Lecture 3

CP Violation
and the Genesis of a Matter Universe

Andreas Höcker, CERN

Lectures at the the 5th Particle Physics Workshop, Islamabad, Pakistan, Nov 20-25, 2006

M.C. Escher

Lecture Themes

I. Phenomenology beyond the Standard Model

- Empirical & theoretical limitations of the Standard Model
- Supersymmetry
- Extra Dimensions
- Little Higgs

II. Experimental Searches

- LHC, ATLAS and CMS: Experimental Challenges
- Searches at the LHC: SUSY, Extra Dimensions, Little Higgs

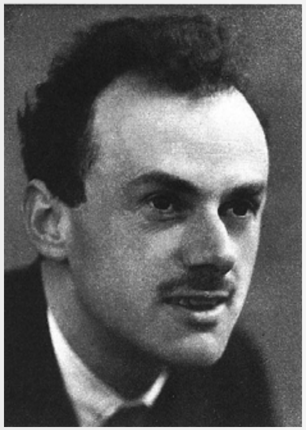
III. *CP* Violation and the Genesis of a Matter Universe
(out-of-series lecture)

Lectures based on introductory course by Werner Bernreuther, hep-ph/0205279

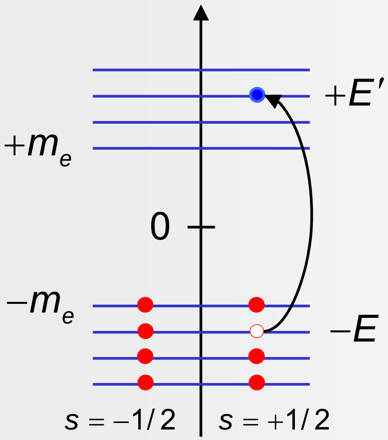
Prerequisites

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

Paul Dirac



Dirac, imagining holes and seas in 1928



This picture fails for bosons !

- Combining quantum mechanics with special relativity, and the wish to linearize $\partial/\partial t$, leads Dirac to the equation

$$i\gamma^{\mu}\partial_{\mu}\psi(x,t) - m\psi(x,t) = 0$$

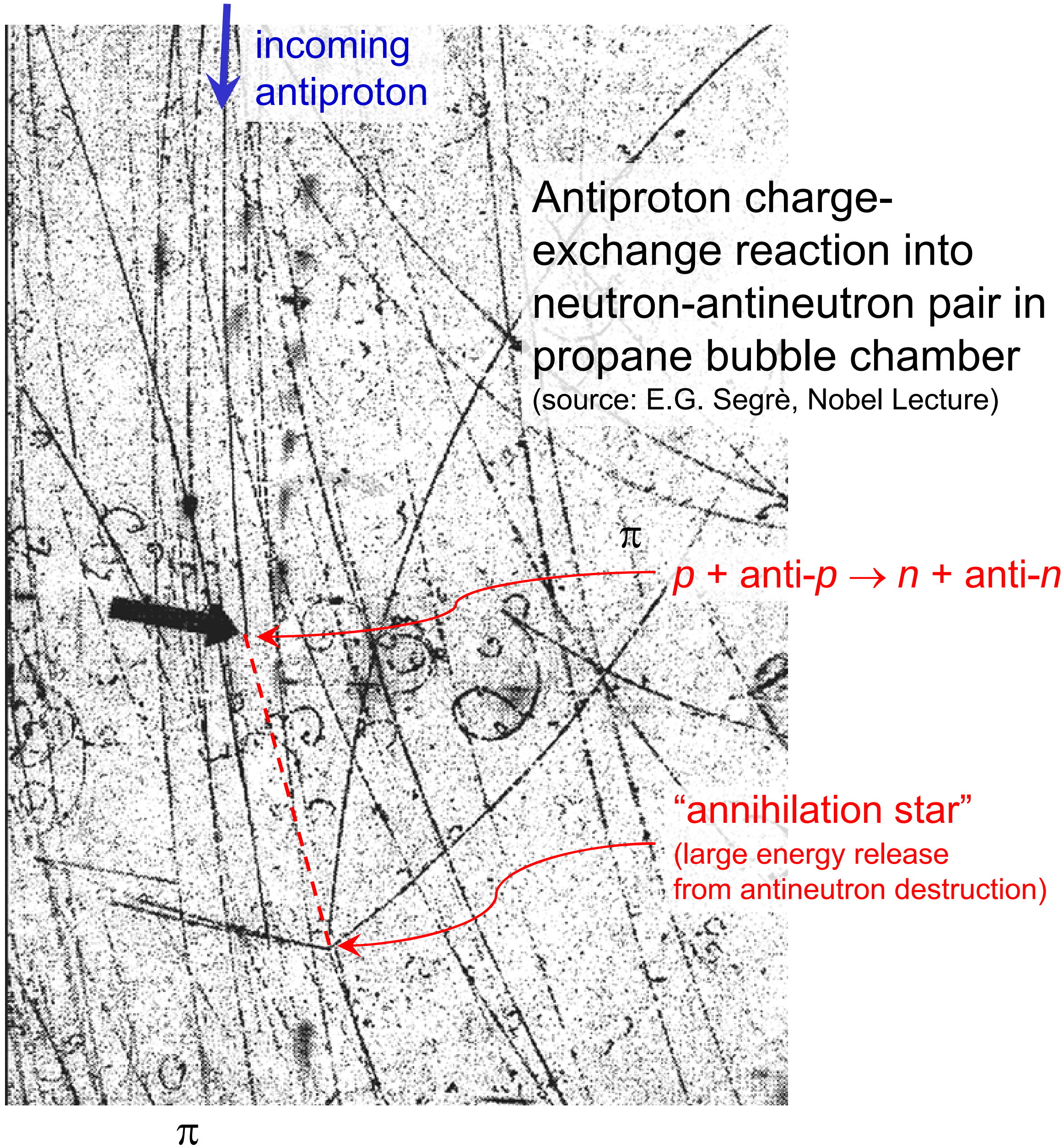
  for which solutions with negative energy appear

- Vacuum represents a "sea" of such negative-energy particles (fully filled according to Pauli's principle)

- Dirac identified holes in this sea as "antiparticles" with opposite charge to particles … (however, he conjectured that these holes were protons, despite their large difference in mass, because he thought "positrons" would have been discovered already)

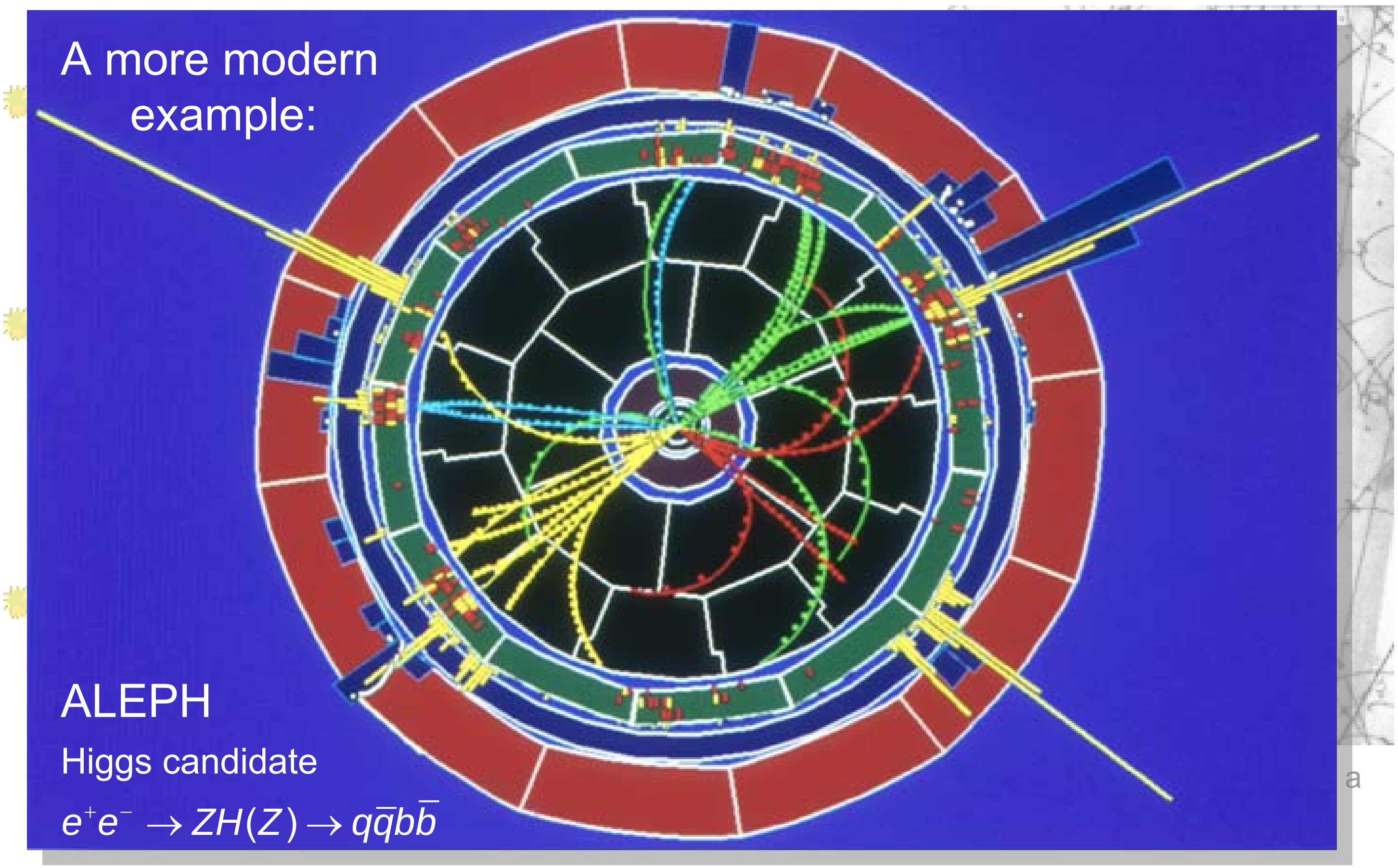
- An electron with energy E can fill this hole, emitting an energy $2E$ and leaving the vacuum (hence, the hole has effectively the charge $+e$ and positive energy).

Antiproton discovery 1956

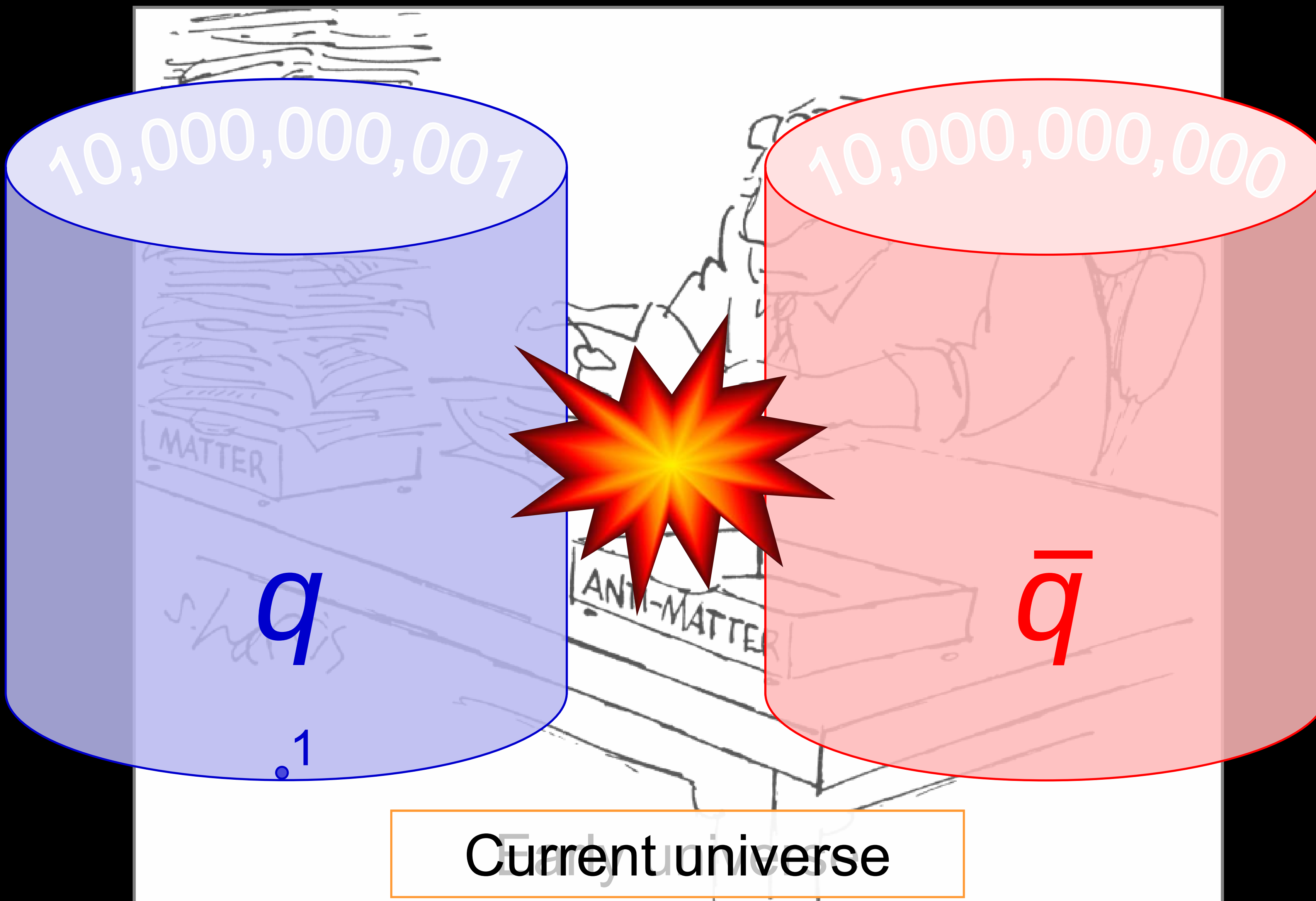


Particles and Antiparticles Annihilate

What happens if we bring particles and antiparticles together ?



Matter-Antimatter Asymmetry



Sakharov Conditions

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

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

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

- Initial condition ? Would this be possible ?
- Dynamically generated ?

Sakharov conditions (1967) for Baryogenesis

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

So, if we believe to have understood CPV in the quark sector, and that it cannot account for the observed baryon asymmetry … what does it signify ?

A sheer accident of nature ?

What would be the consequence of a different value for the CKM phase ?

Expansion of the Universe

- **Robertson-Walker space-time metric** describes curvature and expansion 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 (**defining the Hubble parameter) 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:

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

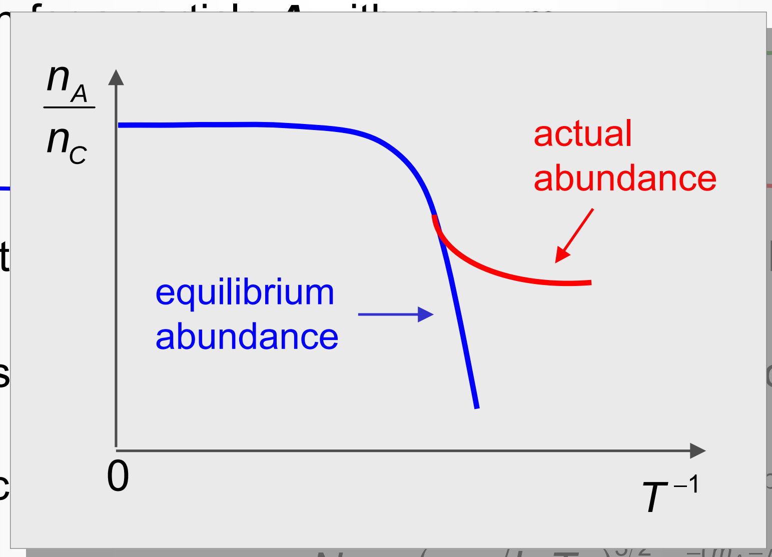
Equilibrium Thermodynamics

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

Chemical potential

Boson/Fermion

Temperature



  - Considering the (fast … brium: $\mu_A + \mu_B = \mu_C$

- The particle number N_A is … of f_A. We can distinguish

  - Ultrarelativistic partic … $\propto R^{-1}$

  - Nonrelativistic particles $(T_A = m_A)$: $N_A \propto (m_A / k_B T_A)^{3/2}\, e^{-(m_A-\mu_A)/kT_A}$

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

  - Γ_A **>** $\boldsymbol{H}$ **:** reaction occurs rapidly enough to maintain thermal equilibrium

  - Γ_A **<** $\boldsymbol{H}$ **:** particles *A* will fall out of equilibrium

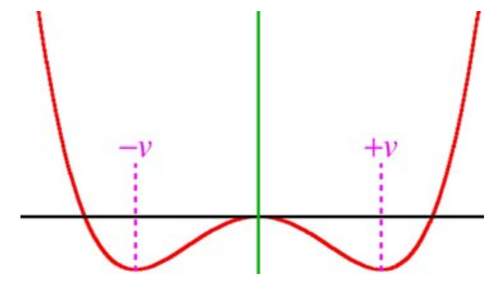
- when $T < m_A$ decreasing, n_A decreases following the exponential law; if *A* stayed in TE it would almost fully disappear; however, **once** Γ_A **<** $\boldsymbol{H}$ **the interactions of** ***A*** **"freeze out"**

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 $T \approx 0$**:

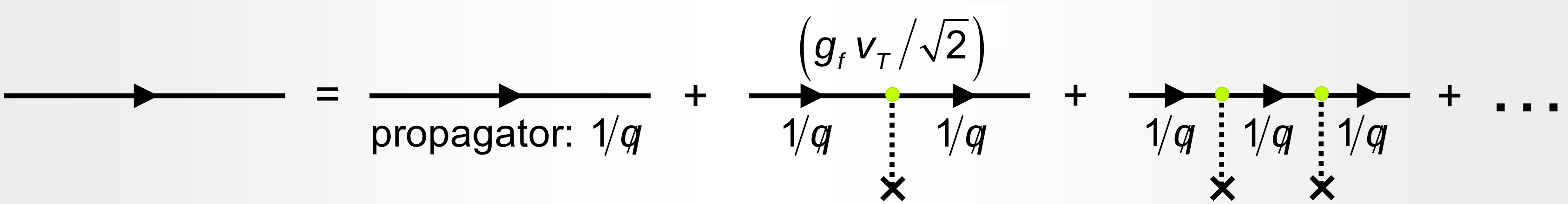
$$V(\phi) = \frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$$

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



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

- At $T < T_{EW}$, the **massless fermion fields** interact with the **non-vanishing Higgs field** that is **always** present:



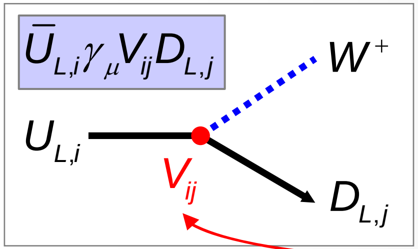
- Geometric series yields **massive propagator** creating **effective mass for fermion**:

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

similar for gauge bosons

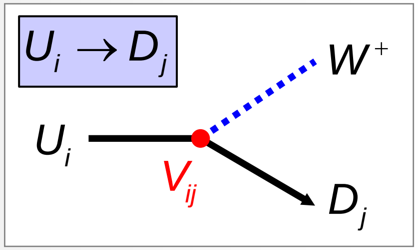
CP Violation in the Quark Sector: the CKM Matrix

- The charged weak current generates transitions between left-handed quark families:

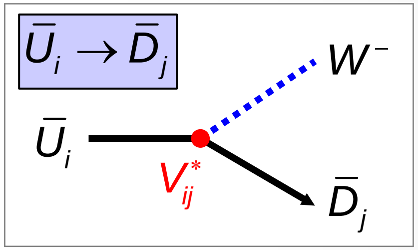


There are 3×3 of these → **CKM matrix**

- *CP* conservation is: $A(U_i \to D_j) = \bar{A}(\bar{U}_i \to \bar{D}_j)$ (up to unphysical phase)



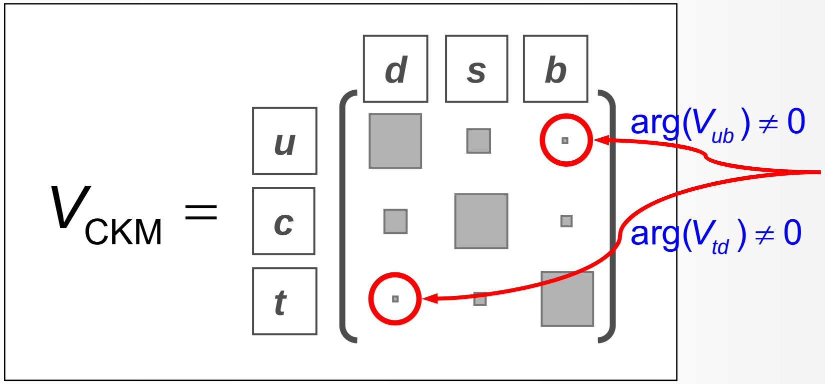
=



only, if: $V_{ij} = V_{ij}^*$

- The CKM matrix:

The KM mechanism describes all *CP*-violating effects observed so far



CP Violation (Im[...] ≠ 0)

Baryogenesis

CP Violation and the Genesis of a Matter Universe

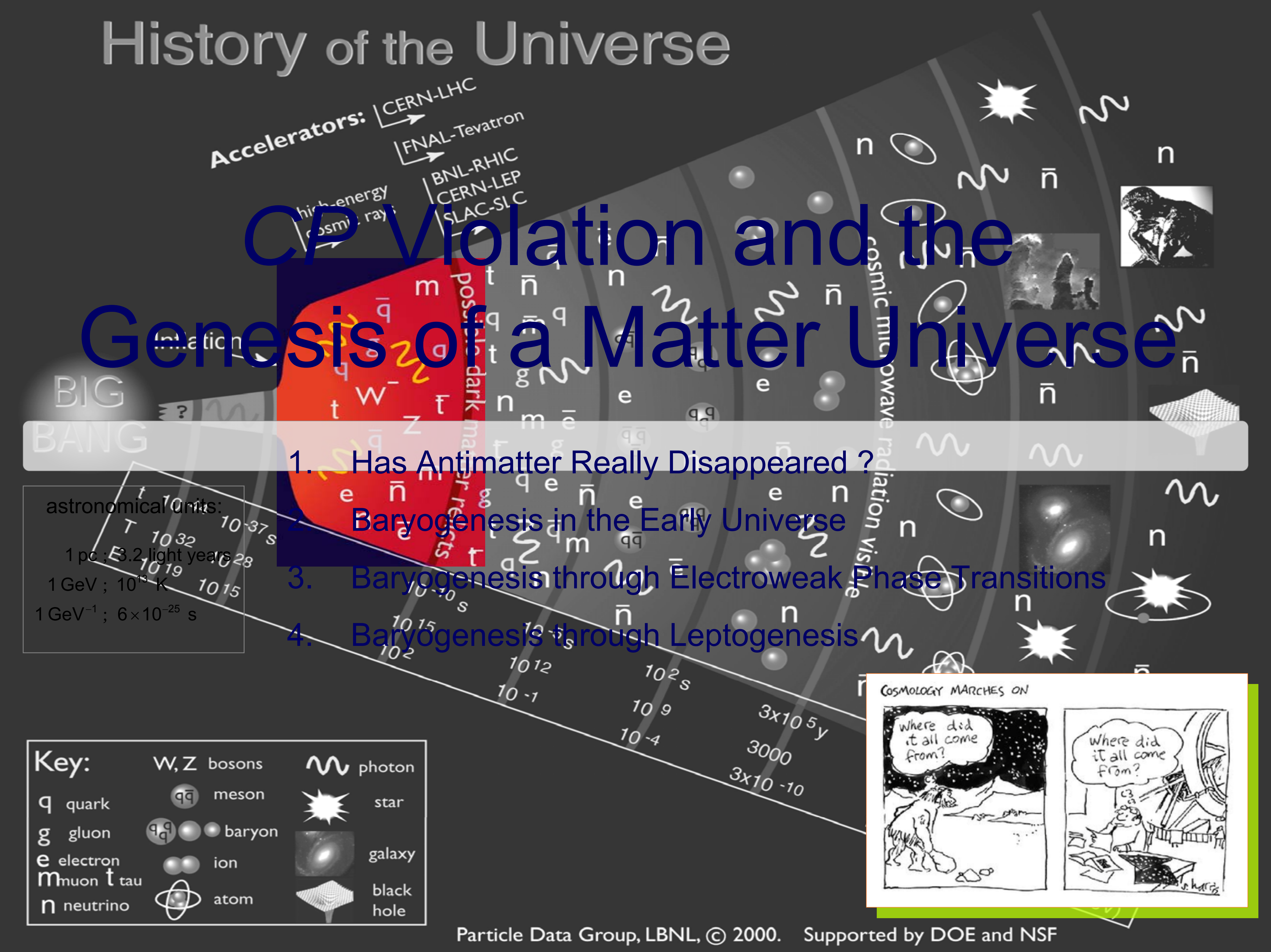
1. Has Antimatter Really Disappeared ?
2. Baryogenesis in the Early Universe
3. Baryogenesis through Electroweak Phase Transitions
4. Baryogenesis through Leptogenesis

astronomical units:

1 pc ; 3.2 light years

1 GeV ; 10^{13} K

1 GeV^{-1} ; 6×10^{-25} s



Through the Looking Glass

What's the Matter with Antimatter ?

David Kirkby, APS, 2003

Antimatter in the Universe ?

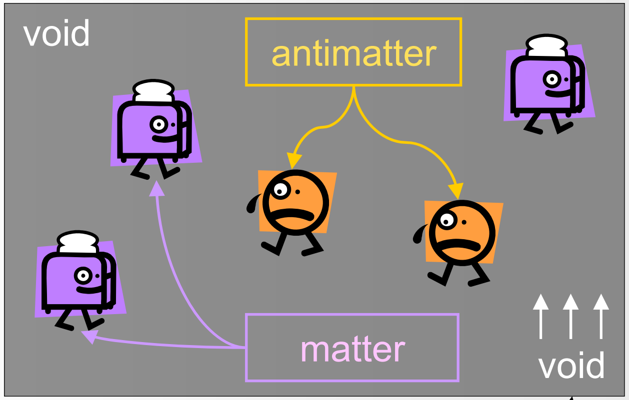
Balloon-borne Superconducting Solenoidal (BESS) spectrometer

- **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



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

- **Likely: no antimatter in our universe**
  (apart from the antimatter created dynamically in particle collisions)

(*) "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)

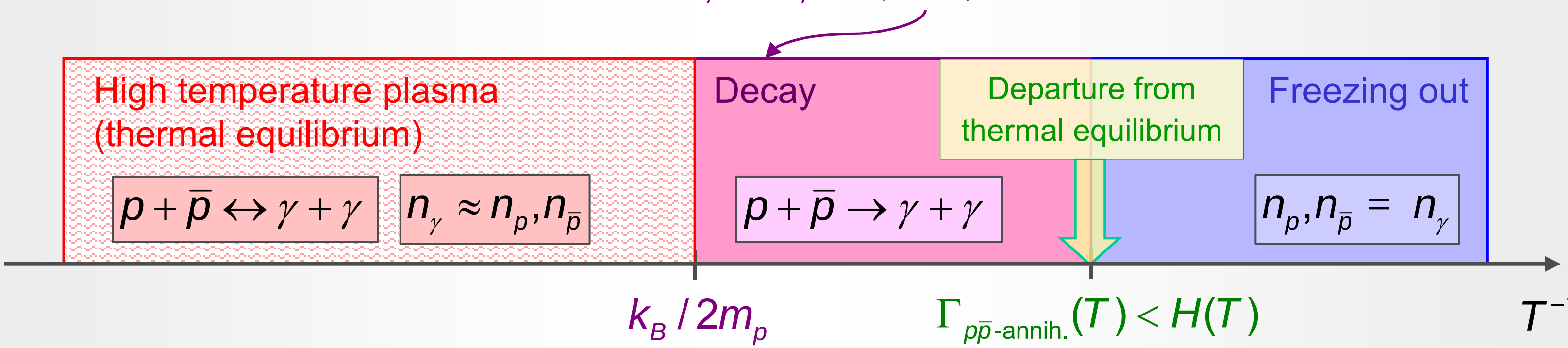
Baryogenesis and *CP* Violation

- **Matter counting:**
  - Asymmetry parameter: $\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} ; \frac{n_B}{n_\gamma}$, 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 (~4.2×10^8/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

- Assuming that at the Big Bang $\eta(t=0)$ = 0 (baryon asymmetry is not an 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 $\langle n_B \rangle_0 = \mathrm{tr}(\rho_0 n_B) = 0$
     time evolution given by: $i\hbar\frac{\partial\rho}{\partial t} + [\rho, H] = 0$
     if $[C,H] = 0$, or $[CP,H] = 0 \rightarrow [C,\rho] = 0$, or $[CP,\rho] = 0$
     since the baryon number operator is C and CP-odd: $C\hat{B}C^{-1} = (CP)\hat{B}(CP)^{-1} = -\hat{B}$
     $\Rightarrow \quad \langle n_B \rangle = \mathrm{tr}(\rho n_B) = \mathrm{tr}(C^{-1}C\rho n_B) = \mathrm{tr}(\rho C n_B C^{-1}) = -\langle n_B \rangle = 0 \qquad [\text{use: } \mathrm{tr}(A\cdot B) = \mathrm{tr}(B\cdot A)]$
  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, and allowing transitions between baryons and leptons; also: $\Gamma_X < H(T)$ for T ? T_{EW} (out of equilibrium decays)

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

0)

$\bar{X} \to (\bar{u} + \bar{u})_{B=-2/3}$ $\bar{X} \to (d + e^-)_{B=+1/3}$

e.g.: $r > \bar{r} \Rightarrow$
$n(u,d,e^-) > n(\bar{u},\bar{d},e^+)$

  - *CPT* invariance holds: total decay rates are equal
  - At $T < m_X$ → Boltzmann-suppressed; at $\Gamma_X < H(T)$ out-of-equilibrium excess develops
    (the real process how an over-abundance develops is quite subtle → based on unitarity)
  - Only tiny *CP* asymmetry is needed to obtain $\eta \sim 10^{-10}$ this way

- Pitfall: larger SO(10) group required to generate necessary $B-L$ violation → see later

(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, **electroweak phase transition (1st order) can occur**
- **Non-abelian theories** (like weak interaction $SU(2)_L$ or QCD) **have a non-trivial vacuum structure** with an infinite number of ground states ("topological charges").

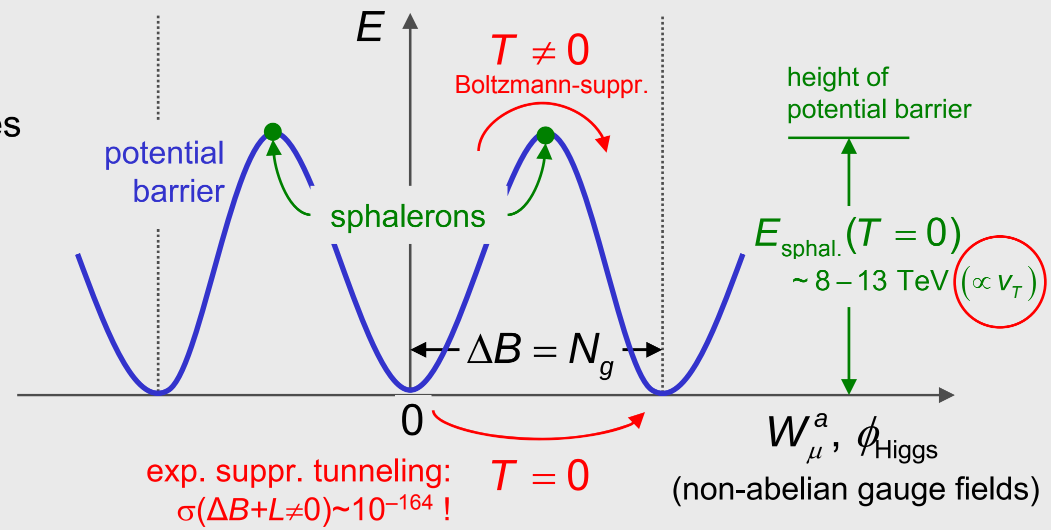
Periodic vacuum structure of EW theory: for N_g=3 generations, the distance between two ground states is $\Delta B = \Delta L = 3$

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

→ **no proton decay**

→ **always: $\Delta(B-L) = 0$** !

(B–L is conserved in the SM)



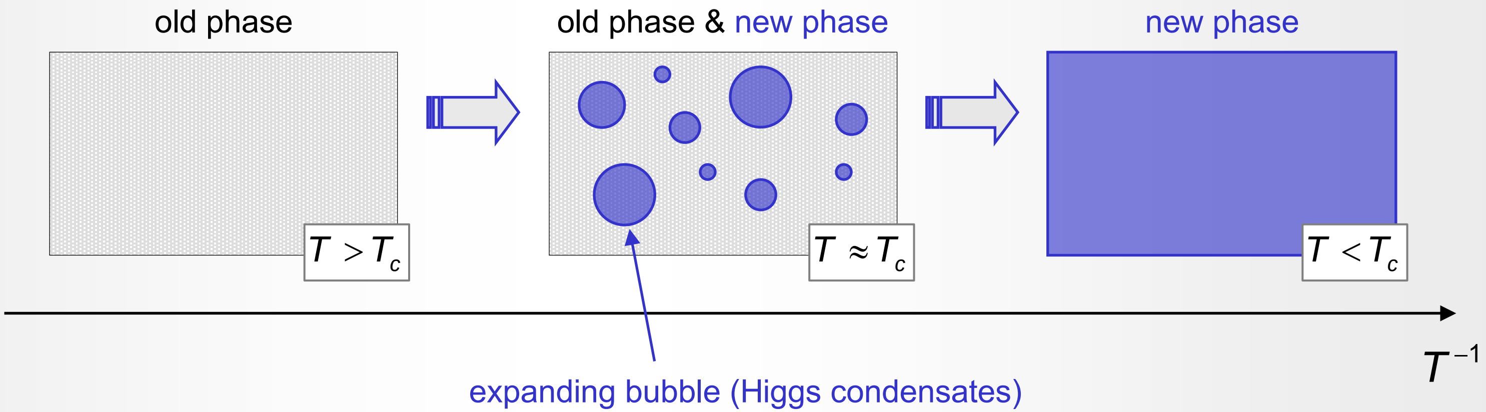
- **Small perturbative changes** in fields around zero charge **will not change *B* and *L***
- **Sphaleron transition rate**: ~ $\exp(-E_{\text{sphal.}}(T)/k_B T)$ for $T < T_{EW}$ (barrier), and ~ T^4 for $T > T_{EW}$

(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

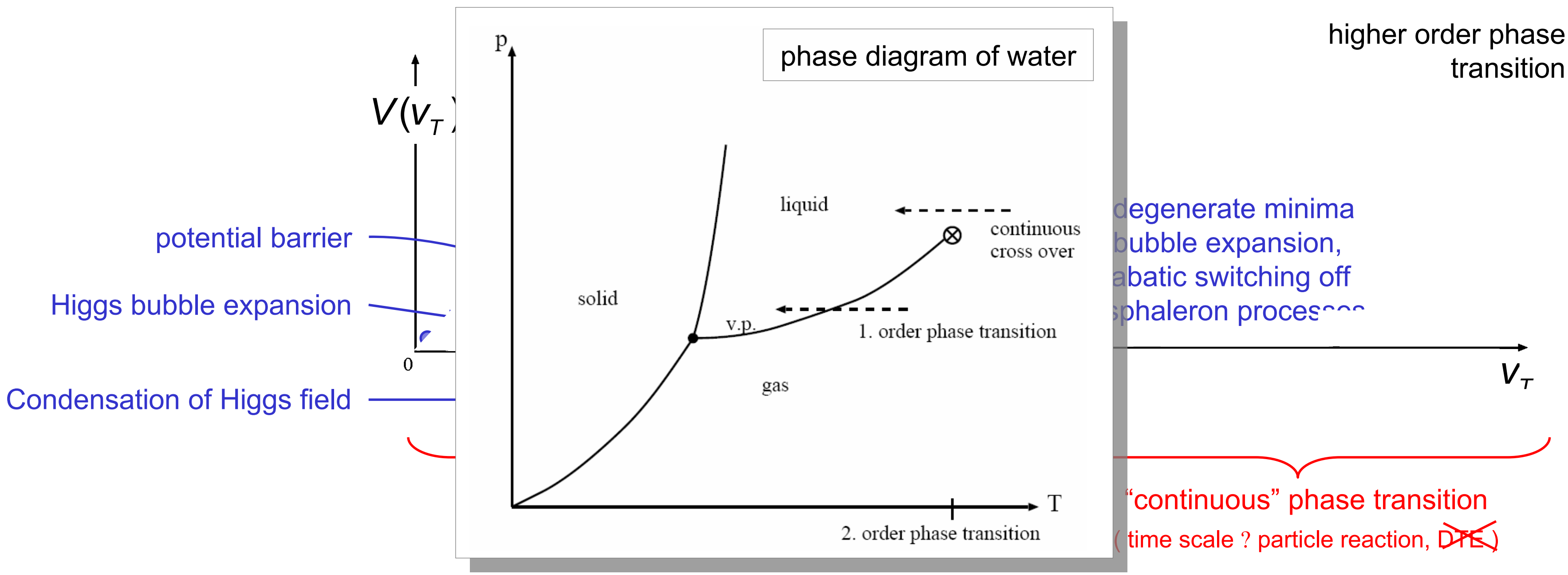
- **In SM for T ?T_{EW}, no departure from thermal equilibrium** (reactions much faster than expansion of universe, $H(T)$)
- SM *CP* violation (KM mechanism) needs non-zero quark masses to occur, but fermions acquire masses only at T_{EW}
- **Need 1st order phase transition at $T_c \sim T_{EW}$:**
  - 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:



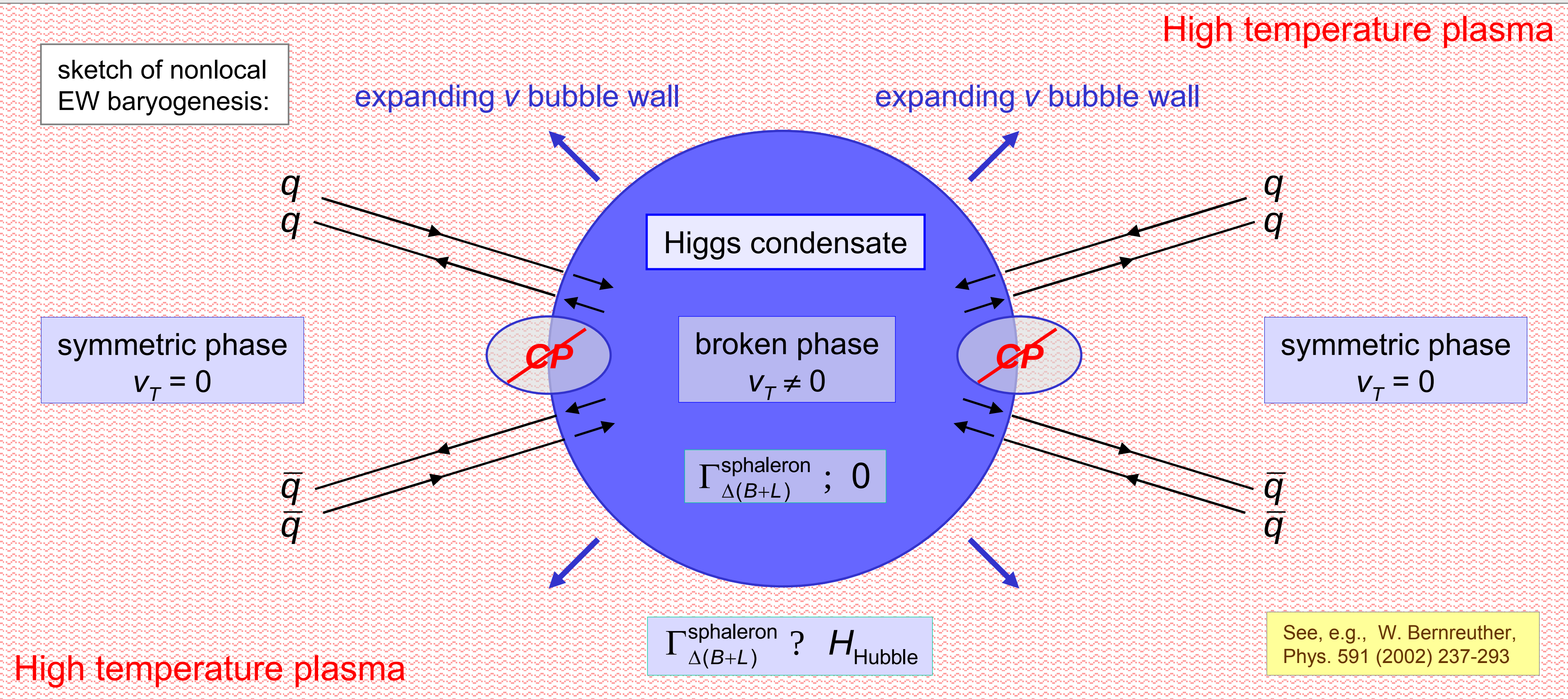
(II) Baryogenesis through EW Phase Transition

- Phase transition
- 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



- **Problem**: the above 1st order phase transition only for m_{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-2 limit for Higgs mass: m_{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: $J = \mathrm{Im}\left(V_{ud}V_{cs}V_{us}^{*}V_{cd}^{*}\right);\ A^2\lambda^6\eta$, and: $\tilde{F}_U = \left(m_t^2 - m_c^2\right)\cdot\left(m_t^2 - m_u^2\right)\cdot\left(m_c^2 - m_u^2\right)$

$= \left(3.1 \pm 0.2\right)\times 10^{-5}$ $\qquad \tilde{F}_D = \left(m_b^2 - m_s^2\right)\cdot\left(m_b^2 - m_d^2\right)\cdot\left(m_s^2 - m_d^2\right)$

- Since (some) 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., electroweak symmetry is broken)

- 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 $[D] = \mathrm{GeV}^{12}$

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

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

(III) Baryogenesis through Leptogenesis

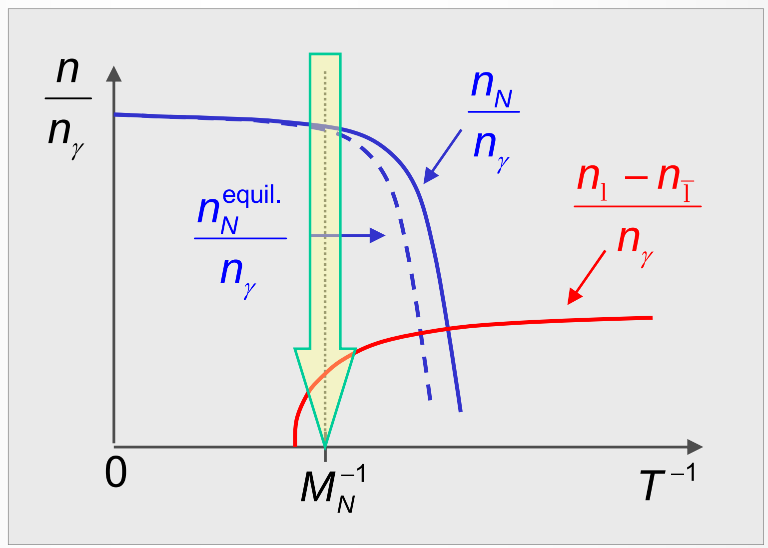
- Assume existence of 3 heavy right-handed ($M_N \sim 10^{10}$–10^{12} GeV) *Majorana* neutrinos $N_{i=1,2,3}$
- The $SU(2)_L \times U(1)_Y$ Lagrangian then allows lepton-number-violating decays

$$N_i \rightarrow l\,\phi \quad \text{and} \quad N_i \rightarrow \bar{l}\,\phi^*$$

lepton-number creating decays

- Sakharov rule 2 : 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 baryogenesis via rapid (B–L)-conserving sphaleron reactions !

Conclusions

- Baryogenesis (most probably) requires Standard Model extension
- We have discussed three mechanisms (others exist):
  1) Baryogenesis via *CP*-violating out-of-equilibrium decays
  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
- Mechanism (3) seems to be most promising: to get the correct baryon asymmetry, the light neutrino masses must lie in ranges consistent with data !

Appendix: CP Violation in the QCD Lagrangian

- It was found in 1976 that the traditional perturbative QCD Lagrangian missed a term L_θ

$$L_{\rm QCD} = \underbrace{L_{\rm pQCD}}_{\text{perturbative QCD}} + \underbrace{L_\theta}_{P,T\text{-violating}}, \quad \text{where: } L_\theta = \theta \frac{\alpha_s}{8\pi} \underbrace{G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}}_{\text{Gluon field tensors}}, \text{ and } \underbrace{\tilde{G}^{\mu\nu,a} = \frac{1}{2}\varepsilon_{\mu\nu\alpha\beta} G^{\alpha\beta,a}}_{\textit{dual}\text{ field tensor}}$$

that breaks through an axial triangle *anomaly* diagram the $U(1)_A$ symmetry of $L_{\rm pQCD}$, which is not observed in nature

when classical symmetries are broken on the quantum level, it is denoted an *anomaly*

- The term $G^a_{\mu\nu} G^{\mu\nu,a}$ contained in $L_{\rm pQCD}$ is *CP*-even, while $G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}$ is *P*-and *T*-odd, since:

$$G G \propto \sum_a \left(\left|\vec{E}_a\right|^2 + \left|\vec{B}_a\right|^2 \right) \xrightarrow{P,T} \sum_a \left(\left|\vec{E}_a\right|^2 + \left|\vec{B}_a\right|^2 \right)$$

$$G \tilde{G} \propto \sum_a \left(\vec{E}_a \cdot \vec{B}_a \right) \xrightarrow{P,T} -\sum_a \left(\vec{E}_a \cdot \vec{B}_a \right)$$

color electric and magnetic fields

Relativistic invariants, similar to electric field tensors: $F_{\mu\nu}F^{\mu\nu}$, $F_{\mu\nu}\tilde{F}^{\mu\nu}$

$$\underbrace{\partial_\mu F^{\mu\nu} = j^\nu, \; \partial_\mu \tilde{F}^{\mu\nu} = 0}_{\text{Maxwell equations}}$$

- This *CP*-violating term contributes to the EDM of the neutron:

$$\underbrace{d_n \sim \theta \cdot 5 \times 10^{-16}\ e\text{cm}, \text{ so that } \theta \text{ tiny or zero}}_{\text{"Strong } CP \text{ (finetuning) Problem"}}$$

The Strong *CP* Problem

- Remarks:
  - If at least one quark were massless, L_θ could be made to vanish; if all quarks are massive, one has uncorrelated contributions, which have no reason to disappear
  - Peccei-Quinn suggested a new global, chiral $U_{PQ}(1)$ symmetry that is broken, with the "axion" as pseudoscalar Goldstone boson; the axion field, ϕ_a ,compensates the contribution from L_θ:

$$L_\theta = \left(\theta - \frac{\phi_a}{f_a}\right)\frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}$$

axion coupling to SM particles is suppressed by symmetry-breaking scale (= decay constant)

QCD nonperturbative effects ("instantons") induce a potential for ϕ_a with minimum at $\phi_a = \theta \cdot f_a$

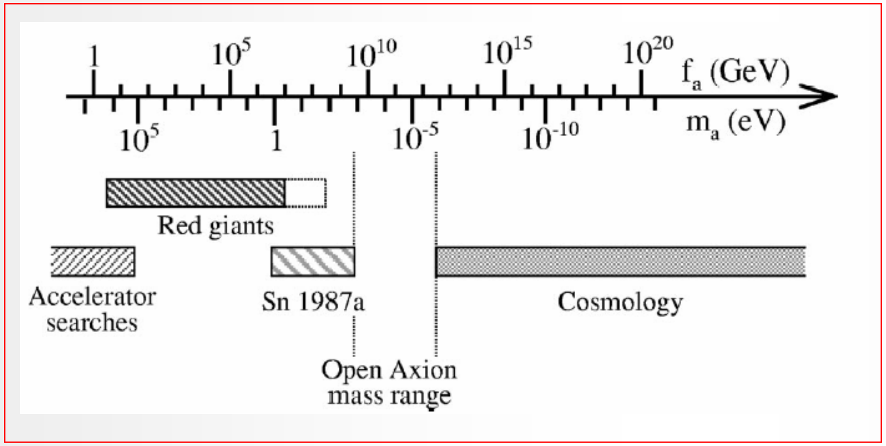
- The axion mass depends on the $U_{PQ}(1)$ symmetry-breaking scale f_a

$$m_a \approx \left(\frac{10^7\ \text{GeV}}{f_a\ (\text{GeV})}\right) \times 0.62\ \text{eV}\,, \qquad \text{and axion coupling strength:} \quad g_a \propto m_a$$

  - If f_a of the order of the EW scale (v), m_a~250 keV → excluded by collider experiments

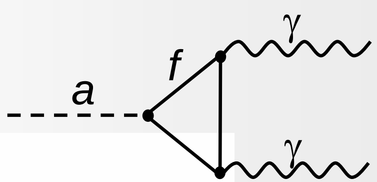
The Search for Axions (the axion is a dark matter candidate)

- The axion can be made "invisible" by leaving scale and coupling free, so that one has: $m_a \sim 10^{-12}$ eV up to 1 MeV → 18 orders of magnitude !



Axion scale and mass, together with the exclusion ranges from experimental non-observation

- Axion decays to 2γ, just as for the π^0, or in a static magnetic field:



Schematic view of CAST experiment at CERN: