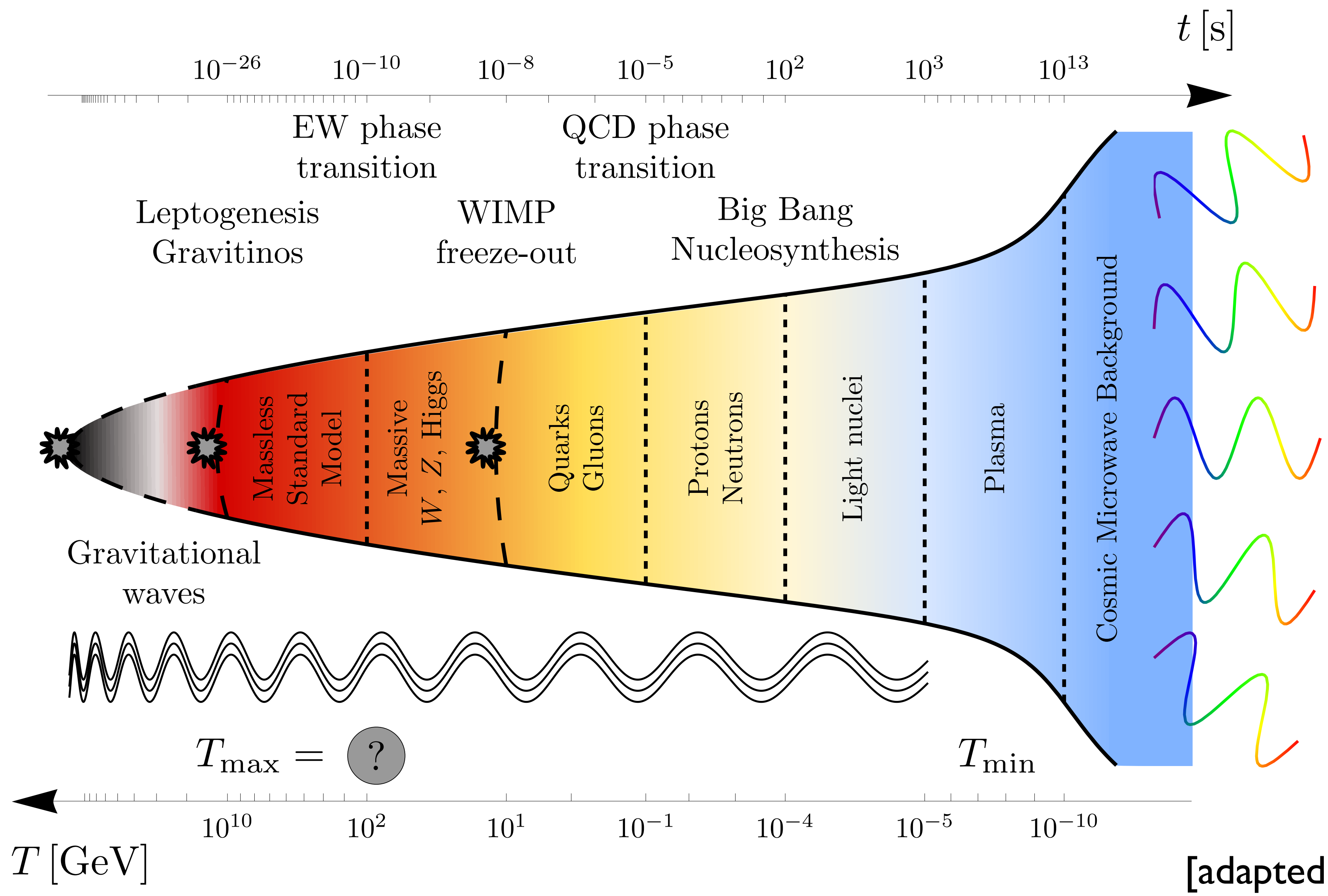
Probing the Early Universe with Baryogenesis & Inflation

Wilfried Buchmüller
DESY, Hamburg

ICTP Summer School, Trieste, June 2015



[adapted from Schmitz '12]

- When and how was the baryon asymmetry generated?
- What caused inflation, and at which energy scale?
- How are inflation, baryogenesis and dark matter related?

Outline

- **BARYOGENESIS**

  1. Electroweak baryogenesis
  2. Leptogenesis
  3. Other models

- **INFLATION**

  1. The basic picture
  2. Recent developments

BARYOGENESIS

What is the origin of matter, i.e., the baryon-to-photon ratio

$$\eta_B = \frac{n_B}{n_\gamma} = (6.1 \pm 0.1) \times 10^{-10}$$

? ? ? ?

Key references

A. D. Sakharov, JETP Lett. 5 (1967) 24
G. 't Hooft, Phys. Rev. Lett. 37 (1976) 8
V. A. Kuzmin, V. A. Rubakov and M. E. Shaposhnikov, Phys. Lett. B 155 (1985) 36
J. A. Harvey and M. S. Turner, Phys. Rev. D 42 (1990) 3344

Sakharov's conditions

Necessary conditions for generating a matter-antimatter asymmetry:

- baryon number violation
- C and CP violation
- deviation from thermal equilibrium

Check of 3rd condition:

$$\begin{aligned}\langle B\rangle = \mathrm{Tr}(e^{-\beta H}B) &= \mathrm{Tr}(\Theta\Theta^{-1}e^{-\beta H}B)\\ &= -\mathrm{Tr}(e^{-\beta H}B)\,, \quad \Theta = CPT\end{aligned}$$

Alternative mechanisms: dynamics of scalar fields, e.g. Affleck-Dine baryogenesis, heavy moduli decay, ...

Sphaleron processes

Baryon and lepton number not conserved in Standard Model,

$$J_\mu^B = \frac{1}{3} \sum_{generations} \left(\overline{q_L}\gamma_\mu q_L + \overline{u_R}\gamma_\mu u_R + \overline{d_R}\gamma_\mu d_R\right) \ ,$$

$$J_\mu^L = \sum_{generations} \left(\overline{l_L}\gamma_\mu l_L + \overline{e_R}\gamma_\mu e_R\right) \ ,$$

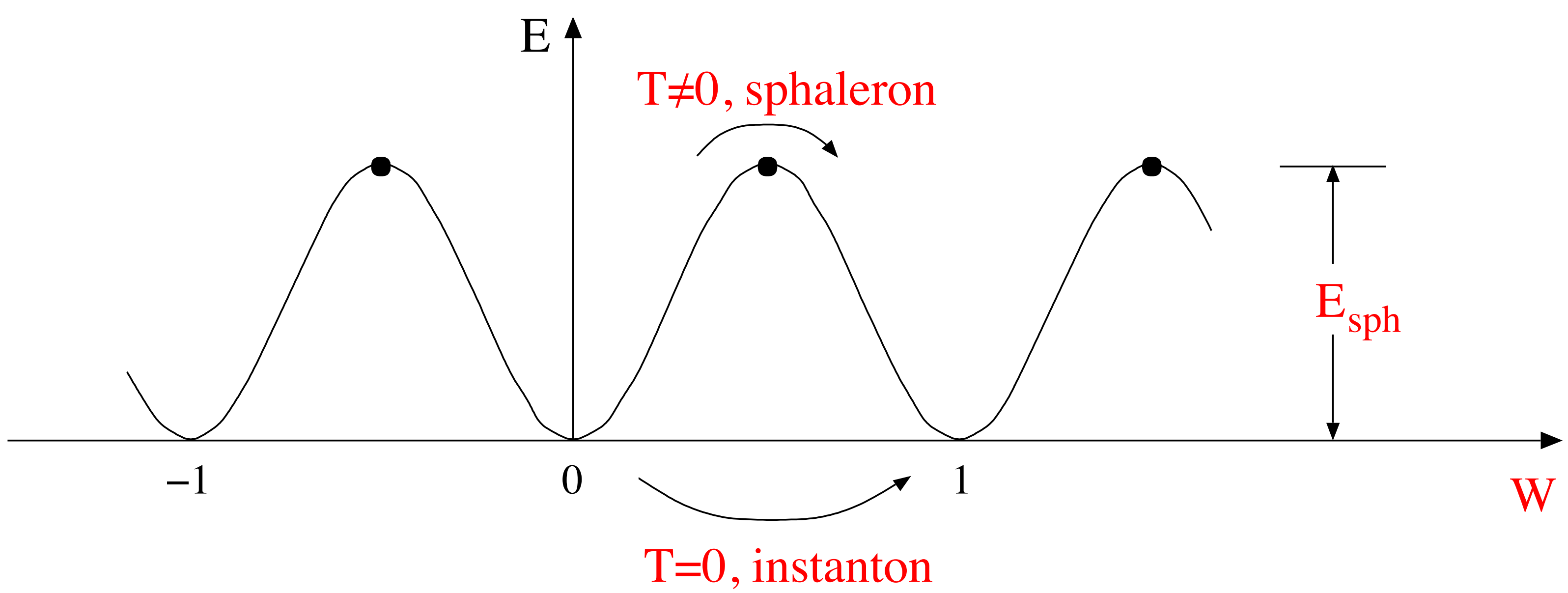
divergence given by triangle anomaly,

$$\begin{aligned} \partial^\mu J_\mu^B &= \partial^\mu J_\mu^L \\ &= \frac{N_f}{32\pi^2}\left(-g^2 W_{\mu\nu}^I \widetilde{W}^{I\mu\nu} + g'^2 B_{\mu\nu}\widetilde{B}^{\mu\nu}\right) \ ; \end{aligned}$$

N_f: number of generations; W_μ^I, B_μ: $SU(2)$ and $U(1)$ gauge fields, gauge couplings g and g'.

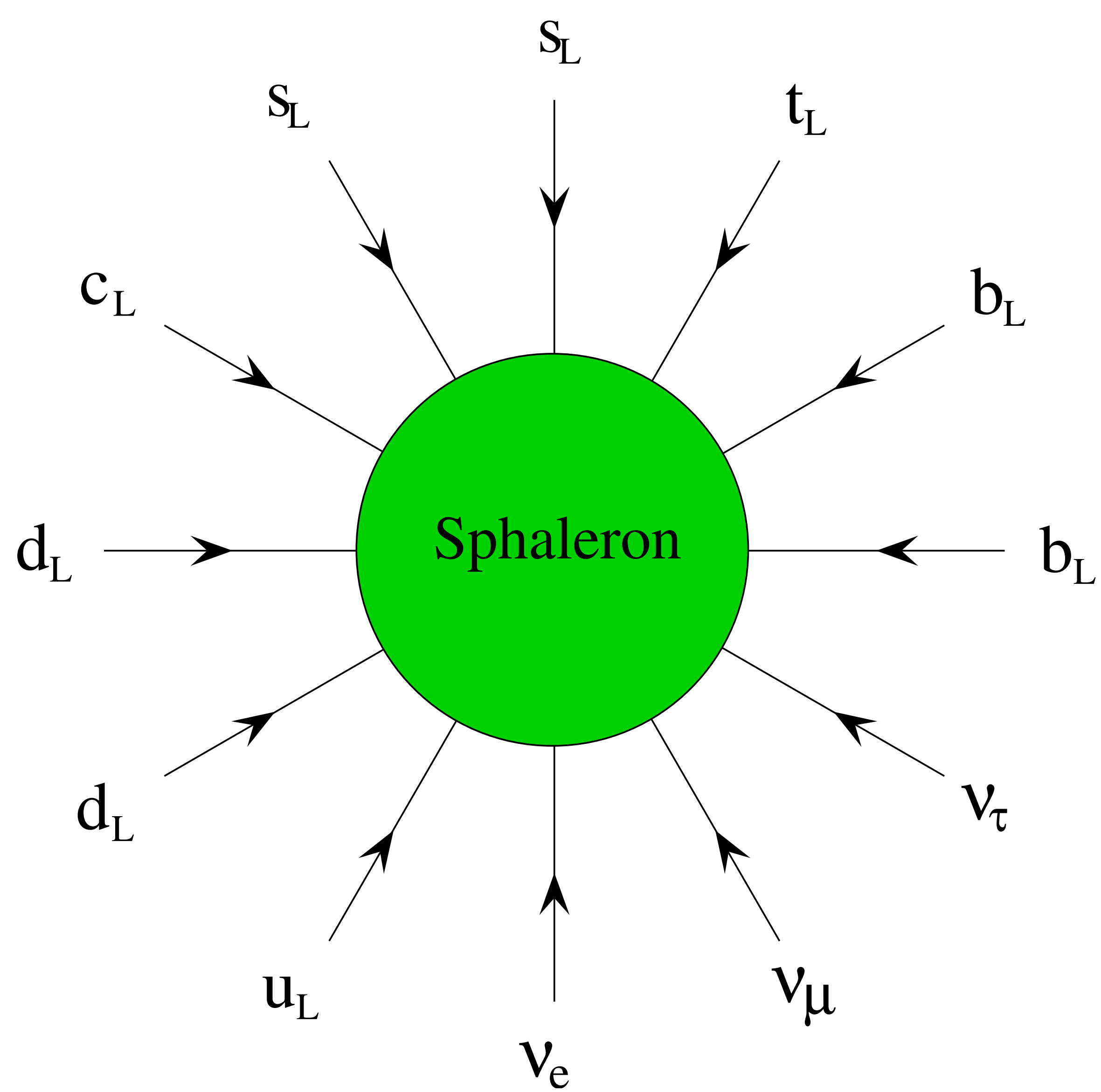
Change in baryon and lepton number related to the change in topological charge the gauge field,

$$
\begin{aligned}
B(t_f) - B(t_i) &= \int_{t_i}^{t_f} dt \int d^3x \partial^\mu J_\mu^B \\
&= N_f [N_{cs}(t_f) - N_{cs}(t_i)] \ , \quad \text{with} \\
N_{cs}(t) &= \frac{g^3}{96\pi^2} \int d^3x \epsilon_{ijk} \epsilon^{IJK} W^{Ii} W^{Jj} W^{Kk}
\end{aligned}
$$



Non-abelian gauge theory: $\Delta N_{cs} = \pm 1, \pm 2, \ldots$. Jumps in Chern-Simons associated with changes of baryon and lepton number,

$$
\Delta B = \Delta L = N_f \Delta N_{cs} \ .
$$



In SM, effective 12-fermion interaction

$$O_{B+L} = \prod_i (q_{Li} q_{Li} q_{Li} l_{Li}) \ , \quad \Delta B = \Delta L = 3$$

$$u^c + d^c + c^c \to d + 2s + 2b + t + \nu_e + \nu_\mu + \nu_\tau$$

Sphaleron rate crucially depends on temperature, only relevant in early universe:

$$\textit{zero temperature:} \quad \Gamma \sim e^{-S_{\text{inst}}} = e^{-\frac{4\pi}{\alpha}} = \mathcal{O}\left(10^{-165}\right)$$

$$\textit{EW phase transition:} \quad \frac{\Gamma_{B+L}}{V} = \kappa \frac{M_W^7}{(\alpha T)^3} \exp\left(-\beta E_{\text{sph}}(T)\right),$$

$$\text{with} \quad E_{\text{sph}}(T) \simeq \frac{8\pi}{g} v(T)$$

$$\textit{high temperature phase:} \quad \frac{\Gamma_{B+L}}{V} = \kappa_s \alpha^5 T^4 \sim 10^{-6}$$

"consensus" among theorists: B+L violating processes in thermal equilibrium in temperature range:

$$T_{EW} \sim 100 \text{ GeV} < T < T_{sph} \sim 10^{12} \text{ GeV}$$

... but no direct experimental evidence for instanton or sphaleron processes ...

Chemical potentials

In SM, with Higgs doublet H and N_f generations, there are $5N_f + 1$ chemical potentials (q_i, ℓ_i, u_i, d_i, e_i); for non-interacting gas of massless particles μ_i give asymmetries in particle and antiparticle number densities,

$$n_i - \overline{n}_i = \frac{gT^3}{6} \begin{cases} \beta\mu_i + \mathcal{O}\left((\beta\mu_i)^3\right) \,, & \text{fermions} \\ 2\beta\mu_i + \mathcal{O}\left((\beta\mu_i)^3\right) \,, & \text{bosons} \end{cases}$$

Relations between the various chemical potentials:

$SU(2)$ *instantons:*

$$\sum_i (3\mu_{qi} + \mu_{li}) = 0$$

QCD *instantons:*

$$\sum_i (2\mu_{qi} - \mu_{ui} - \mu_{di}) = 0$$

vanishing hypercharge of plasma:

$$\sum_i \left(\mu_{qi} + 2\mu_{ui} - \mu_{di} - \mu_{li} - \mu_{ei} + \frac{2}{N_f}\mu_H \right) = 0$$

Yukawa interactions:

$$\mu_{qi} - \mu_H - \mu_{dj} = 0 \,, \quad \mu_{qi} + \mu_H - \mu_{uj} = 0 \,,$$
$$\mu_{li} - \mu_H - \mu_{ej} = 0$$

Relations determine B and L in terms of B-L :

$$B = \sum_i (2\mu_{qi} + \mu_{ui} + \mu_{di}) \;, \quad L = \sum_i (2\mu_{li} + \mu_{ei})$$

$$B = c_s(B - L) \,, \quad L = (c_s - 1)(B - L) \,, \quad c_s = \frac{8N_f + 4}{22N_f + 13}$$

Electroweak baryogenesis and leptogenesis fundamentally different!
In EWBG B-L conserved, generation of B in strong phase transition;
in LG generation of B from initial generation of B-L (then unaffected by sphaleron processes)

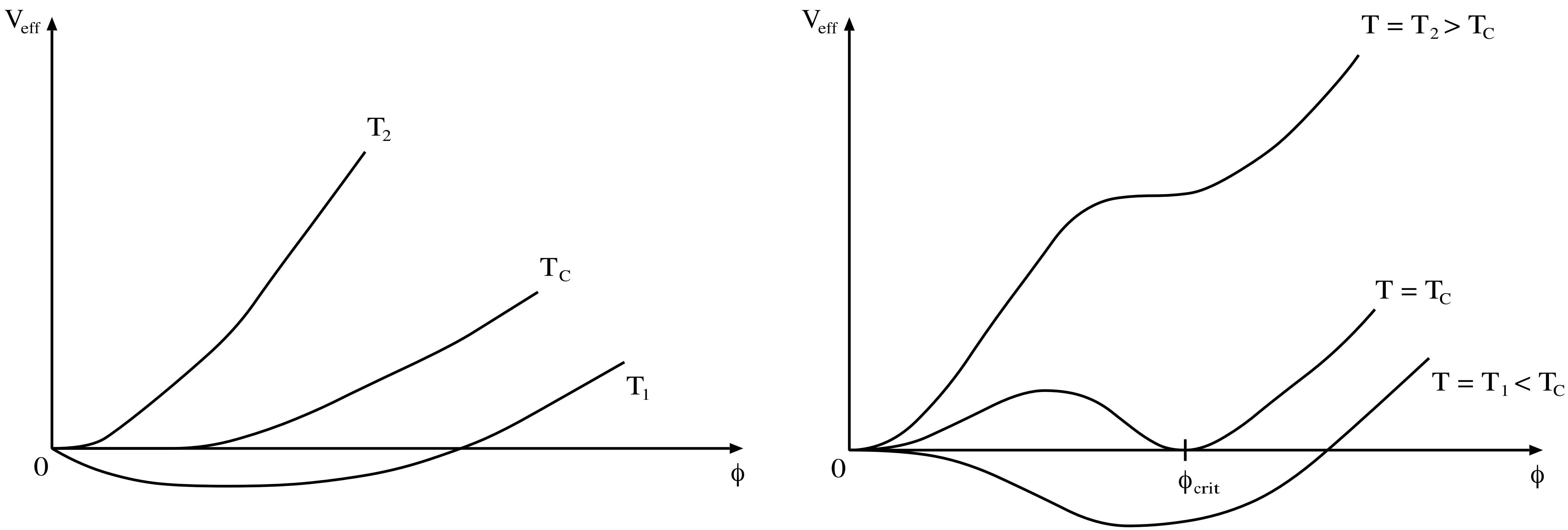
I. Electroweak Baryogenesis

Key references

D. A. Kirzhnits and A. D. Linde, Phys. Lett. B 42 (1972) 471
A. G. Cohen, D. B. Kaplan and A. E. Nelson, Phys. Lett. B 336 (1994) 41

Reviews

W. Bernreuther, Lect. Notes Phys. 591 (2002) 237
D. E. Morrissey and M. J. Ramsey-Musolf, New J. Phys. 14 (2012) 125003
T. Konstandin, Physics - Uspekhi 56 (8) 747 (2013)



2nd order vs 1st order (electroweak) phase transition, as universe cools down. What determines the shape of the effective potential? How does the phasetransition proceed in an expanding universe? How can the complicated nonequilibrium process be calculated, where all masses are generated?

Finite-temperature effective potential

Massive scalar field:

$$S_\beta = \int_\beta \left(\frac{1}{2}(\partial_\tau \phi)^2 + \frac{1}{2}(\partial_i \phi)^2 + V(\phi) \right)$$

$$V(\phi) = \frac{1}{2}\mu^2 + \frac{\lambda}{4}\phi^4\,, \quad \int_\beta = \int_0^\beta d\tau \int d^3x\,, \quad \beta = \frac{1}{T}$$

Euclidean field theory with finite time range β; add source term, calculate free energy (constant source, volume Ω):

$$Z_\beta[j] = \int_\beta D\phi \exp\left(-S_\beta[\phi] - \int_\beta j\phi\right) = \exp\left(-\beta\Omega W_\beta(j)\right),$$

$$\frac{\partial W_\beta}{\partial j} = \frac{1}{\beta\Omega}\langle \int_\beta \phi(x) \rangle \equiv \varphi$$

Legendre transformation yields effective potential:

$$V_\beta(\varphi) = W_\beta(j) - \varphi j\,, \quad j = -\frac{\partial V_\beta}{\partial \phi}$$

explicit calculation, high temperature expansion:

$$V_\beta(\varphi) = V_{T=0}(\varphi) - \frac{\pi^2}{90}T^4 + \frac{1}{24}m^2(\varphi)T^2 - \frac{1}{12\pi}m^3(\varphi)T + \ldots$$

$$m^2(\varphi) = m^2 + 3\lambda\varphi^2\,, \quad \frac{m(\varphi)}{T} \ll 1$$

$$= \frac{1}{2}(m^2 + \frac{\lambda}{4}T^2)\varphi^2 + \frac{\lambda}{4}\varphi^2 + \ldots$$

2nd term is free energy of massless boson; thermal bath generates “thermal mass” of boson; usefull concept to understand some effects in thermal field theory qualitatively, but different from kinematic mass; in gauge theories problem of gauge invariance ...

Higgs model & symmetry breaking

In (Abelian) Higgs symmetry "broken" in ground state:

$$S_\beta = \int_\beta \left((D_\mu \phi)^* D_\mu \phi + \mu^2 |\phi|^2 + \lambda |\phi|^4\right) \; ,$$

$$D_\mu = \partial_\mu + igA_\mu \, , \quad \mu^2 < 0 \, , \quad \mathrm{Re}\; \phi_0 = \left(-\mu^2/\lambda\right)^{1/2} \equiv \varphi_0/\sqrt{2} \, ,$$

$$m_A = g\varphi_0 \, , \quad m_H = \sqrt{2\lambda}\, \varphi_0$$

finite-temperature potential (with "barrier temperature", where the barrier dissappears):

$$V_\beta(\varphi) = \frac{a}{2}(T^2 - T_b^2)\varphi^2 - \frac{b}{3} T\varphi^3 + \frac{\lambda}{4}\varphi^4 + \ldots$$

$$\left.\frac{\partial^2 V_\beta}{\partial^2 \varphi}\right|_{\varphi=0} = 0 \; : \; T_b^2 = -\frac{\mu^2}{a} \, , \quad a = \frac{3g^2}{16} + \frac{\lambda}{2}$$

Cooling down, at critical temperature, Higgs vev jumps to critical vev:

$$V_{\beta_c}(\varphi_c) = V_{\beta_c}(0) \ : \ \frac{T_c^2 - T_b^2}{T_c^2} \simeq \frac{b^2}{a\lambda} > 0\,,$$
$$\frac{\varphi_c}{T_c} = \frac{2b}{3\lambda}$$

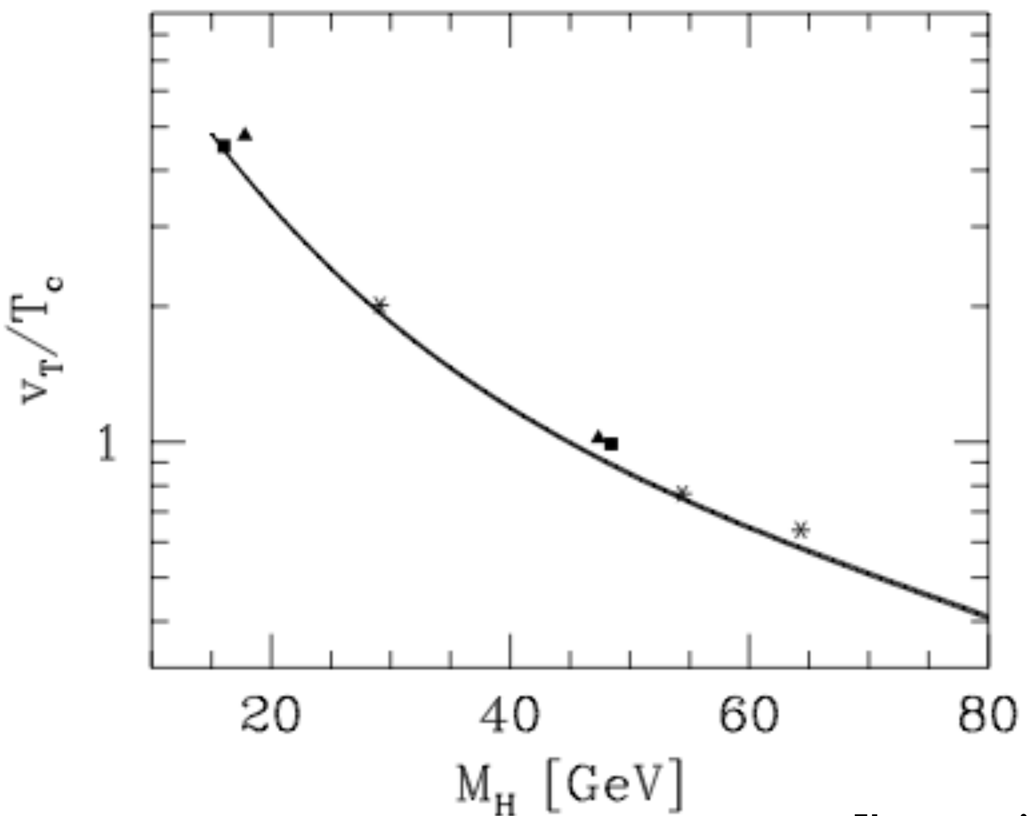
phase transition weak for large Higgs mass (small coupling λ); Standard model and extensions: "a" and "b" in effective potential more complicated functions of gauge and Yukawa couplings.

Much work on effective potential (mostly mid-nineties): loop corrections, gauge dependence, infrared divergencies, treatment of Goldstone bosons, resummations, nonperturbative effects (gap equations, rigorous lattice studies!), beautiful work ... Baryogenesis needs strong phase transition:

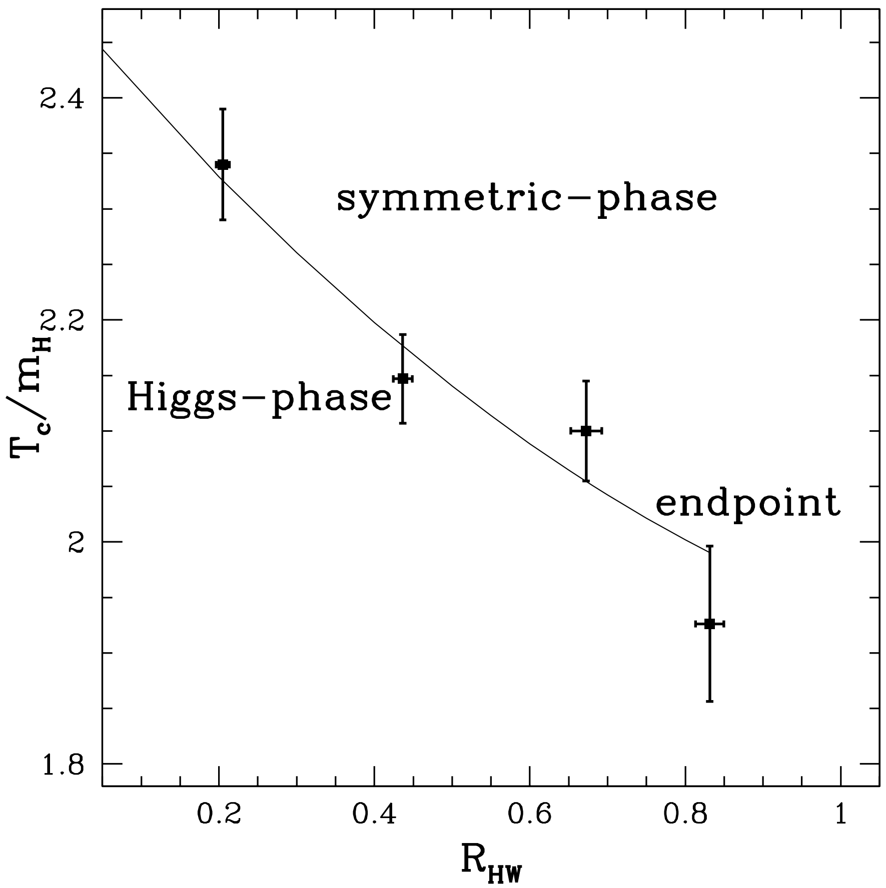
$$\frac{\varphi_c}{T_c} > 1$$

not possible in SM, but possible in extensions ...

Phase diagram



[Jansen '96]



[Csikor, Fodor, Heitger '98]

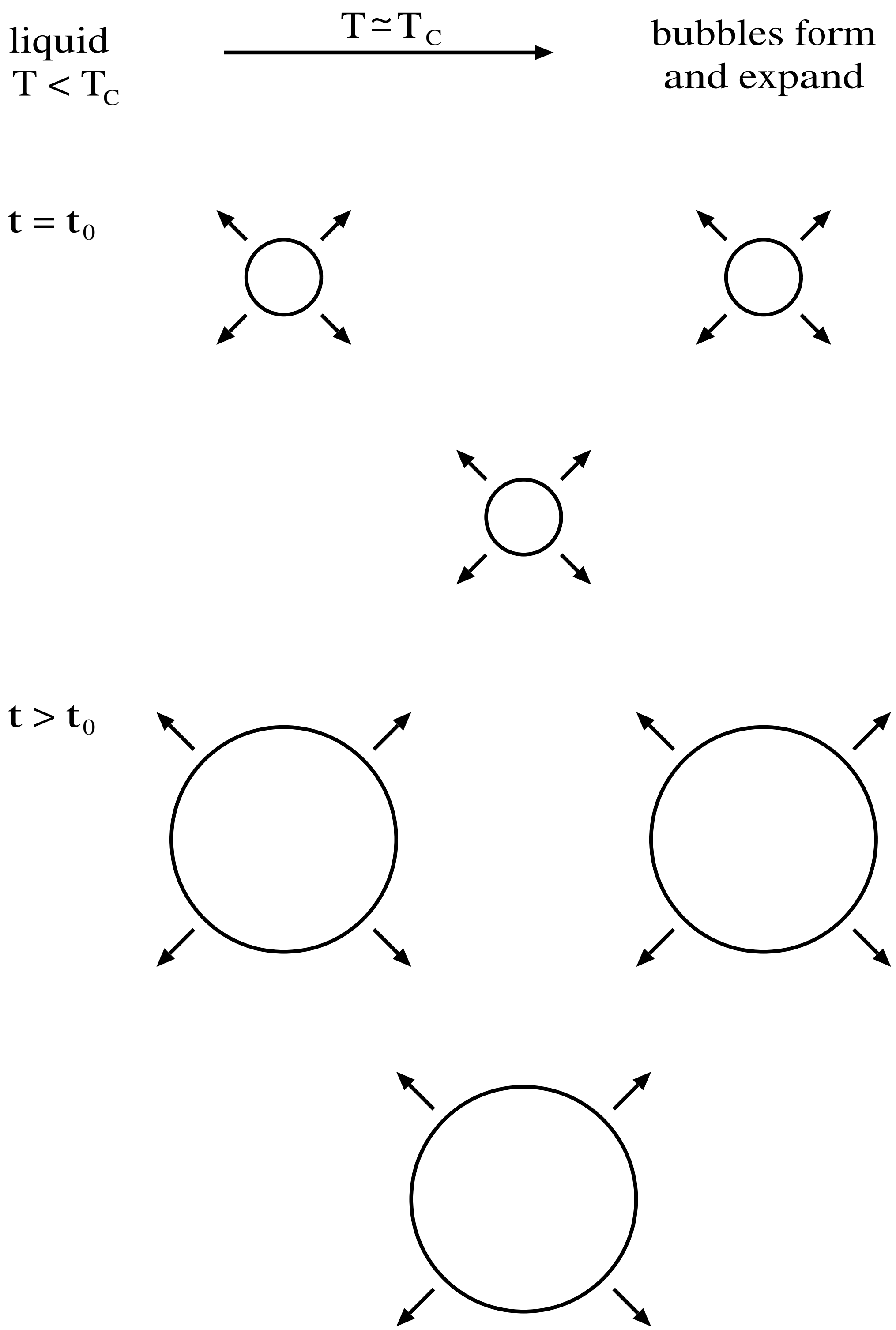
Nonperturbative effects change 1st order transition to crossover at critical Higgs mass:

$$\textit{critical endpoint, lattice: } R_{HW} = \frac{m_H}{m_W}\,, \quad m_H^c = 72.1 \pm 1.4 \text{ GeV}$$

$$\textit{gap equations, magnetic mass: } m_H^c = \left(\frac{3}{4\pi C}\right)^{1/2} \simeq 74 \text{ GeV}\,,$$

$$m_{SM} = C g^2 T\,, \quad C \simeq 0.35$$

Bubble nucleation & growth

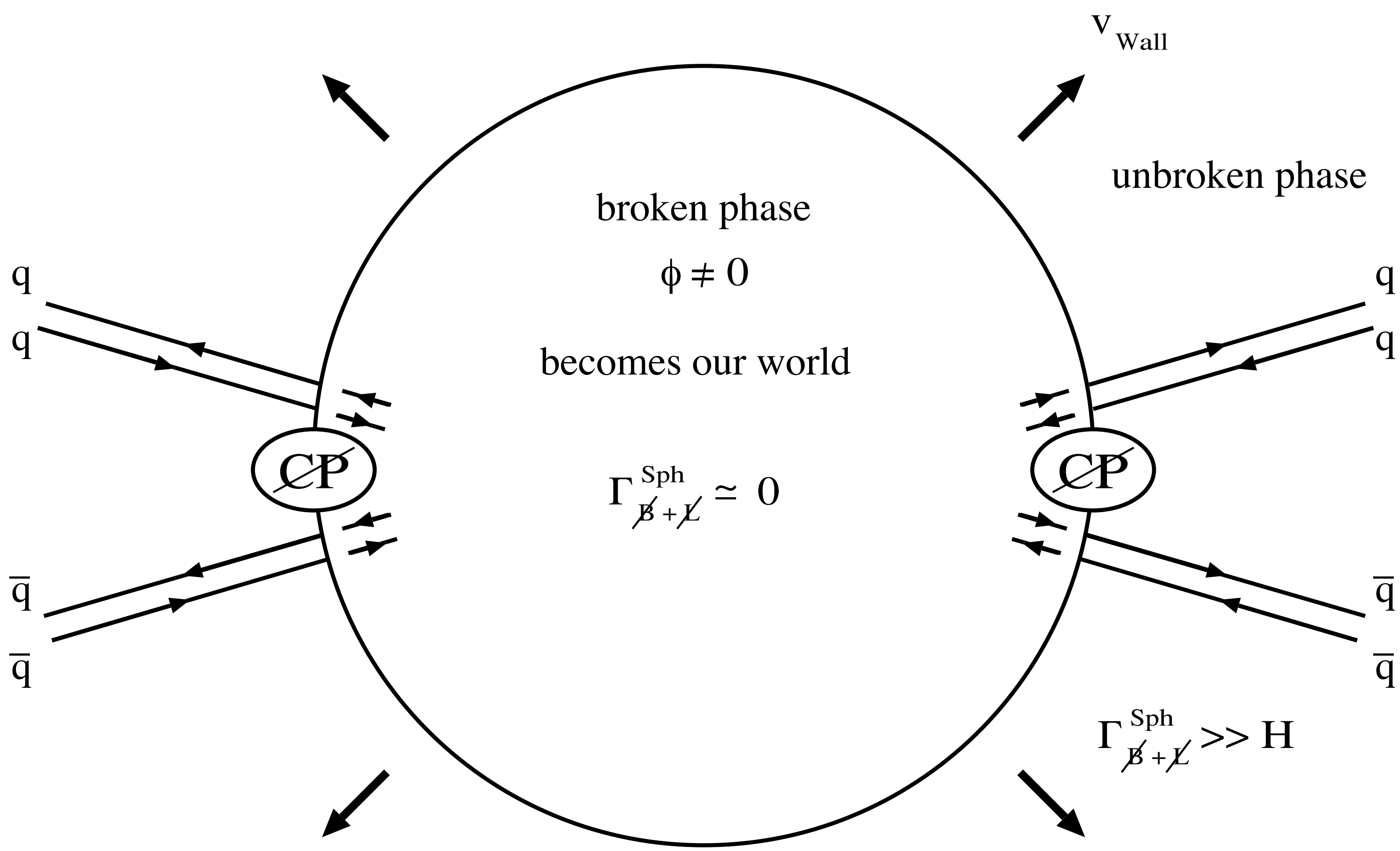


no 1st-order phase transition in SM, but in extensions (singlet model, 2HDM,...)

nucleation rate per volume:

$$\frac{\Gamma}{V} = A \ \exp\left(-\Gamma_{eff}[\overline{\Phi}]\right),$$

$\overline{\Phi}$: *saddle point of effective action, interpolating between the two phases, Langer's theory, ...*



CP violating scatterings at bubble wall (one-dimensional approximation):

$$\mathcal{L}_f = -\sum_\psi y_\psi \bar{\psi}_L \psi_R \phi\,, \quad \phi(z) = \frac{\rho(z)}{\sqrt{2}} e^{i\theta(z)}\,, \quad \rho(z) = \frac{v_c}{2}\left(1 - \tanh\frac{z}{L_w}\right)$$

Calculating the baryon asymmetry

very difficult, series of approximations: Schwinger-Keldysh → Boltzmann equations → diffusion equations ... ; CP violating interactions with bubble wall generate in front of wall excess of left-handed "tops", converted to baryon asymmetry by sphaleron processes; in frame of wall chemical potentials only depend on distance from wall:

$$\textit{chemical potentials:} \quad \mu_{q_L}(z) = 3(\mu_{q_1}(z) + \mu_{q_2}(z) + \mu_{q_3}(z))$$

$$\textit{baryon number density:} \quad \frac{\partial n_B}{\partial t} = \frac{3}{2}\frac{\Gamma_{\rm sph}}{T}\left(\mu_{q_L} - \kappa_{\rm cs}\frac{n_B}{T^2}\right)$$

$$\textit{diffusion equations:} \quad v_w \partial_z \mu_i - \sum_j \Gamma_{ij}\mu_j + \cdots = S_i$$

$$\textit{final result:} \quad n_B = \frac{3}{2}\frac{\Gamma_{\rm sph}}{v_w T}\int_0^\infty \mu_{q_L}(z) e^{-k_B z}\,, \qquad k_B = \frac{3\kappa_{\rm cs}}{2 v_w}\frac{\Gamma_{\rm sph}}{T^3}$$

important parameters: critical Higgs vev, bubble wall velocity, bubble wall width, diffusion parameters, ...

Example 1: 2 Higgs-doublet model (2HDM)

$$
\begin{aligned}
V(H_1, H_2) = & -\mu_1^2 H_1^\dagger H_1 - \mu_2^2 H_2^\dagger H_2 - \mu_3^2 (e^{i\alpha} H_1^\dagger H_2 + \text{h.c.}) \\
& + \frac{\lambda_1}{2} (H_1^\dagger H_1)^2 + \frac{\lambda_2}{2} (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) \\
& + \lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2} \left((H_1^\dagger H_2)^2 + \text{h.c.} \right) \\
\mathcal{L}_Y = & \; y H_2 q_3 t^c + \text{h.c.} + \ldots
\end{aligned}
$$

approximate Z_2 symmetry, broken by μ_3; measure for size of couplings, one-loop corrections:

$$
\Delta = \max |\delta\lambda_i / \lambda_i|
$$

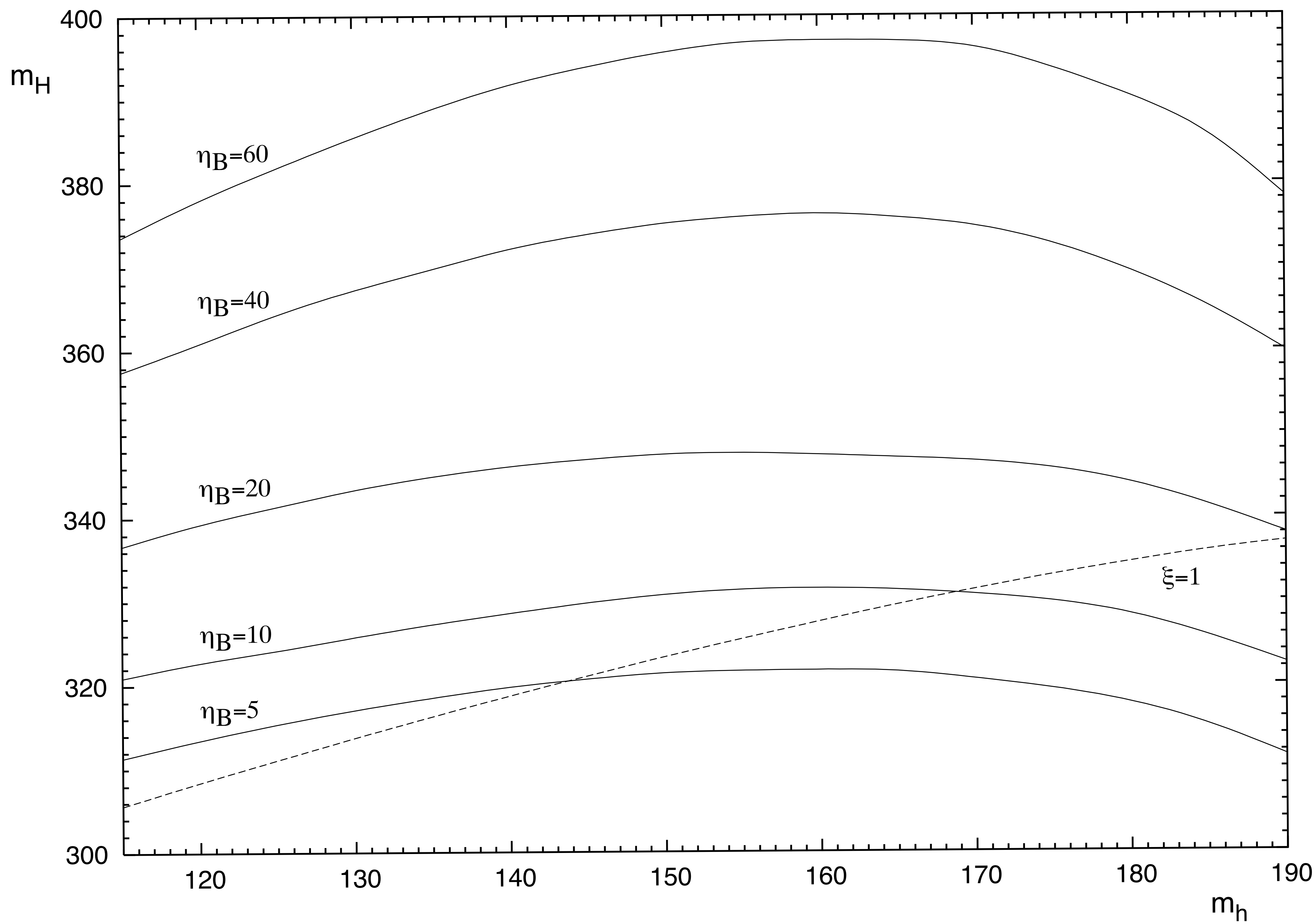
Recent work:

Dorsch, Huber, No '13: $\quad m_{H^\pm} \lesssim m_{H_0} < m_{A^0}\,, \quad m_{A^0} \gtrsim 400 \text{ GeV}\,,$

$$
R_{\gamma\gamma} = \Gamma(h^0 \to \gamma\gamma)/\Gamma(h^0 \to \gamma\gamma)_{SM} \neq 1
$$

Blinov, Profumo, Stefanik '15: Inert Doublet Model OK, predictions:

$(M_H, M_A, M_{H^\pm}, R_{\gamma\gamma}) = (66, 300, 300, 0.90), (200, 400, 400, 0.93), (5, 265, 265, 0.90)$



[Fromme, Huber, Seniuch ’06]

η_B in units of 10^{-11}; large enough baryon asymmetry requires $\xi = v_c/T_c \gtrsim 1.5$ and $\Delta \sim 0.5$, i.e. 2HDM is strongly coupled! Watch electric dipole moments!

Example 2: Standard Model with singlet

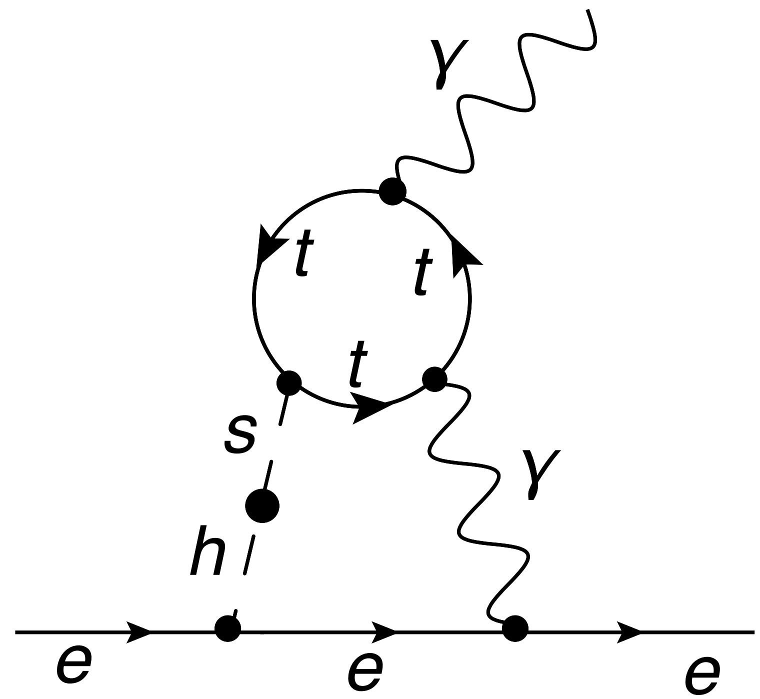
Motivation: non-minimal composite Higgs models, additional singlet in low energy effective Lagrangian; strong first-order phase transition from tree-level potential, thermal instability for singlet and Higgs; CP violation via additional dim5-operator:

[Espinosa, Gripaios, Konstandin, Riva '12]

$$V(h,s,T) = \frac{\lambda_h}{4}\left[h^2 - v_c^2 + \frac{v_c^2}{w_c^2}s^2\right]^2 + \frac{\kappa}{4}\,s^2h^2$$
$$+\frac{1}{2}(T^2 - T_c^2)(c_h\,h^2 + c_s\,s^2)$$

	m_h	m_s	v_c	f/b	$L_w v_c$	v_c/T_c
S1	120 GeV	81 GeV	188 GeV	1.88 TeV	7.1	2.0
S2	140 GeV	139.2 GeV	177.8 GeV	1.185 TeV	3.5	1.5

Light singlet scalar in principle observable at LHC; problem: coupling only via Higgs! Dedicated searches needed; also modification of Higgs properties, electroweak precision observables, ...



$$\mathcal{L}_{tHs} = \frac{s}{f} H \bar{q}_{L3}(a + ib\gamma_5)t_R + \text{h.}c.$$

CP violation for baryogenesis implies EDMs for electron and neutron; predictions close to upper experimental bound! Energy scale f/b ~ 1 TeV, i.e. low compositeness scale - other resonances due to compositeness should be in LHC range!

Note: baryogenesis in MSSM popular for many years, but stop lighter than stop required ... ! Possibility in NMSSM ... ?

Summary: electroweak baryogenesis

- Very interesting topic in nonequilibrium QFT, huge activity during the past past 30 years since closely related to Higgs mechanism

- Theoretical uncertainty considerable:

$$\frac{n_B}{s} \sim \frac{\Gamma_{\rm sph}}{T^4}\frac{1}{L_w T_c}\frac{\delta_{\rm CP}}{4\pi} e^{-m_\psi/T_c}\left(\frac{v_c}{T_c}\right)^\gamma \kappa_d \lesssim 10^{-9}\,,$$

$$\Gamma_{\rm sph}/T^4 \sim 10^{-6}\,,\quad \gamma = 3\ldots 4\,,\quad \kappa_d = 10^{-2}\ldots 10^{-1}$$

$$\simeq 6.2\cdot 10^{-10}$$

- Strong interactions and new particles are unavoidable; 2 HDM: charged Higgs bosons,... ; SM with singlet: light neutral scalar; ...

- Dedicated searches at the LHC, stronger bounds on dipole moments and electroweak precision tests should settle the issue of EWBG