CP-violation and baryogenesis

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Outline

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- Electroweak sphalerons
- Leptogenesis: CP-violation via interference
- Electroweak baryogenesis: CP-violation in bubble wall
- Affleck–Dine baryogenesis: CP-violation by initial conditions
- Conclusions

Baryon asymmetry of the Universe

- There is matter and no antimatter in the present Universe.
- Baryon-to-photon ratio, almost constant in time:

$$\eta_B \equiv \frac{n_B}{n_\gamma} = 6 \cdot 10^{-10}$$

Baryon-to-entropy, constant in time: $n_B/s = 0.9 \cdot 10^{-10}$

What's the problem?

Early Universe ($T > 10^{12}$ K $= 100$ MeV):
creation and annihilation of quark-antiquark pairs $\Rightarrow$

$$n_q, n_{\bar{q}} \approx n_\gamma$$

Hence

$$\frac{n_q - n_{\bar{q}}}{n_q + n_{\bar{q}}} \sim 10^{-9}$$

How was this excess generated in the course of the cosmological evolution?

Sakharov'67, Kuzmin'70

Sakharov conditions

To generate baryon asymmetry, three necessary conditions should be met at the same cosmological epoch:

- B-violation
- Honest C- and CP-violation
- Thermal inequilibrium

NB. Reservation: L-violation with B-conservation at $T \gg 100$ GeV would do as well $\Longrightarrow$ Leptogenesis.

Electroweak sphalerons

One of ingredients: Baryon number violation in electroweak interactions.
Triangle anomaly in baryonic current B^μ:

$$\partial_\mu B^\mu = \left(\frac{1}{3}\right)_{B_q} \cdot 3_{colors} \cdot 3_{generations} \cdot \frac{g_W^2}{16\pi^2} F\tilde{F}$$

$F^a_{\mu\nu}$: $SU(2)_W$ field strength; g_W: $SU(2)_W$ coupling

Likewise, each leptonic current $(n = e, \mu, \tau)$

$$\partial_\mu L_n^\mu = \frac{g_W^2}{16\pi^2} \cdot F\tilde{F}$$

Hence, selection rules $\Delta B = 3\Delta L_e = 3\Delta L_\mu = 3\Delta L_\tau$ or

$$B - L = \text{conserved}$$

where $L = L_e + L_\mu + L_\tau$.

NB: Valid even for heavy quarks (unlike in QCD).
Quarks obtain masses via Yukawa interactions with the Higgs field. Higgs expectation value vanishes in the center of instanton or sphaleron. Usual zero mode/level crossing picture at work.

Sphaleron rate

- Unbroken phase, $\langle\Phi\rangle \equiv \Phi(T) = 0$ (modulo log):

G. Moore's talk

$$\Gamma_{sph} = \# \cdot \alpha_W^5 T^4$$

- Higgs phase, $\langle\Phi\rangle \neq 0$

$$\Gamma_{sph} \sim \# \cdot T^4 \mathrm{e}^{-F_{sph}/T}$$

with

$$F_{sph}(T) \simeq \# \cdot \frac{M_W(T)}{\alpha_W}$$

and $M_W(T) \simeq g_W \Phi(T)$

NB: In fact, “unbroken” and “Higgs” phases are indistinguishable. No order parameter in EW theory. Whether or not there is EW phase transition is a dynamical question (like water–vapor).

Sphaleron processes are in thermal equiliribrium at

$$\Gamma_{sph}/T^3 > H(T)$$

(where $H(T)$ is the Hubble parameter) $\Longrightarrow$ $\Phi < T < 10^{12}$ GeV

NB: $F_{sph}/T \gg 1$ at $\Phi = T$ $\Longrightarrow$ rate is small. But the Universe expands slowly at $T \sim 100$ GeV, unlike RHIC fireball

$$H^{-1} \sim 10^{-10} \text{ s} \quad \text{at} \quad T \sim 100 \text{ GeV}$$

In thermal equilibrium (n_f fermion families, n_H Higgs doublets)

$$B = \frac{8n_f + 4n_H}{22n_f + 13n_H} \cdot (B-L) = \frac{28}{79} \cdot (B-L)$$

Three popular mechanisms of baryogenesis

- GUT. Thermal GUT operates at $T_{GUT} \gtrsim 10^{14}$ GeV.
  Hard to reconcile with inflation.
  Non-thermal: may well operate at reheating epoch between inflation and hot stage
- Leptogenesis (thermal or non-thermal)
- Electroweak baryogenesis

Leptogenesis

Idea:

- generate lepton asymmetry beyond the Standard Model
- EW sphalerons automatically reprocess part of it into baryon asymmetry

See-saw for neutrino masses

Generate neutrino masses by adding three left fermions N_α neutral w.r.t. SM gauge interactions
They are allowed to have Majorana masses. Hence the Lagrangian

$$\mathscr{L} = \frac{1}{2} M_{\alpha\beta} \bar{N}^c_\alpha N_\beta + y_{\alpha\beta} \bar{N}^c_\alpha \tilde{H}^\dagger L_\beta + h.c.$$

By field redefinition $M_{\alpha\beta} = (M_1, M_2, M_3)$ real,
then $y_{\alpha\beta}$ are complex (CP-violation).   Note L-violation.

In vacuo $\langle \tilde{H} \rangle = (v, 0)$, hence Dirac mass term $m_D \bar{N}^c \nu$ with

$$m_{\mathrm{D}\alpha\beta} = y_{\alpha\beta} v$$

Integrate out N's $\Longrightarrow$ active neutrino Majorana mass matrix

$$m = -m_{\mathrm{D}} M^{-1} m_{\mathrm{D}}^T$$

Naturally light ν's for heavy N's

Thermal leptogenesis

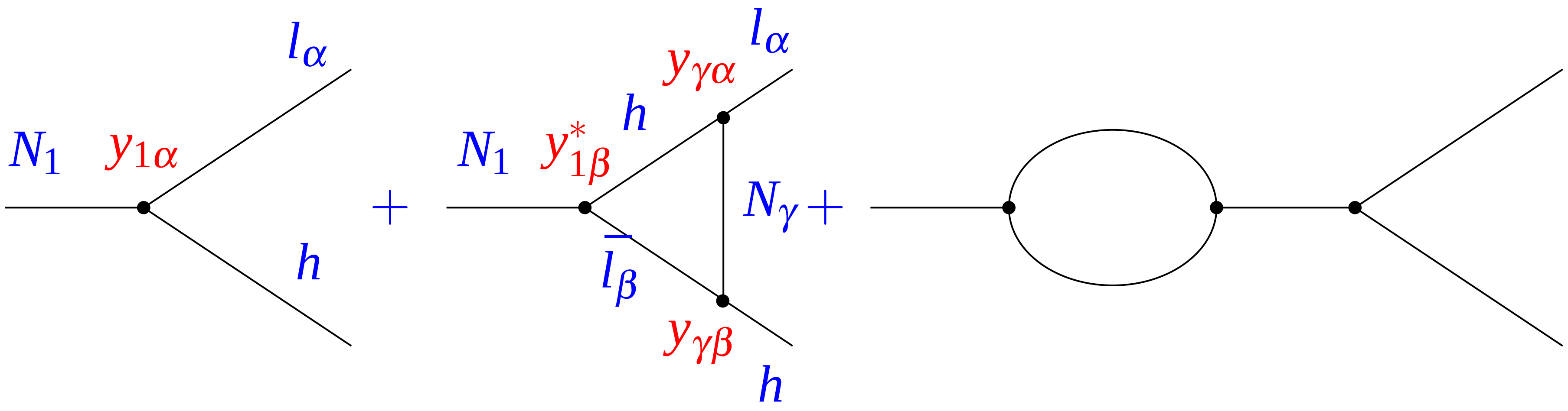
- Complete thermal equilibrium at $T \gtrsim M$.
  Rapid violation of lepton numbers.

- Lepton violation rapid until the lightest N_1 gets out of thermal equilibrium at $T \lesssim M_1$.

- Decays of N_1 are out of equilibrium if $\Gamma_{N_1} < H$ at $T \sim M_1$

  Lepton asymmetry is generated in decays of N_1 because of CP-violation encoded in complex Yukawas $y_{\alpha\beta}$.

CP-violation due to interference



$$\Gamma(N_1 \to lh) = \text{const} \cdot \sum_{\alpha} \left| y_{1\alpha} + \sum_{\beta,\gamma} D(M_1/M_\gamma) \cdot y^*_{1\beta} y_{\gamma\alpha} y_{\gamma\beta} \right|^2$$

D = loop diagrams (complex)

Lepton asymmetry in decay of one N_1 ("microscopic asymmetry")

$$\delta \equiv \frac{\Gamma(N_1 \to lh) - \Gamma(N_1 \to \bar{l}\bar{h})}{\Gamma_{tot}}$$

$$= \frac{1}{8\pi} \sum_{\gamma=2,3} \mathrm{Im}D \cdot \frac{\mathrm{Im}(\sum_\alpha y_{1\alpha} y^*_{\gamma\alpha})^2}{\sum_\alpha |y_{1\alpha}|^2}$$

NB: Need $N_\gamma \neq N_1$ in loop.

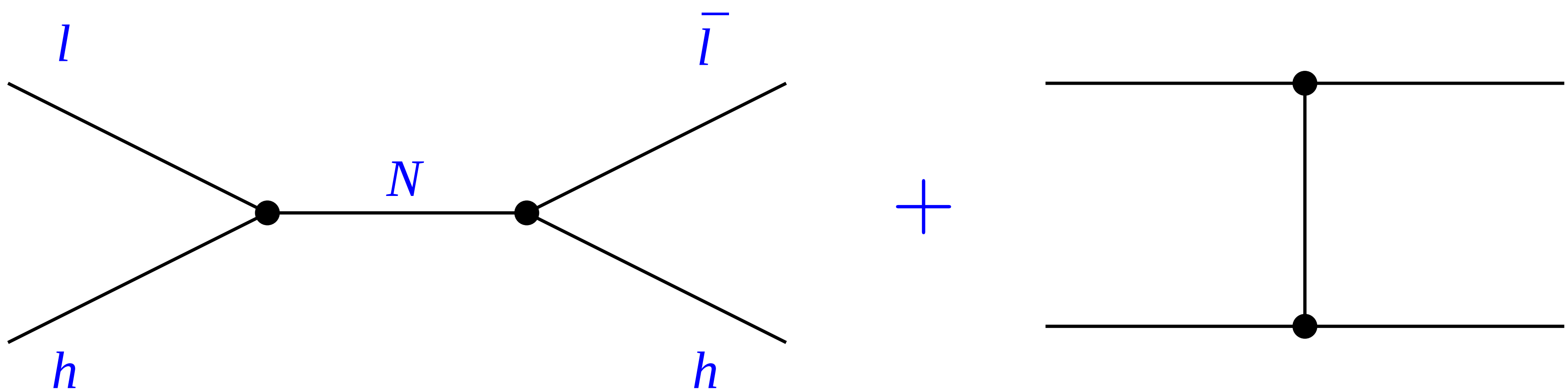
NB: $\mathrm{Im}D(M_1/M_\gamma) = -\frac{2}{3}\frac{M_1}{M_\gamma}$ suppressed for $M_\gamma \gg M_1$

All N's work together

NB: Phases that determine the asymmetry are not phases in mass matrix of light neutrinos: no distinction between lepton flavors for $M \gg m_D \implies CP$-violation in neutrino oscillations is of no direct relevance.

Neutrino masses in right ballpark

- $\Gamma_1 \lesssim H$ at $T \sim M_1 \Longleftrightarrow$ contribution of N_1 to neutrino masses at the level of 10^{-3} eV. Mild suppression for 0.1 eV.
- No washout of lepton asymmetry in scattering



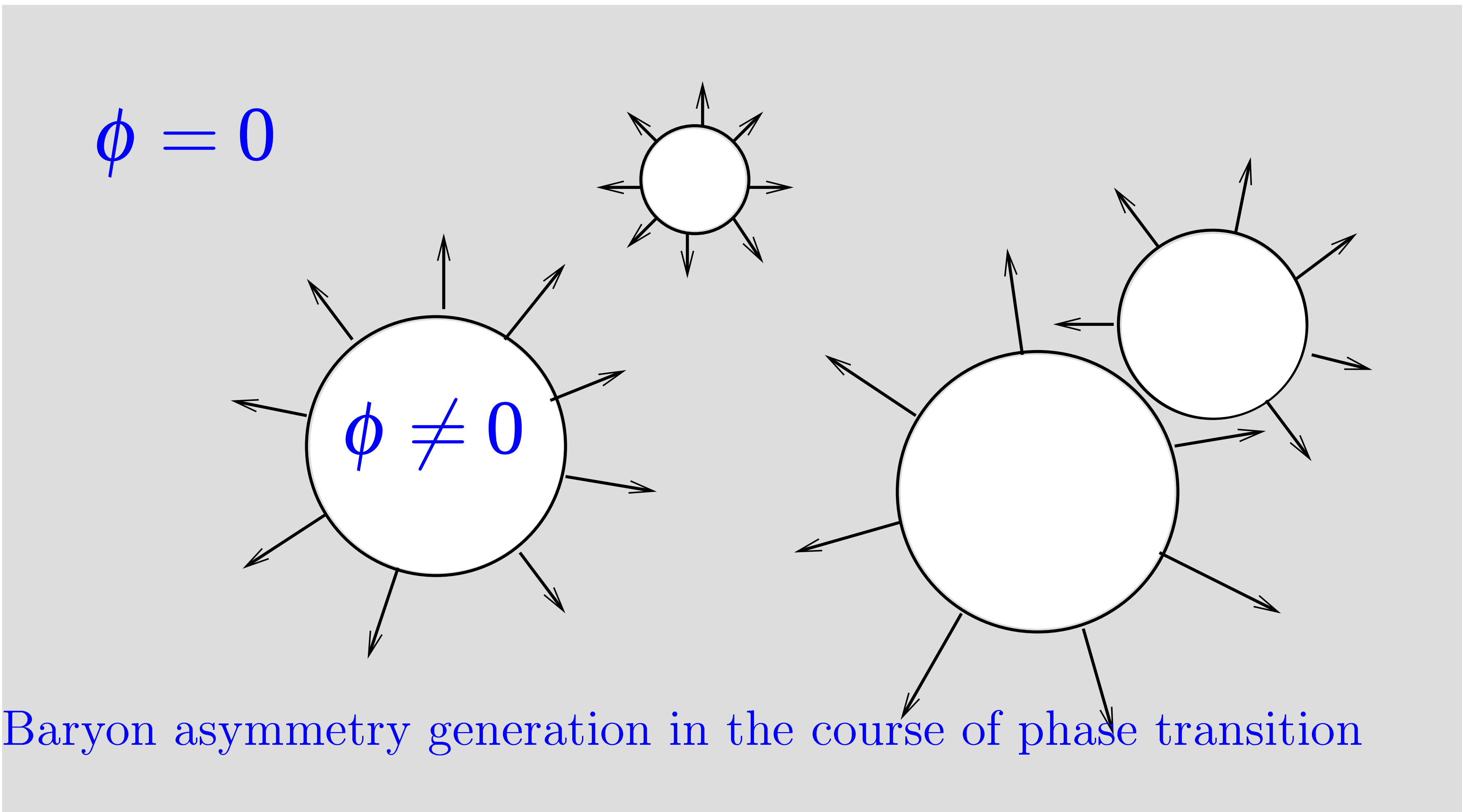
Masses of all neutrinos smaller than ~ 0.1 eV

- Correct value of asymmetry obtained for $M_1 \gtrsim 10^9$ GeV

Electroweak baryogenesis

Occurs when sphalerons get out of thermal equilibrium, $T \sim 100$ GeV

Low expansion rate $\Longrightarrow$ need 1st order phase transition. Standard Model not suitable: no phase transition at all for $m_H > 114$ GeV. Still possible in extensions, will be ruled out (or discovered) by LHC.



Baryon asymmetry generation in the course of phase transition

1st order phase transition occurs from supercooled state via spontaneous nucleation of bubbles of new (broken) phase in old (unbroken) phase.

Bubbles then expand at $v \sim 0.1c$

Beginning of transition: a few bubbles per horizon

Bubbles born microscopic, $r \sim 10^{-16}$ cm, grow to macroscopic size, $r \sim 0.1 H^{-1} \sim$ mm, before their walls collide

Boiling Universe, strongly out of equilibrium

Baryon asymmetry can be generated in interactions of fermions with bubble walls.

CP-violation in bubble wall

Need more than one Higgs doublet, CP-violation in the Higgs sector

Example:

$$V(H_1,H_2) = V_1\left(H_1^\dagger H_1\right) + V_2\left(H_2^\dagger H_2\right) + \lambda_+\left[\mathrm{Re}(H_2^\dagger H_1) - v_1 v_2 \cos 2\xi\right]^2 + \lambda_-\left[\mathrm{Im}(H_2^\dagger H_1) - v_1 v_2 \sin 2\xi\right]^2$$

Inside the broken phase $H_1 = \mathrm{e}^{i\xi} v_1\ , \quad H_2 = \mathrm{e}^{-i\xi} v_2.$

Near unbroken phase H_{12} small, and

$$H_1 = \mathrm{e}^{i\zeta}\rho_1\ , \quad H_2 = \mathrm{e}^{-i\zeta}\rho_2$$

$$\tan 2\zeta = \frac{\lambda_-}{\lambda_+}\tan 2\xi .$$

Relative phase varies across the wall,
$H_1 = \mathrm{e}^{i\theta(x)}\rho_1(x)\ , \quad H_2 = \mathrm{e}^{-i\theta(x)}\rho_2(x)$

Quark interaction with moving bubble wall: at given point in space

$$L_{int} = h\bar{Q}_{\mathrm{L}} H_1 q_{\mathrm{R}} + \mathrm{h.c.} \quad \Longrightarrow \quad h\rho_1(t) e^{i\theta(t)} \bar{Q}_{\mathrm{L}} q_{\mathrm{R}} + \mathrm{h.c.}$$

Reflection/transmission different for quark and antiquark
$\Longrightarrow$ separation of baryon number.

NB: time-dependent phase $\Longleftrightarrow$ violation of thermal equilibrium

Baryon number in excess behind the wall (broken phase, sphalerons switched off)

Excess of antiquarks in front of the wall (unbroken phase) washed out by sphalerons.

Net baryon number generated.

CP-violating interaction of quarks and Higgses $\Longrightarrow$
sizeable e.d.m. of neutron

Less known example: Affleck–Dine baryogenesis

- Assume that there exists complex scalar field ϕ carrying baryon number -1, $\phi \to \mathrm{e}^{-i\alpha}\phi$. It interacts with other fields via

$$L_{int} = h\hat{Q}\phi + \mathrm{h.c.}$$

$\hat{Q}$ carries baryon number 1, $\hat{Q} \to \mathrm{e}^{i\alpha}\hat{Q}$.

- Assume weak violation of baryon number in scalar potential,

$$V(\phi) = m^2\phi^*\phi + \lambda\,(\phi^*\phi)^2 + \lambda'\left(\phi^4 + \phi^{*4}\right)$$

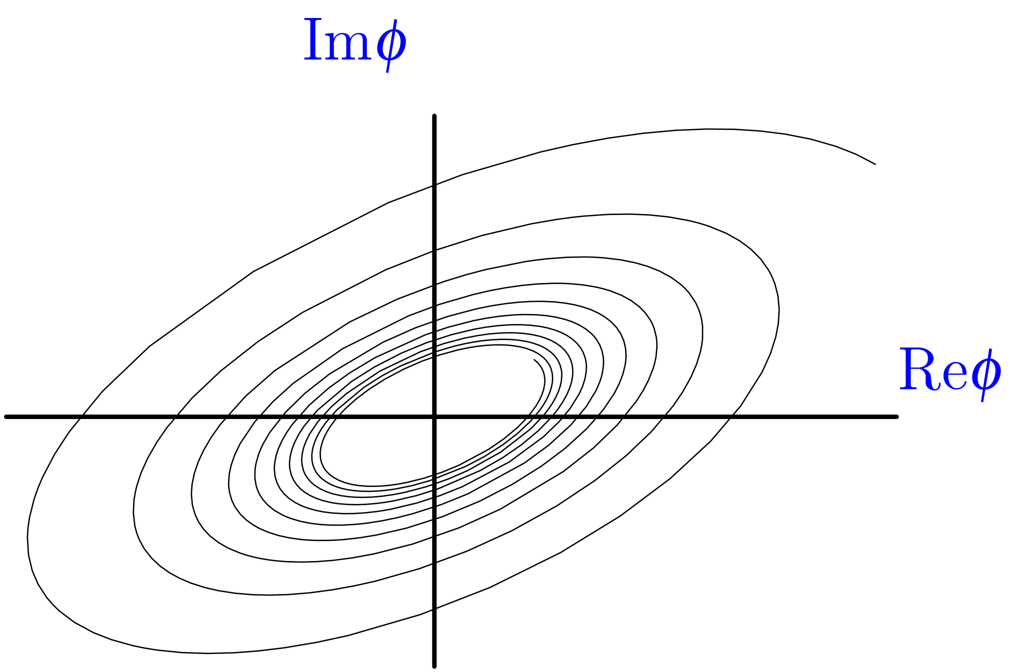
- h, λ, λ' real $\Longrightarrow$ No CP-violation yet
- CP-violation by initial conditions

Expanding Universe, homogeneous scalar field: ϕ stays constant in time until $H^2 \sim V''$.

Then ϕ starts to evolve.

Assume that initially $\mathrm{Im}\phi \neq 0$ (CP-violation by initial condition)

Because of λ'-term (baryon number violation), ϕ spirals



Spiraling scalar field carries baryon number density

$$n_{\mathrm{B}} = i\,(\partial_t \phi^* \cdot \phi - \phi^* \cdot \partial_t \phi)$$

It is gradually transmitted to quarks via $h\hat{O}\phi$ interaction

Cosmic plasma becomes baryon-asymmetric.

To conclude

- *CP*-violation, together with baryon and lepton number non-conservation, is crucial for generating baryon asymmetry, and hence for our existence.

- Kobayashi–Maskawa *CP*-violation in the Standard Model insufficient

- Relevant mechanism of *CP*-violation may be quite non-trivial

- Electroweak sphalerons are important in many (but not all) scenarios of baryogenesis.