature and scale of the Universe

Cosmic scale factor with [*R*] = length

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

k = (–1, 0, +1) for negative, vanishing, positive spatial curvature

- The Friedmann equation describes the time evolution of *R*(*t*)

Total energy density of Universe

$$H^2(t) = \left(\frac{\dot{R}(t)}{R(t)}\right)^2 = \frac{8\pi G_N}{3}\rho(t) - \frac{k}{R(t)} + \frac{\Lambda}{3}$$

Cosmological constant

  - For a flat universe (*k* = 0), the sign of Λ determines the universes fate
  - Hubble "constant": $H_0 = H(t = \text{today}) \approx 71\ \text{km}\,s^{-1}\text{Mpc}^{-1}$

- **Baryogenesis** happens at a time *t* where the universe is **radiation dominated**, and where the Λ term can be neglected. In this era one finds:

$$\rho(t) \propto R^{-1}(t), \quad \text{and} \quad H(t) \propto t^{-1}$$

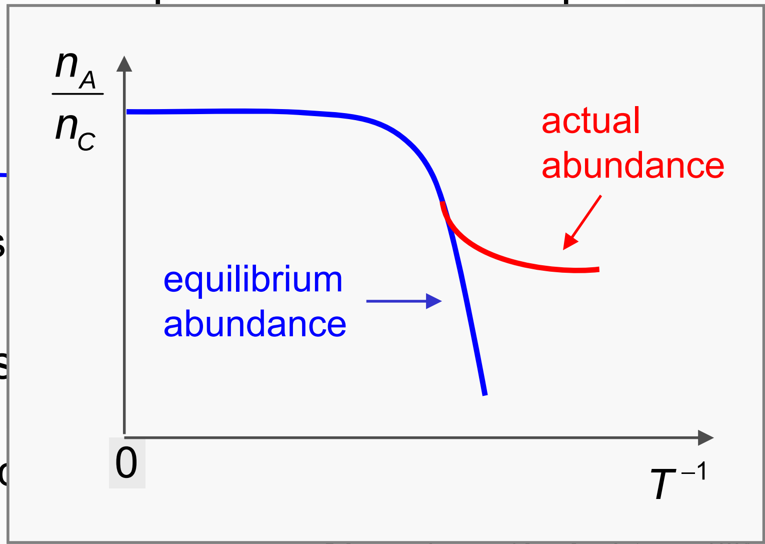
Equilibrium Thermodynamics

- **The early Universe** can be seen as a **dense plasma** of particles in thermal equilibrium (TE) with phase space function for a particle ***A*** with mass m_A:

Chemical potential

Boson/Fermion

Temperature



  - Considering the (fas … ibrium: $\mu_A + \mu_B = \mu_C$

- N_A (particle number) is … tion of f_A. We distinguish

  - Ultrarelativistic partic … $\propto R^{-1}$
  - Nonrelativistic particles ($T_A = m_A$) : $N_A \propto (m_A/k_B T_A)$ … e … $-\mu_A)/kT_A$

- **Departure from TE**: consider reaction rate [s^{-1}]: $\Gamma_A = \sigma(A + \text{target} \rightarrow C) \cdot n_{\text{target}} \cdot |v_{A\text{-target}}|$

  - Γ_A **>** $\boldsymbol{H}$ **:** reaction occurs rapidly enough to maintain thermal equilibrium
  - Γ_A **<** $\boldsymbol{H}$ **:** particles *A* will fall out of equilibrium

- when $T < m_A$ decreasing, n_A decreases following the exponential law; if *A* stayed in TE it would almost fully disappear; however, **once** Γ_A **<** $\boldsymbol{H}$ **the interactions of** ***A*** **"freeze out"**

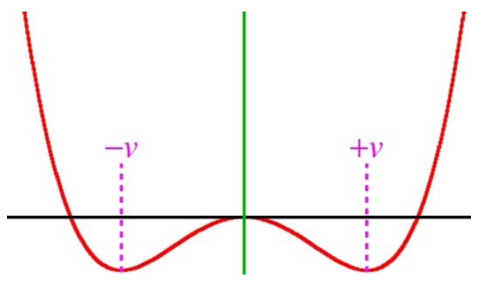
The Higgs Mechanism

- The fermion and gauge-boson masses of the SM are dynamically generated via the **Higgs mechanism** when spontaneously breaking electroweak symmetry

- Recall the **Higgs** "Mexican hat" **potential at $T \approx 0$**:

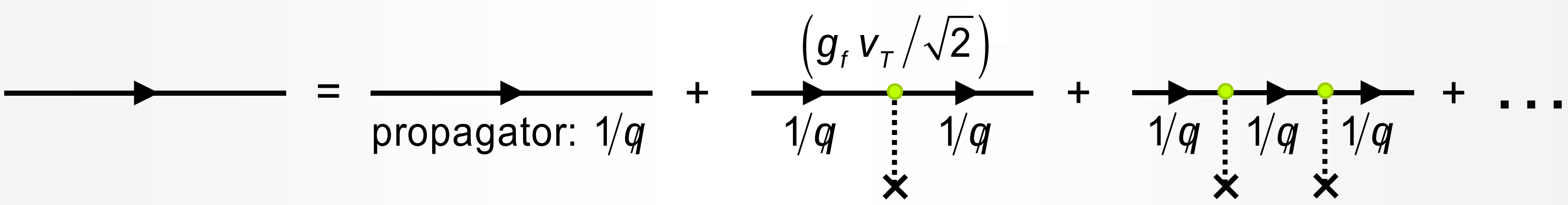
$$V(\phi) = \frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$$

with vacuum expectation value: $\langle 0|\phi|0\rangle_{T=0} = \upsilon_{T=0}/\sqrt{2}$



$$\upsilon_{T=0} = \sqrt{-\frac{\mu^2}{\lambda}} = \frac{1}{\sqrt{\sqrt{2}G_F}} = 246\text{ GeV}$$

- At $T < T_{EW}$, the massless fermion fields interact with the non-vanishing Higgs "condensates":



- Geometric series yields massive propagator creating effective mass for fermion:

$$\frac{1}{q} + \frac{1}{q}\left(\frac{g_f v_T}{\sqrt{2}}\right)\frac{1}{q} + \frac{1}{q}\left(\frac{g_f v_T}{\sqrt{2}}\right)\frac{1}{q}\left(\frac{g_f v_T}{\sqrt{2}}\right)\frac{1}{q} + \ldots = \frac{1}{q}\sum_{n=0}^{\infty}\left(\left(\frac{g_f v_T}{\sqrt{2}}\right)\frac{1}{q}\right)^n = \frac{1}{q - m_f}$$

similar for gauge bosons

B a r y o g e n e s i s

Antimatter in the Universe ?

Balloon-borne Superconducting Solenoidal (BESS) spectrometer

- Does stable antimatter exist in the universe ?
  - No antinuclei (e.g., Antihelium) seen in cosmic rays (relative limit from BESS: $< 10^{-6}$)
  - No significant (diffuse) cosmic γ rays from nucleon-antinucleon annihilation in the boundary between matter & antimatter regions

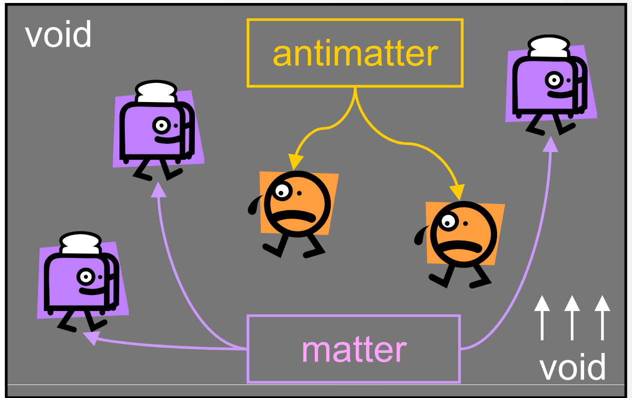
→ No evidence of antimatter in our domain of the universe (~20 Mpc = 0.6×10^{8} light years)

- Could our universe be like inverse Suisse cheese, with distant matter or antimatter regions(*) ?

→ Difficult within the current limits

- Likely: no antimatter in our universe

(apart from the antimatter created dynamically in particle collisions)



The *voids* would create anisotropy in CMB spectrum, which is not seen

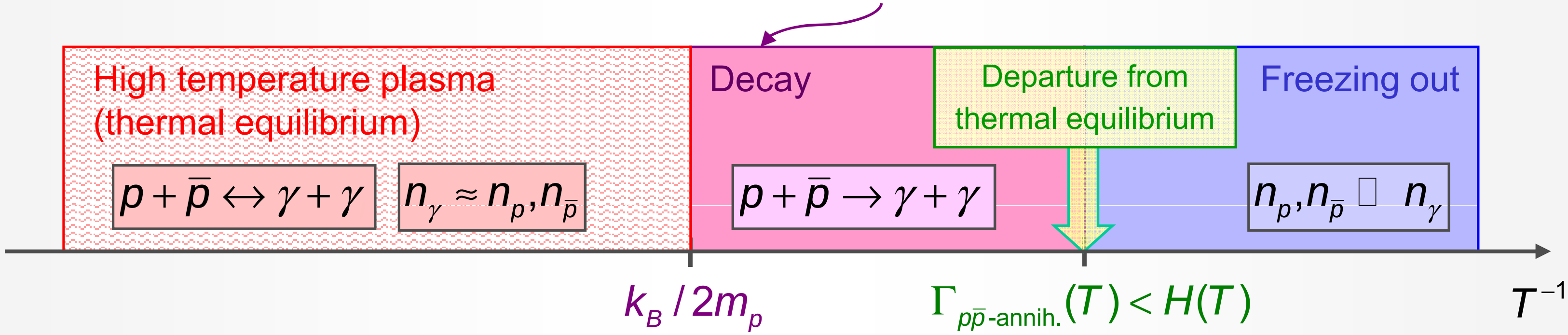
(*) "If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of nature,we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. In fact there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them from present astronomical methods." P. A. M. Dirac, Nobel Lecture (1933)

Baryogenesis and *CP* Violation

- **Matter counting:**
  - Asymmetry parameter: $\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \frac{n_B}{n_\gamma}$, observed to be ~ $1 \times 10^{-10} < \eta < 6 \times 10^{-10}$

    Obtain naïve guess by comparing the estimated atom density in the universe (~1.6/m^3) with the photon gas density at 2.73 K cosmic background radiation temperature (~$4.2{\times}10^8$/m^3)

- **Problem**: (anti)nucleon densities in thermal equilibrium: $\frac{n_p}{n_\gamma} = \frac{n_{\bar{p}}}{n_\gamma} \approx \left(\frac{m_N}{k_B T}\right)^{3/2} e^{-m_N / k_B T}$



For $n_B/n_\gamma = 10^{-10}$, one has: T ~ 40 MeV, but $T_{\text{freeze-out}}$ ~ 20 MeV $\Rightarrow n_B/n_\gamma = 10^{-18}$ ☹

➡ Significant $\eta > 0$ already at $T > 40$ MeV

The Sakharov Conditions – Again !

- Assuming that at the Big Bang $\eta(t{=}0) = 0$ (baryon asymmetry not initial condition),

  Let's recall the three Sakharov conditions for a dynamical generation of the asymmetry:

However: an initial $\eta(t{=}0) > 0$ would be futile, since inflation would have wiped out the trace of it

Examples for DTEs:
- Net baryon asymmetry
- Cosmic photon & neutrino backgrounds
- Nucleosynthesis
- … many more

- Proofs (*digression*):
  1. See later
  2. Be ρ_0 initial density of the universe with time evolution given by: $i\hbar\frac{\partial\rho}{\partial t} + [\rho, H] =$

     if $[C,H] = 0$, or $[CP,H] = 0$ → $[C,\rho] = 0$, or

     since the baryon number operator is C and CP-odd: $C\hat{B}C^{-1} = (CP)\hat{B}(CP)^{-1} = -\hat{B}$

     $$\Rightarrow \quad \langle n_B \rangle = \mathrm{tr}\left(\rho n_B\right) = \mathrm{tr}\left(C^{-1}C\rho n_B\right) = \mathrm{tr}\left(\rho C n_B C^{-1}\right) = -\langle n_B \rangle = 0 \qquad \left[\text{use: } \mathrm{tr}(A\cdot B) = \mathrm{tr}(B\cdot A)\right]$$
  1. Similar as 2. using the fact that the baryon number operator is *CPT* odd

(I) Baryogenesis in the Early Universe (much simplified!)

- Grand unification (GUT) of the forces at ~10^{16} GeV
  - Simplest GUT model, SU(5), has 5^2–1=24 gauge fields, of which 12 belong to SM
  - 12 New *heavy* leptoquark fields, *X*, *Y*, carrying charge and color, allow transitions between baryons and leptons; also: $\Gamma_X < H(T)$ for T ? T_{EW} (out of equilibrium decays)

- *B*=0)

Discovery of proton decay, *e.g.*, $p \to e^+\pi^0$, would support the hypothesis of GUT-type baryogenesis

→ Current upper limit: $\tau_p > 1.6{\times}10^{33}$ years (90% CL, Super-Kamiokande, 1998)

e.g.: $T > T \Rightarrow$

(At $T > m_X$: ΔB = 0 TE due to "wash-out", e.g., *X*-exchange reactions (CPT))

$n(u,d,e^-) > n(\bar{u},\bar{d},e^+)$

  - *CPT* invariance holds: total decay rates are equal
  - At $T < m_X$ → Boltzmann-suppressed; at $\Gamma_X < H(T)$ out-of-equilibrium excess develops
  - Only tiny *CP* asymmetry, O(10^{-8}), is needed to obtain $\eta \sim 10^{-10}$ this way

- Pitfall: SU(5) is $B-L$ conserving → problem (see later) → at least SO(10) required

(II) Baryogenesis through EW Phase Transition

- Within a picosecond, at the electroweak (EW) scale (100 GeV ~ 10^{15} K), where EW forces are still unified, **EW phase transition (1st order) can occur**
- Non-abelian theories (like weak interaction $SU(2)_L$) **have a non-trivial vacuum structure** with an infinite number of ground states ("topological charges").

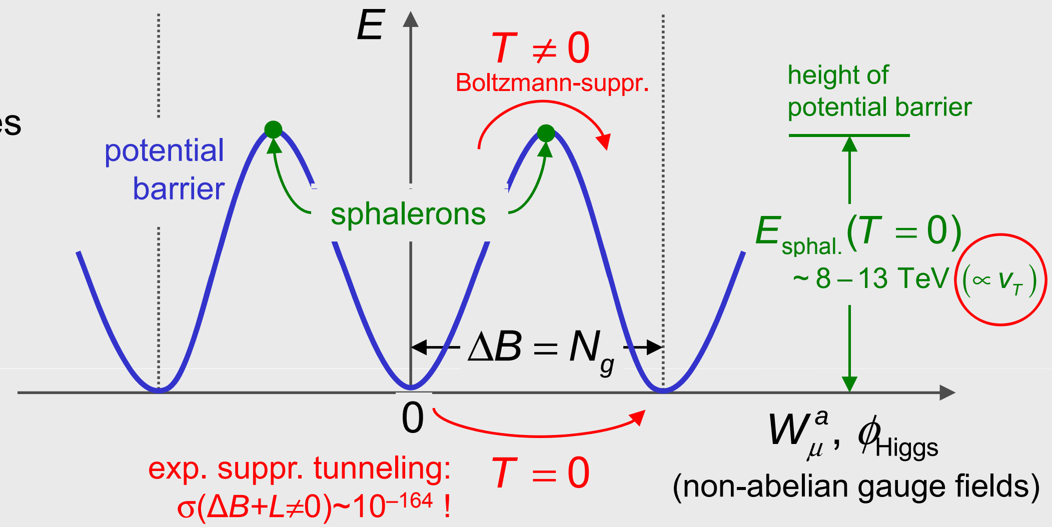
Periodic vacuum structure of EW theory: for N_g=3 generations, the distance between two ground states is $\Delta B = \Delta L = 3$

(*e.g.*, conversion of baryons into antileptons)

→ **no proton decay**

→ **always: $\Delta(B - L) = 0$!**

(B–L is conserved in the SM)



- Small perturbative changes in fields around zero charge **will not change *B* and *L***
- Sphaleron transition rate: ~ $\exp(-E_{sphal}(T)/k_B T)$ for $T < T_{EW}$ (barrier), and ~ T^4 for $T > T_{EW}$

(B–L conserving sphaleron processes for 10^2~10^{12} GeV → any B+L violating asymmetry in this energy range will be washed out → requires B–L violation)

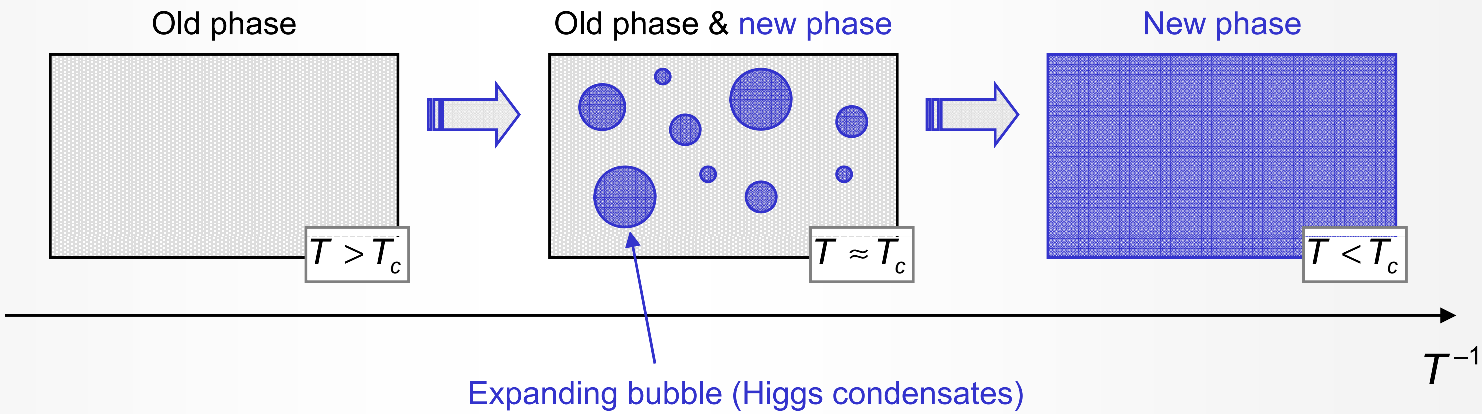
(II) Baryogenesis through EW Phase Transition

- In SM for T ?T_{EW}, no departure from thermal equilibrium (sphaleron reactions much faster than expansion of universe, $H(T)$)

- In case of SM: *CP* violation (KM mechanism) needs non-zero quark masses to occur, but fermions acquire masses only at T_{EW}

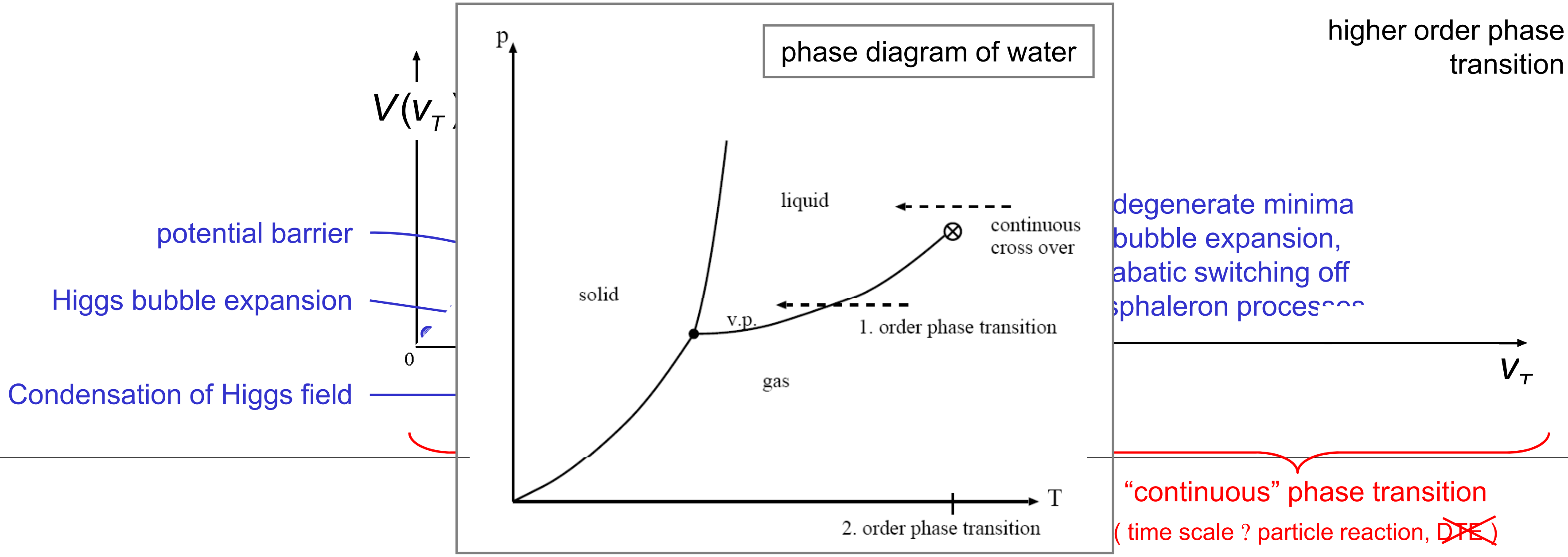
- In any case: need **1st order phase transition** at $T_c \sim T_{\text{EW}}$:
  - Discontinuous change of $v_T = \langle 0 | \phi_{\text{Higgs}} | 0 \rangle_T$, since $v_T = 0$ for $T > T_c$
  - Condensation of Higgs field at $T \sim T_c$

Schematic view of 1st order phase transition:



(II) Baryogenesis through EW Phase Transition

- Phase transitions
- Higgs potential versus Higgs vacuum expectation value:



- The bubbles must get filled with more quarks than antiquarks (CPV)

→ Baryogenesis has to take place outside the bubbles (since η must be conserved), while the sphaleron-induced (B+L)-violating reactions must be strongly suppressed inside the bubbles

(II) Baryogenesis through EW Phase Transition

Low temperature world

Sketch of nonlocal EW baryogenesis:

$N(q) > N(\bar{q})$

Higgs condensate

broken phase
$v_T \neq 0$

$\Gamma^{\text{sphaleron}}_{\Delta(B+L)}$ □ 0

$N(q) > N(\bar{q})$

See, e.g., W. Bernreuther, Phys. 591 (2002) 237-293

Low temperature world

- Problem: the above 1st order phase transition only for $m_{\text{Higgs}} < 73$ GeV; beyond this, the phase transition becomes of 2nd order, and the thermal instability needed for baryogenesis (3rd Sakharov rule) is not provided

➡ LEP limit for Higgs mass: $m_{\text{Higgs}} > 114$ GeV ☹

Requires SM extensions …
(SUSY could do it !)

The Role of the *CP*-Violating CKM Phase

- If the SM extensions do not violate *CP* (this would be rather unnatural), **could the CKM phase generate the observed baryogenesis ?**

- KM *CP*-violating asymmetries, d_{CP}, must be proportional to the Jarlskog invariant *J*

$$d_{CP} = J \cdot \tilde{F}_U \cdot \tilde{F}_D$$

where: $J = \mathrm{Im}\left(V_{ud} V_{cs} V_{us}^* V_{cd}^*\right) \square\ A^2 \lambda^6 \eta$, and: $\tilde{F}_U = \left(m_t^2 - m_c^2\right) \cdot \left(m_t^2 - m_u^2\right) \cdot \left(m_c^2 - m_u^2\right)$

$$= \left(3.1 \pm 0.2\right) \times 10^{-5}$$

$$\tilde{F}_D = \left(m_b^2 - m_s^2\right) \cdot \left(m_b^2 - m_d^2\right) \cdot \left(m_s^2 - m_d^2\right)$$

- Since non-zero quark masses are required, *CP* symmetry can only be broken where the Higgs field has already condensed to $v_T \neq 0$ (i.e., in the broken phase)

- To make d_{CP} dimensionless, we divide by dimensioned parameter $D = T_c$ at the EW scale ($T_c = T_{\mathrm{EW}} \sim 100$ GeV), with $[D] = \mathrm{GeV}^{12}$

$$\hat{d}_{CP} = \frac{d_{CP}}{D^{12}} \approx 10^{-19} \ \square\ \ \eta \approx O\left(10^{-10}\right)$$

KM *CP* violation seems to be *irrelevant* for baryogenesis !

(III) Baryogenesis through Leptogenesis

- Assume existence of 3 heavy right-handed (M_N ~ 10^{12} GeV) *Majorana* ν's: $N_{i=1,2,3}$
- The $SU(2)_L \times U(1)_Y$ Lagrangian then allows lepton-number-violating decays

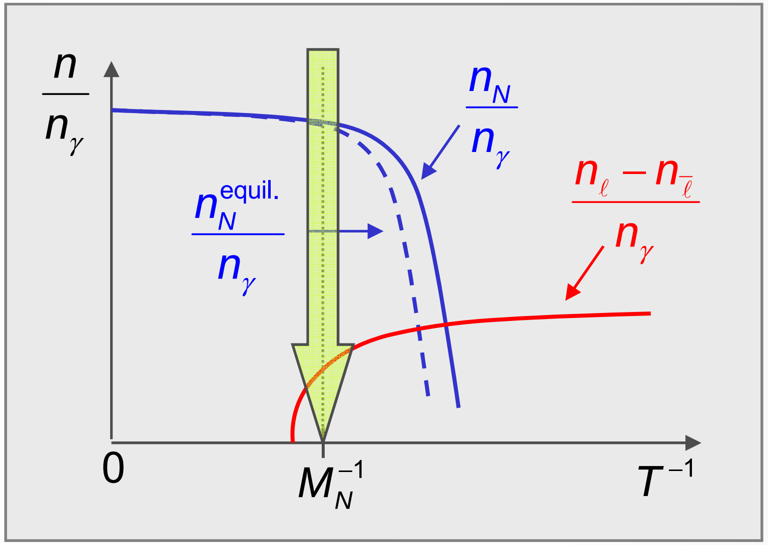
$$N_i \to \ell\phi \quad \text{and} \quad N_i \to \bar{\ell}\phi^*$$

lepton-number creating decays

- Sakharov rule 2 : ~~CP~~ would create rate differences (only tiny ~10^{-6} *CP*-violating asymmetry required) → needs interference !

- Sakharov rule 3 :

Sketch for evolution of n_N/n_γ as universe expands (cools down):



Departure from thermal equilibrium for

$\Gamma_{\Delta L=2}(T) < H(T)$

(to avoid ΔL wash-out reactions)

at $T < M_N$

- Sakharov rule 1: ΔL feeds baryongenesis via rapid (B–L)-conserving sphaleron reactions !

Conclusions

- All observed *CP*-violating phenomena are described by single CKM phase (!)
- However: Baryogenesis (most probably) requires Standard Model extension
- We have discussed three mechanisms (others exist):
  1) **Baryogenesis via *CP*-violating out-of-equilibrium decays of GUT particles**
  2) **Baryogenesis via electroweak phase transition**
  3) **Baryogenesis via leptogenesis**
- Due to heavy Higgs, electroweak phase transition (2) fails in SM → SUSY ?
- GUT-type baryogenesis (1) cannot be verified in laboratory; however, proton decay would give empirical support (model may have problem with inflation)
- Mechanism (3) seems to be most promising: experimental evidence that neutrinos are Majorana particles would provide empirical support

Siumulated Higgs-boson event at CMS, CERN