Sphalerogenesis

Masanori Tanaka (Peking U.)

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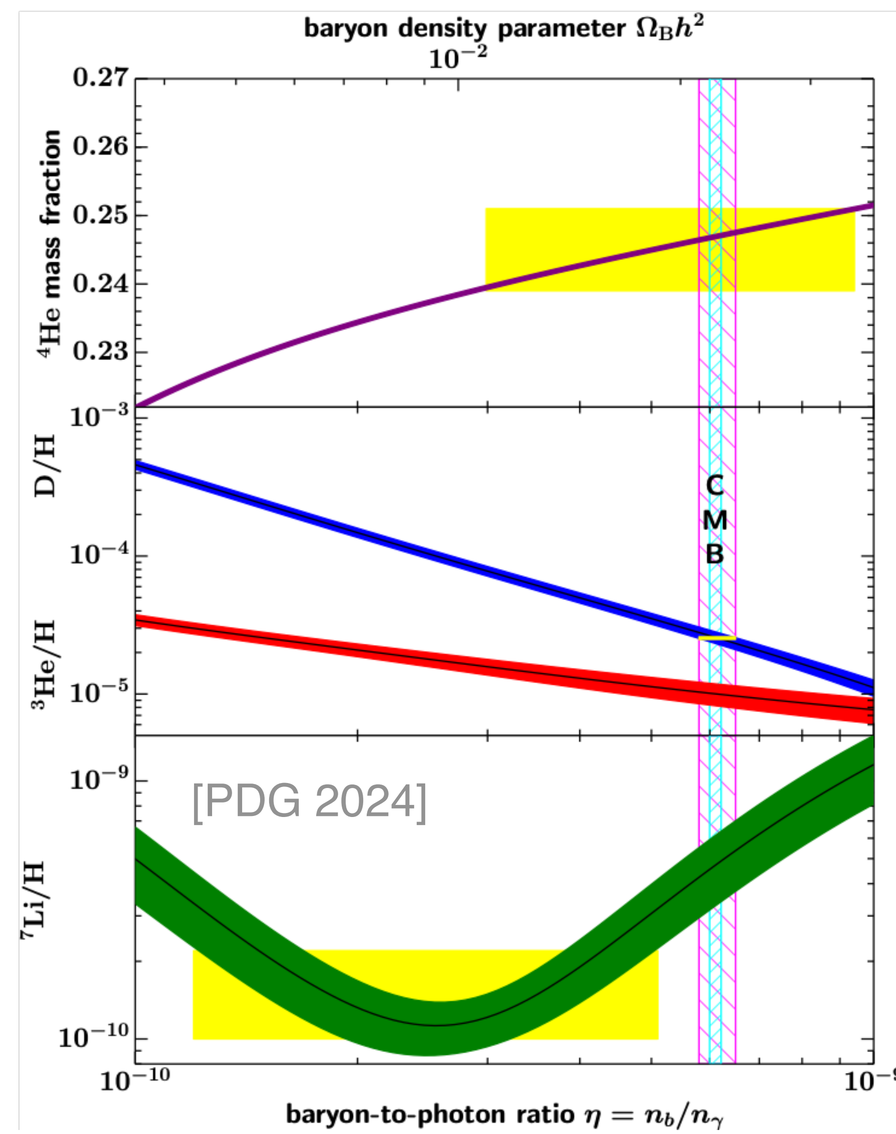
Baryon asymmetry of the Universe

- The Standard Model (SM) is consistent with collider experiments
- Unsolved problems in the SM
  - Baryon asymmetry of the Universe (BAU)
  - Existence of dark matter
- Big Bang nucleosynthesis

$$\eta_b \equiv \frac{n_b - n_{\bar{b}}}{s} = 8.41 - 8.75 \times 10^{-10}$$

- A mechanism to reproduce this asymmetry is needed
  - EW baryogenesis [Kuzmin et al., PLB155 (1985)]
  - Leptogenesis [Fukugita & Yanagida, PLB 174 (1986)]

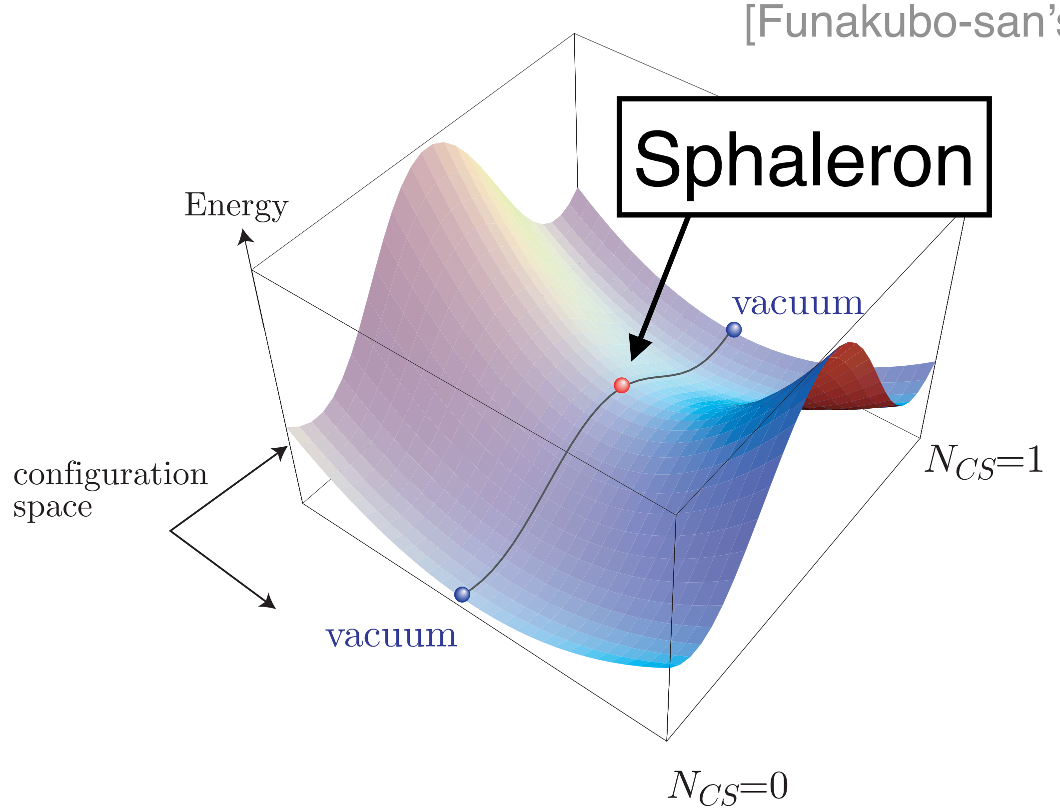


Electroweak sphaleron

[Manton: PRD 28 (1983)]

- Saddle points of field configuration space in SU(2) gauge theory
- EW sphaleron is obtained by considering a noncontractive loop
- Baryon number is violated via sphaleron processes

[Funakubo-san's slide]



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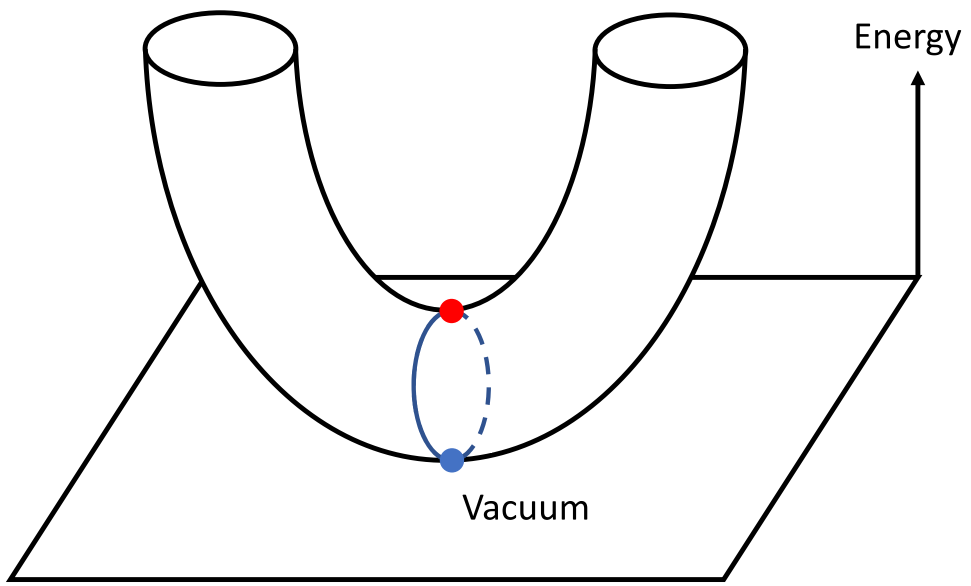


Existence of EW sphaleron is a sufficient condition for BAU?

Sphalerogenesis

[Kharzeev et al., PRD 102 (2020)]

① Baryon asymmetry : EW sphaleron processes

② CP violation : CP asymmetry in EW sphaleron processes

③ Non-thermal equilibrium : decoupling of EW sphaleron processes

Good points of this scenario

- 1st order EW phase transition is not needed
- Extensions of the SM are not required (unfortunately, incorrect)

Problems in this scenario (new parts in our work)

- Estimation of the CP asymmetry in the EW sphaleron process
- Which kinds of new physics models can realize this scenario?

Baryon number violating processes

- Topological distinct vacua are distinguished by Chern-Simons numbers

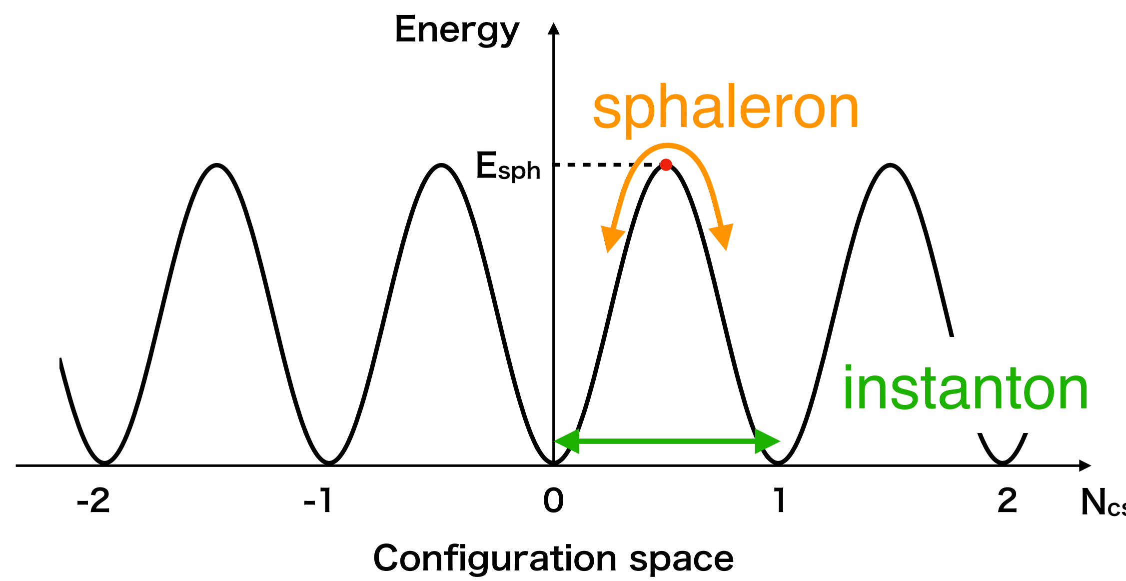
$$N_{CS}(t) = \frac{1}{16\pi^2}\int_t d^3x \epsilon^{ijk}\left(W_i^a \partial_j W_k^a + \frac{1}{3}\epsilon^{abc} W_i^a W_j^b W_k^c\right)$$

- Chiral anomaly [t'Hooft, PRL 37 (1976)]

$$\Delta(B+L) = 6\left[N_{\rm CS}(t) - N_{\rm CS}(t=-\infty)\right]$$

- Zero temperature: instanton process

$$\Gamma_{\rm instanton} \sim \exp\left[-16\pi^2/g^2\right] \ll 1$$



- Finite temperatures: sphaleron process

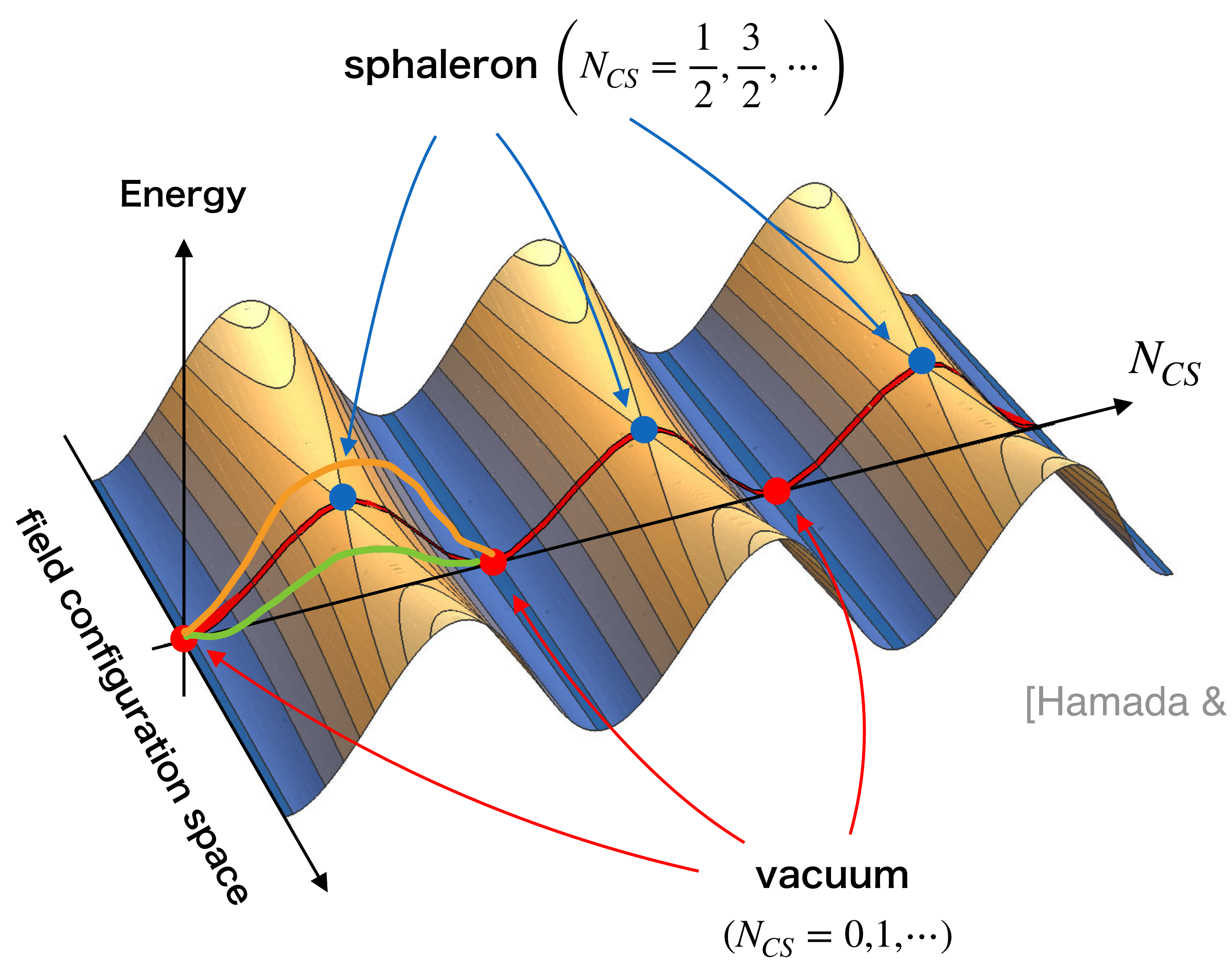
$$\Gamma_{\rm sph} \simeq A(T)\exp\left[-E_{\rm sph}(T)/T\right] \qquad E_{\rm sph}(T=0) = 1.92\frac{4\pi v}{g} \simeq 9\,{\rm TeV}$$

Sphaleron transition rate

- Sphaleron transition rate $\Gamma_{\rm sph} \simeq \underline{A(T)}\exp\left[-E_{\rm sph}(T)/T\right]$

  Fluctuations around the true sphaleron are taken into account

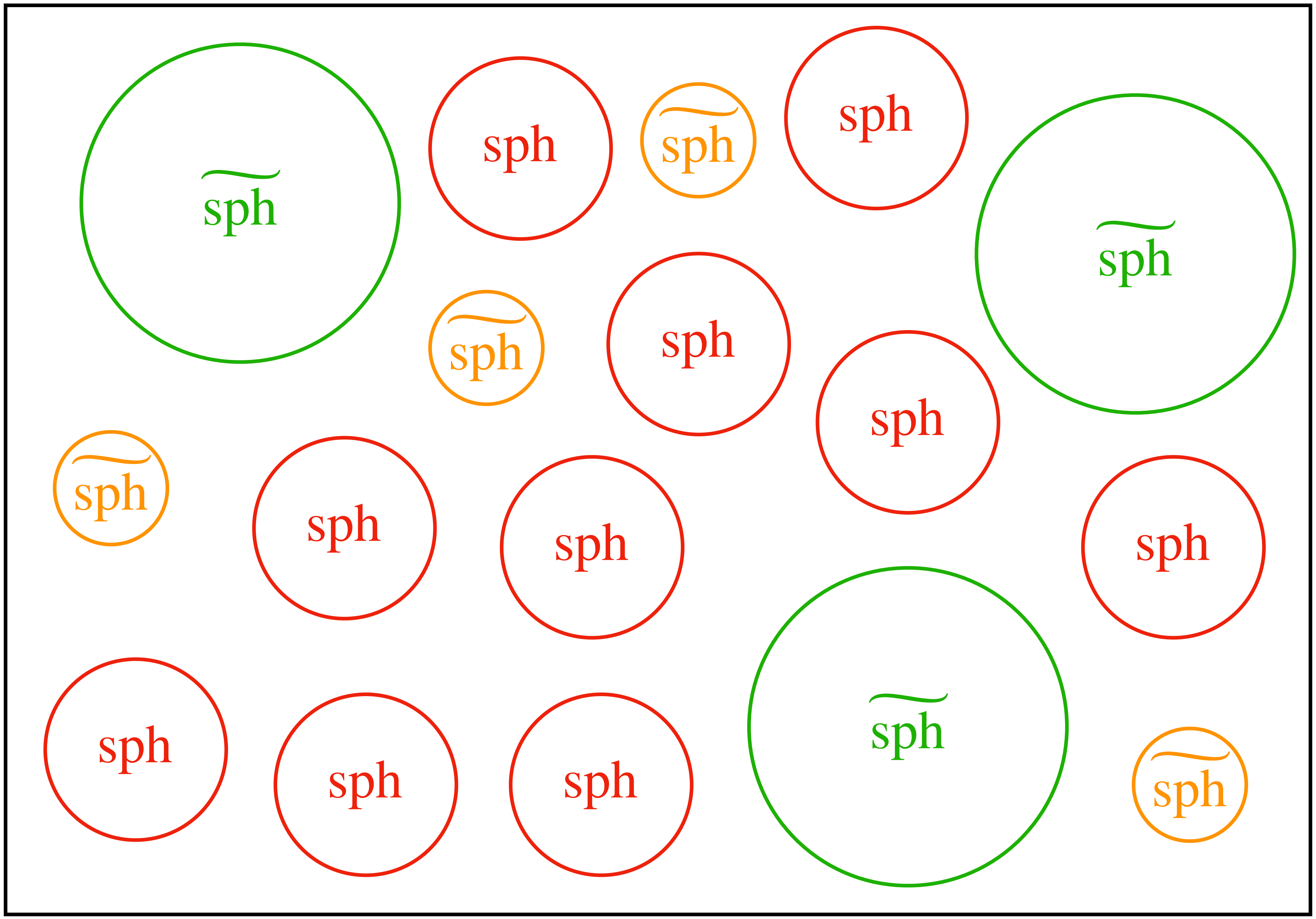
- Sphaleron-like transition processes are important in our scenario



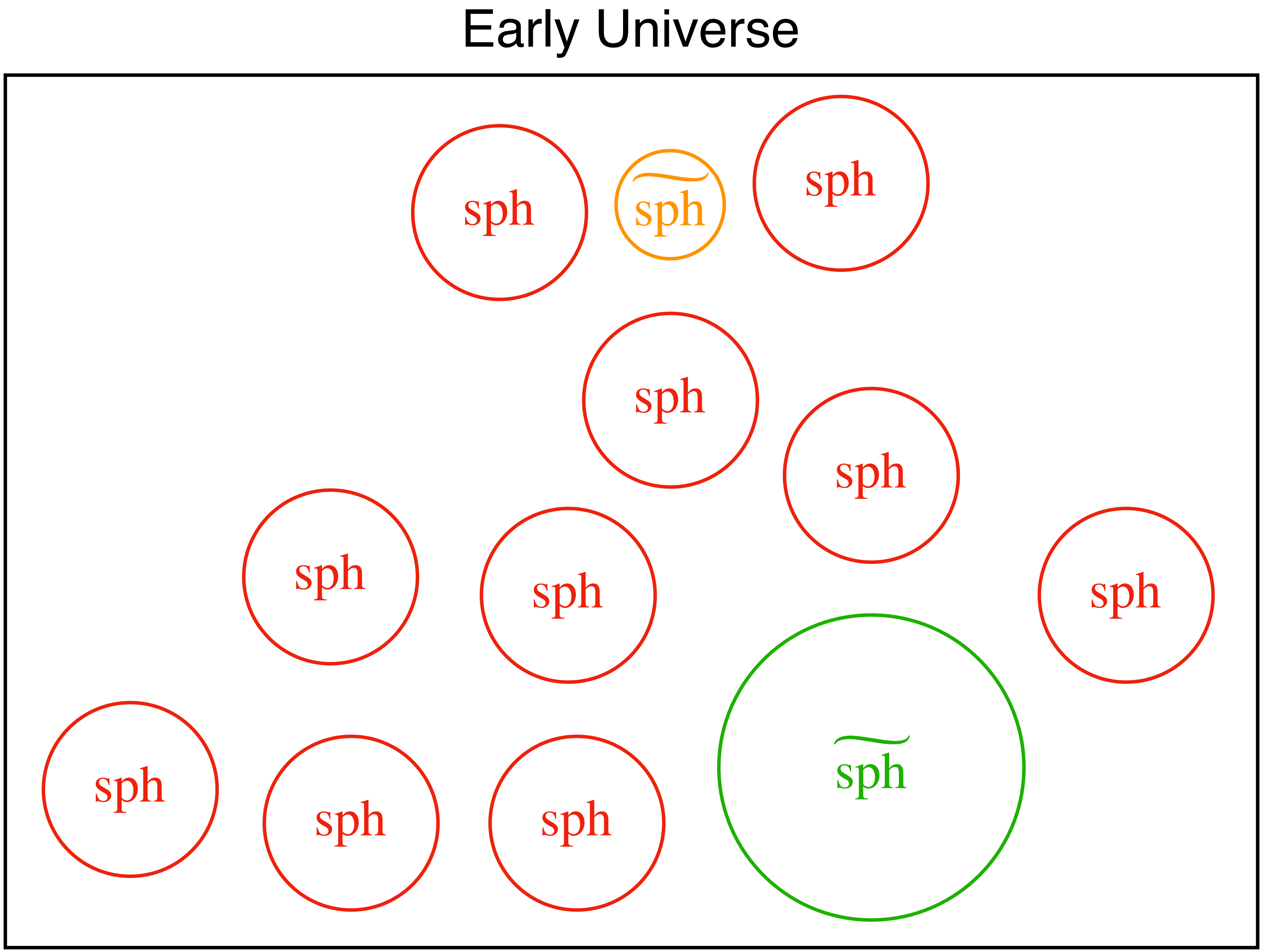
[Hamada & Kikuchi, PRD 101 (2020)]

Decoupling of sphaleron processes

Early Universe



Decoupling of sphaleron processes



Decoupling of sphaleron processes

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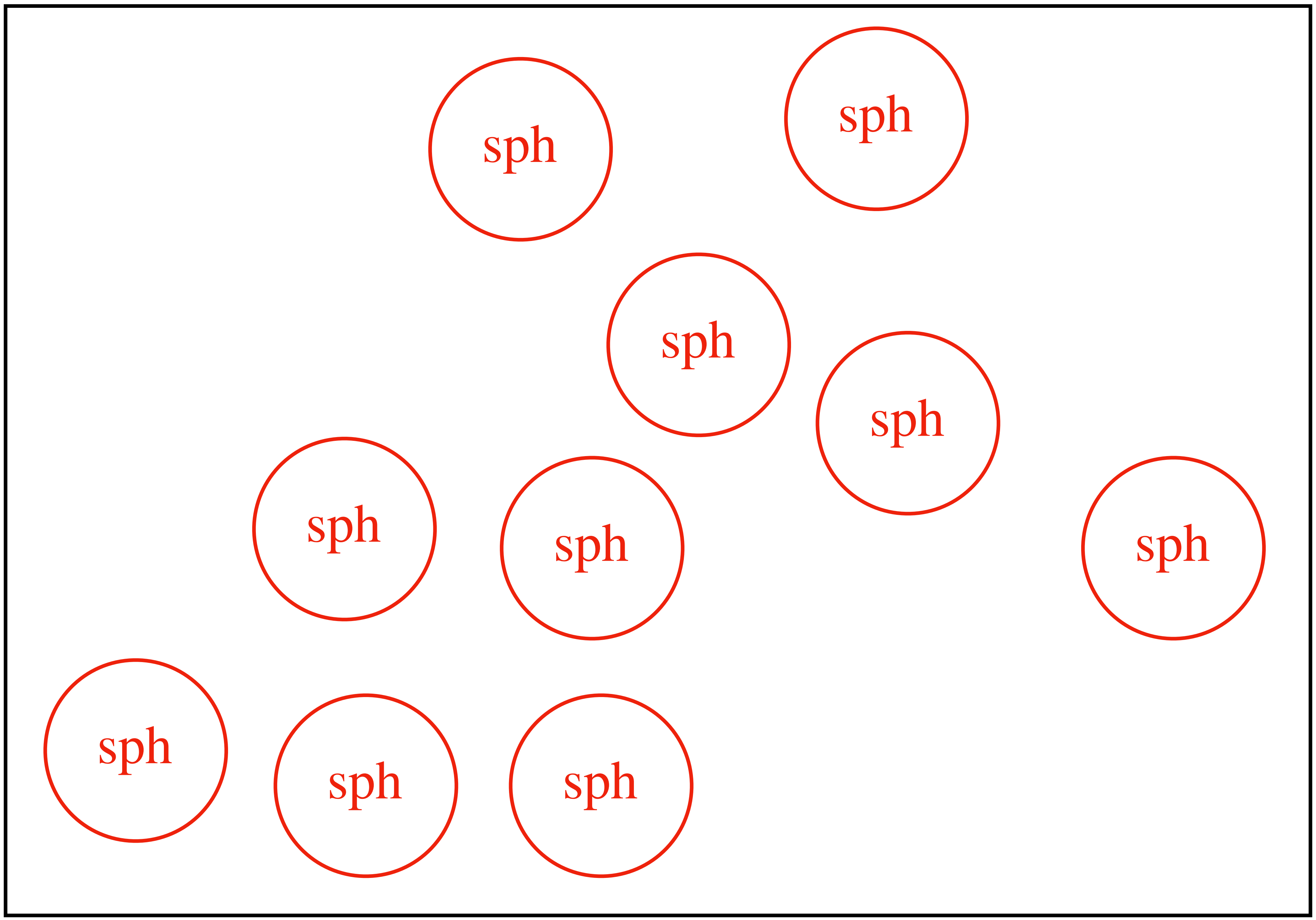

Decoupling of sphaleron processes

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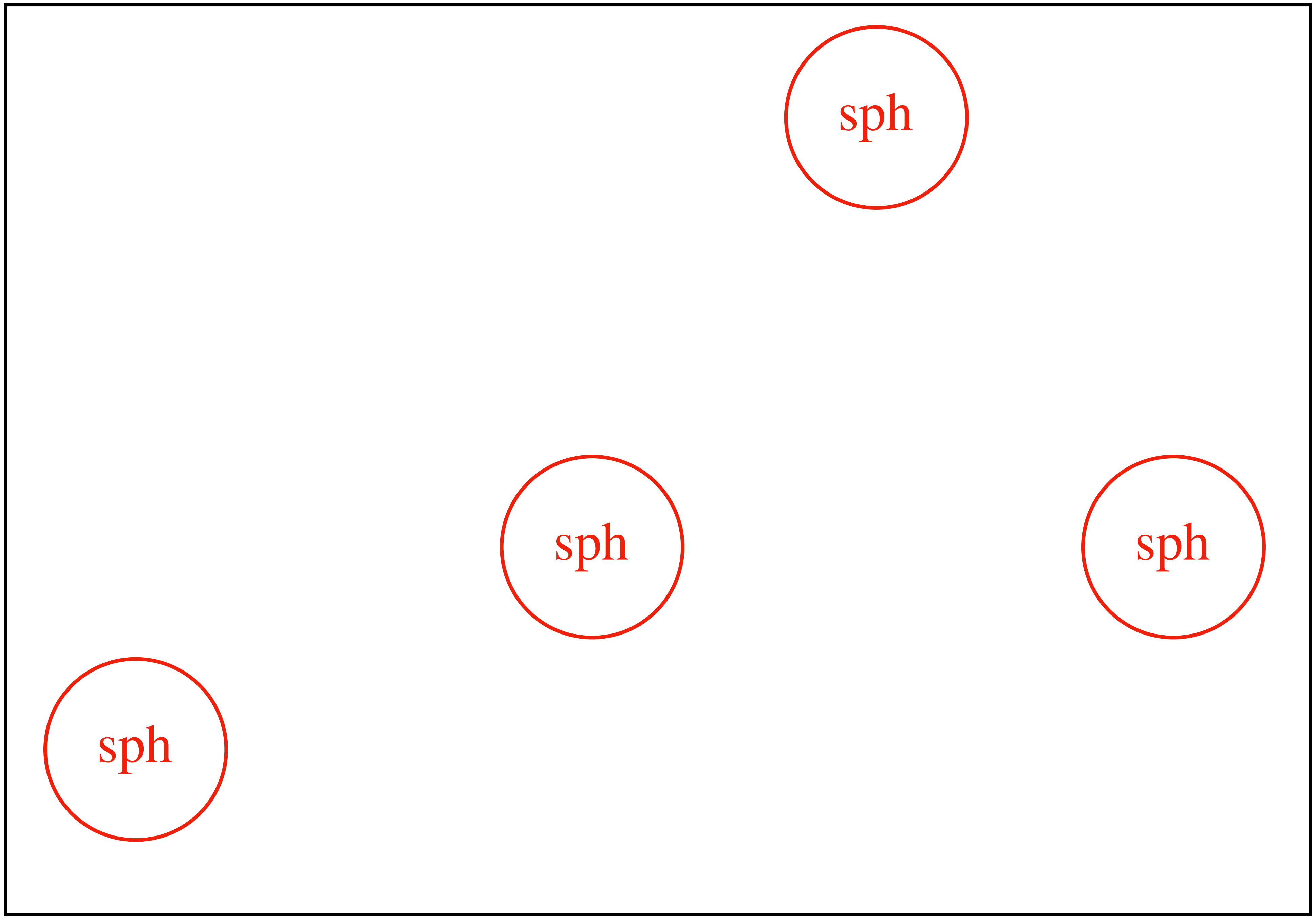


Decoupling of sphaleron processes

Early Universe

Sphalerogenesis

All Sakharov's conditions can be satisfied via sphaleron decoupling

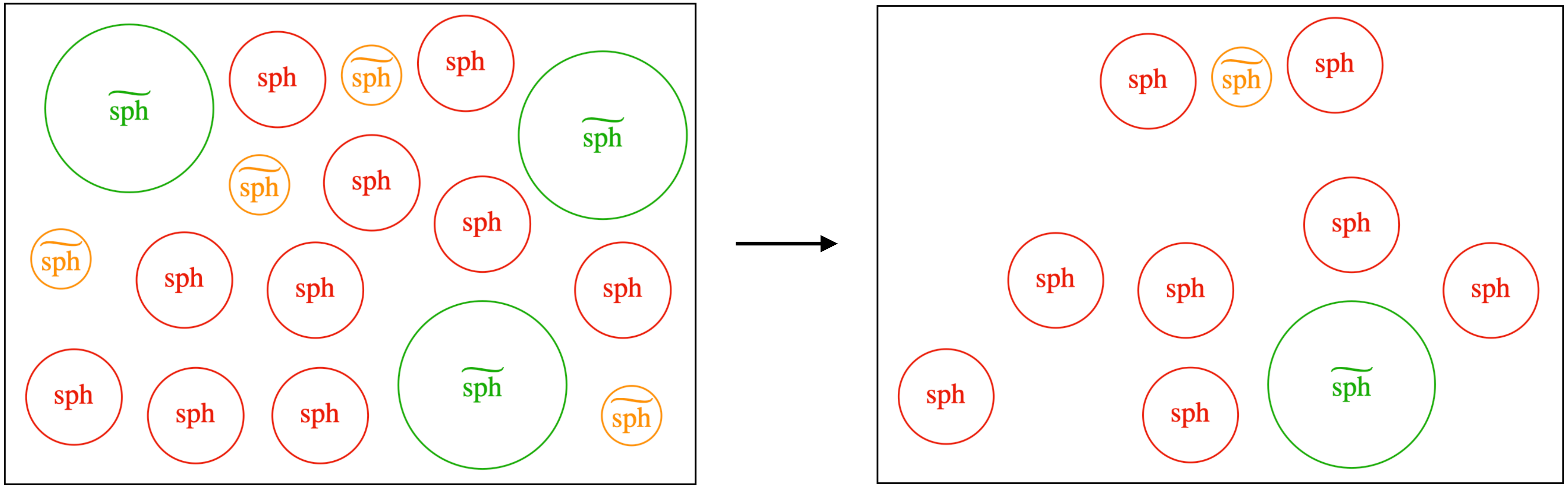
[Kharzeev et al., PRD 102 (2020)]

① Baryon asymmetry : <u>sphaleron processes</u>

② CP violation : CP asymmetry in <u>sphaleron processes</u>

③ Non-thermal equilibrium : decoupling of <u>sphaleron processes</u>

Baryon asymmetry can be produced via sphaleron decoupling



Sphaleron-like transition rate

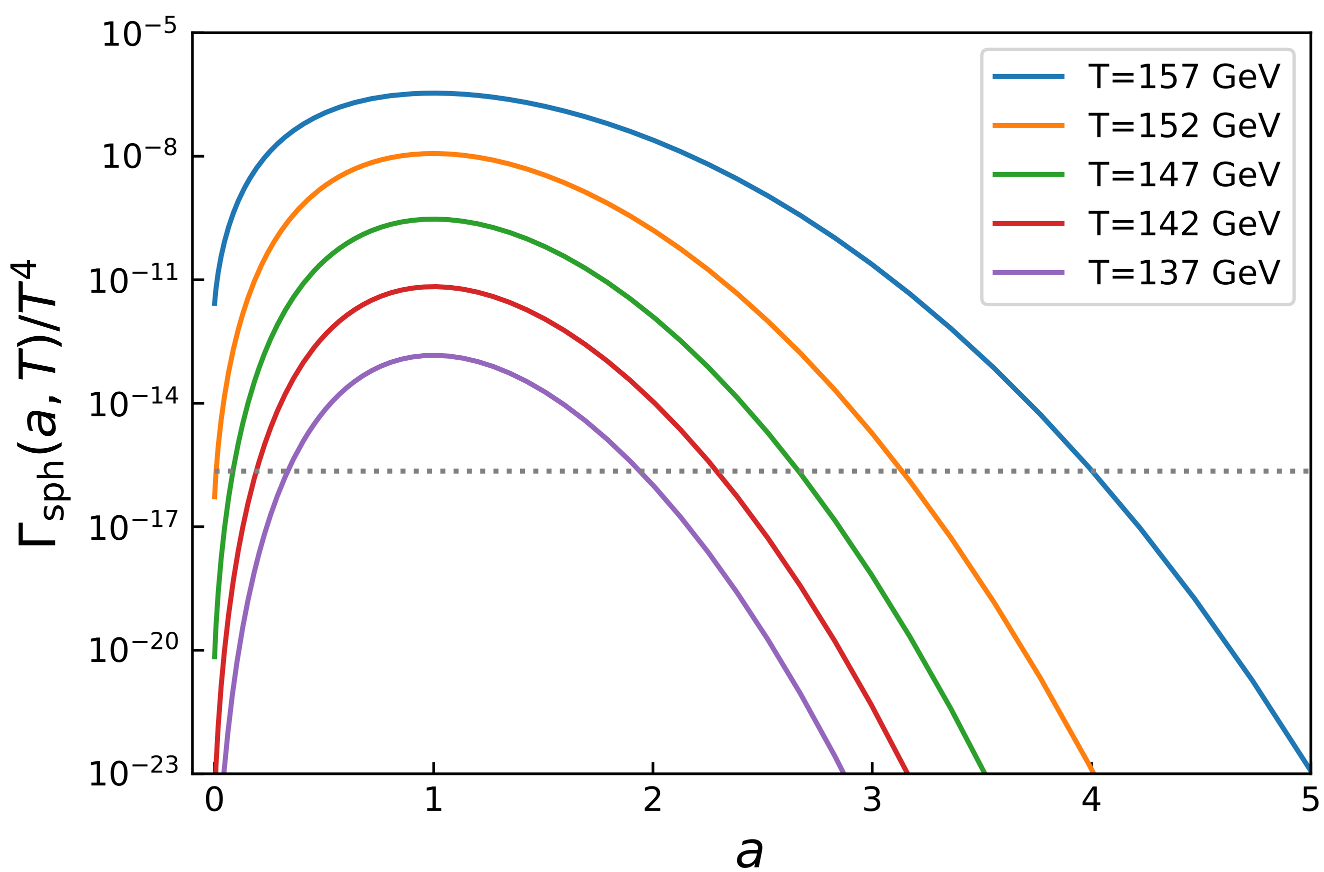
- Sphaleron-like transition rate is determined by lattice simulations

[Hong, Kamada, Yokoyama, PRD 108 (2023)]

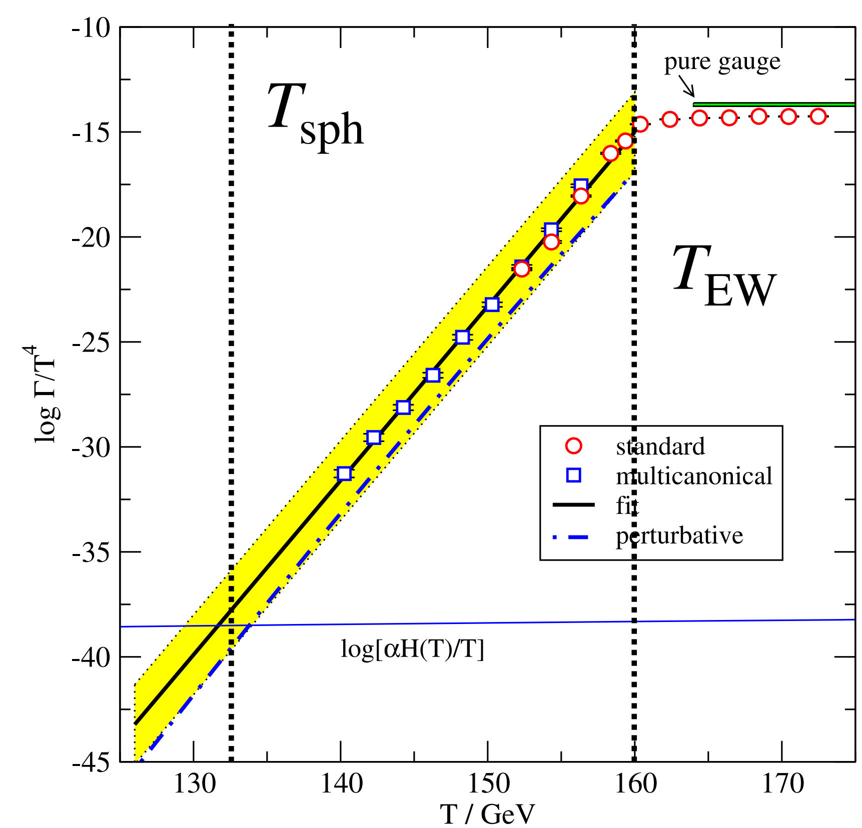
$$\Gamma_{\rm sph}(a,T) = \frac{e^{-E_{\rm sph}(a,T)}}{\int da' e^{-E_{\rm sph}(a',T)/T}} \Gamma_{\rm lattice}(T)$$

Size of sphaleron-like fields is parameterized by a

- Small/Large sphalerons are decoupled earlier than true sphalerons



$$\frac{H(T_{\rm sph})}{T_{\rm sph}}$$



[D'Onofrio et al., PRL 113 (2014)]

Two problems in sphalerogenesis

① How to estimate the CP violation (CPV) in sphaleron process?

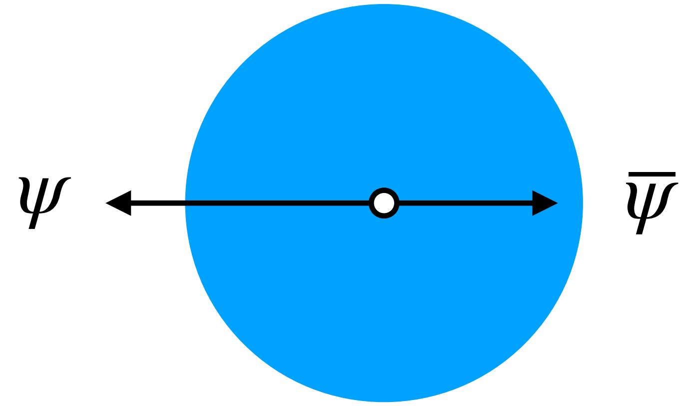
Eg) Interactions b/w emitted fermions and gauge fields

Emission rate for fermions is different from that for anti-fermions

→ CP asymmetry can be produced [Burnier & Shuryak, PRD 84 (2011); Shuryak & Zahed, arXiv: 1610.05144]

Problem

- Dynamics of fermion emission from the sphaleron process is not known
- Extension of their method to new physics is not trivial



Our new point: a new method to estimate the CPV is suggested

Two problems in sphalerogenesis

② Sphalerogenesis cannot explain the observed BAU in the SM

The SM prediction based on sphalerogenesis: $\eta_b \sim 10^{-14} \ll 10^{-10}$

[Kharzeev et al., PRD 102 (2020); Hong et al., PRD 108 (2023)]

→ New physics is needed even if we consider sphalerogenesis

Problem

- What kinds of new physics can make the CP asymmetry in the EW sphaleron process large?

Eg) EW Weinberg operator $\mathcal{O}_{\tilde{W}} = -\frac{g}{3\Lambda^2}\epsilon_{ijk}\widetilde{W}^i_{\mu\nu}W^{j\nu\rho}W^{k\mu}_{\rho}$

- How can we test the scenario of sphalerogenesis?

Good observable: Electron electric dipole moments (EDM)

Loop parameter as dynamical variable

- Ansatz for the sphaleron configuration [Manton: PRD 28 (1983)]

$$\Phi(\mu, r, \theta, \phi) = \frac{v}{\sqrt{2}} \left\{ (1 - h(r)) \begin{pmatrix} 0 \\ e^{-i\mu} \cos\mu \end{pmatrix} + h(r) U(\mu, \theta, \phi) \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right\}$$

$$W_\mu(\mu, r, \theta, \phi) = -if(r)\partial_\mu U(\mu, \theta, \phi) U^{-1}(\mu, \theta, \phi), \quad W_r = 0$$

- Non-contractive loop describes the time evolution of fields: $\mu \to \mu(t)$

Dynamical variable: $Q(t) = \mu(t)/(gv)$

[Aoyama, Goldberg & Ryzak, PRL 60 (1988);
Funakubo et al., PTP 87 (1992);
Nauta, PLB 478 (2000);
Tye & Wong, PRD 92 (2015);
Funakubo et al., arXiv: 1612.05431]

- Sphaleron action in the SM

$$S_{\text{sph}} = \int dt \left[\frac{M(Q)}{2} \left(\frac{dQ}{dt} \right)^2 - V_{\text{sph}}(Q) \right] \equiv \int L \, dt$$

Sphaleron action with CPV operators

- The operator $\mathcal{O}_{\tilde{W}} = -\frac{g}{3\Lambda^2}\epsilon_{ijk}\widetilde{W}^i_{\mu\nu}W^{j\nu\rho}W^{k\mu}_{\rho}$ causes a term with $\dot{Q}^3$

$$S_{\rm sph} = \int dt \left[\frac{M(Q)}{2}\left(\frac{dQ}{dt}\right)^2 + G(Q)\left(\frac{dQ}{dt}\right)^3 - V_{\rm sph}(Q)\right]$$

  - Dynamical evolutions along $Q > 0$ and $Q < 0$ can be different

[Nauta, PLB 478 (2000), Nauta & Arrizabalaga, NPB 635 (2002)]

CP asymmetry in sphaleron processes is produced dynamically

- Note: other dim6 operators cannot cause $\dot{Q}^3$ terms

$\mathrm{tr}\left[W_{\mu\nu}\widetilde{W}^{\mu\nu}\right]\Phi^\dagger\Phi \propto \dot{Q}$ → No contribution to the sphaleron action

We found $\mathcal{O}_{\widetilde{W}}$ is a dominant source of CP asymmetry

CP asymmetry in sphaleron process

- Hamilton formalism [Nauta, PLB 478 (2000), Nauta & Arrizabalaga, NPB 635 (2002)]

$$\mathscr{H}_{\rm sph} = \frac{1}{2M(Q)}\pi_Q^2 - \frac{G(Q)}{M^3(Q)}\pi_Q^3 + V_{\rm sph}(Q)\,, \quad \pi_Q \equiv \frac{\partial L}{\partial \dot{Q}}$$

- Mean velocity at $Q = \pm\,\overline{Q}$

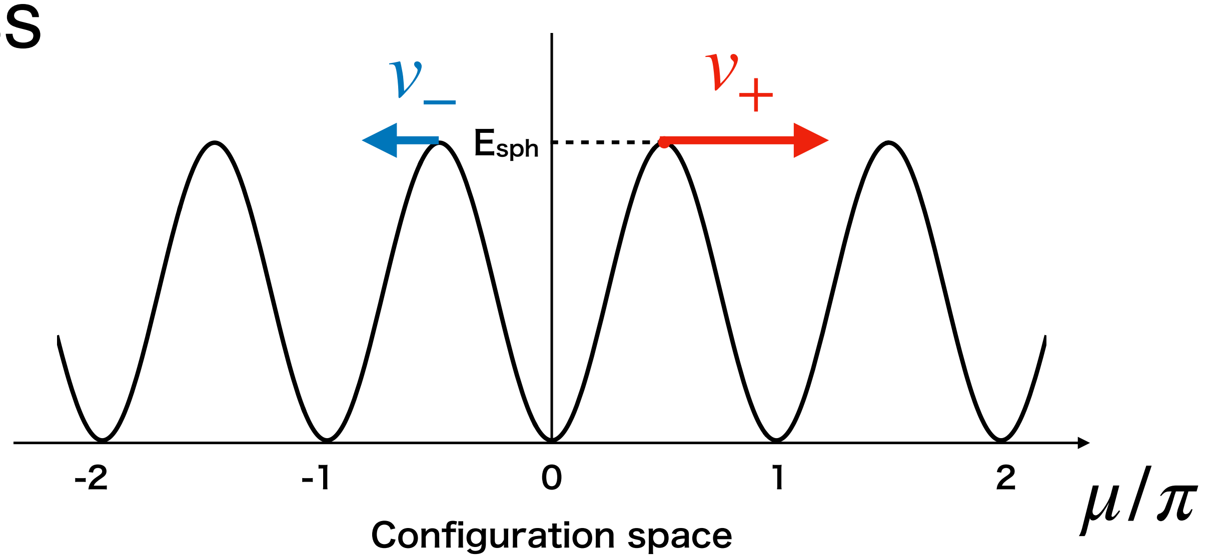
$$\langle \mathcal{O} \rangle \equiv \frac{1}{Z_0}\iint dQ d\pi_Q \mathcal{O} e^{-\mathscr{H}_{\rm sph}/T}$$

$$v_\pm(\overline{Q}) = \frac{\langle \dot{Q}\,\Theta(\pm\dot{Q})\delta(Q \mp \overline{Q})\rangle}{\langle \Theta(\pm\dot{Q})\delta(Q \mp \overline{Q})\rangle}$$

- CP asymmetry in sphaleron process

$$A_{\rm CP} = \frac{v_+(Q_{\rm sph}) - v_-(Q_{\rm sph})}{v_+(Q_{\rm sph}) + v_-(Q_{\rm sph})}$$

$$Q_{\rm sph} = \mu/(gv)\Big|_{\mu=\pi/2}$$



CP asymmetry in sphaleron process

- Precise formula of $A_{\rm CP}$ with the sphaleron ansatz

$$A_{\rm CP}(a,T) = \sqrt{\frac{8T}{gv(T)}\frac{G(Q_{\rm sph})}{[M(a,Q_{\rm sph},T)]^{3/2}}}$$

$$G(Q_{\rm sph}) = \frac{256\pi}{15}\left[\frac{v(T)}{\Lambda}\right]^2$$

- The previous estimation of $A_{\rm CP}$ could not include information of sphaleron size a and temperature [Kharzeev et al., PRD 102 (2020)]

→ Our scheme is more reasonable for new physics models

- However, our formalism does not work well in the SM

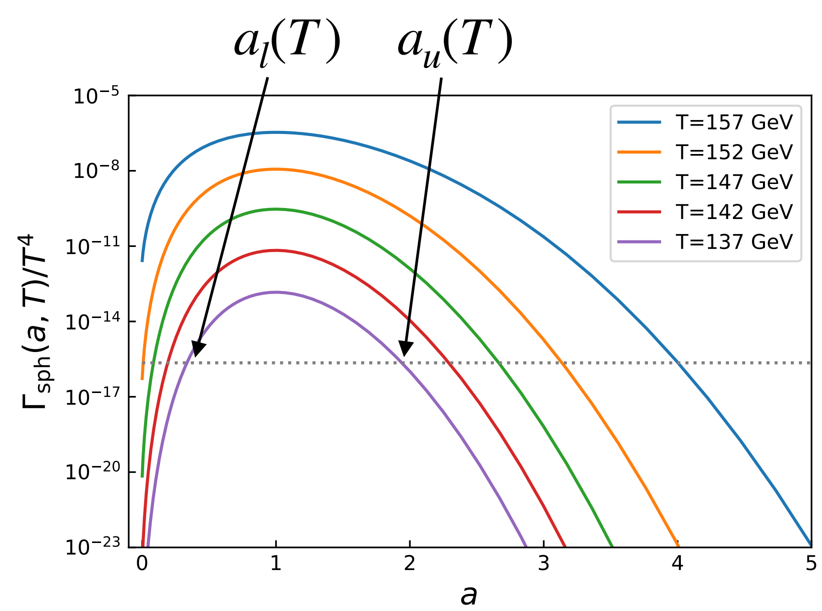
∵ CP-violating higher-order operators related to CKM phase is only applicable when $T < 5\,\mathrm{GeV}$ [Brauner, Taanila, Tranberg &Vuorinen, JHEP 11 (2012)]

Boltzmann equation

[Hong, Kamada, Yokoyama, PRD 108 (2023)]

- Boltzmann equation for baryon asymmetry

$$-HT\frac{dn_B}{dT} + 3Hn_B = -\Gamma_B(T)n_B + P(T)\,,$$



- Source term $P(T)$ and washout term $\Gamma_B(T)$

$$P(T) = \begin{cases} \int_{a_{\min}}^{a_l(T)} da\,\widetilde{\Gamma}_{\rm sph}(a,T) + \int_{a_u(T)}^{a_{\max}} da\,\widetilde{\Gamma}_{\rm sph}(a,T) & (T_{\rm sph} < T < T_{\rm EW}) \\ \Gamma_{\rm lattice}(T)\cdot A_{\rm CP}(a=1,T) & (T < T_{\rm sph}) \end{cases},$$

$$\Gamma_B(T) = \begin{cases} \frac{39}{4T^3}\int_{a_l(T)}^{a_u(T)} da\,\Gamma_{\rm sph}(a,T) & (T_{\rm sph} < T < T_{\rm EW}) \\ 0 & (T < T_{\rm sph}) \end{cases}.$$

$$a_{\min} = 0.005\,, \quad a_{\max} = 5\,, \quad \widetilde{\Gamma}_{\rm sph}(a,T) \equiv 3\Gamma_{\rm sph}(a,T)A_{\rm CP}(a,T)$$

Final results

- Deviation in the electron EDM

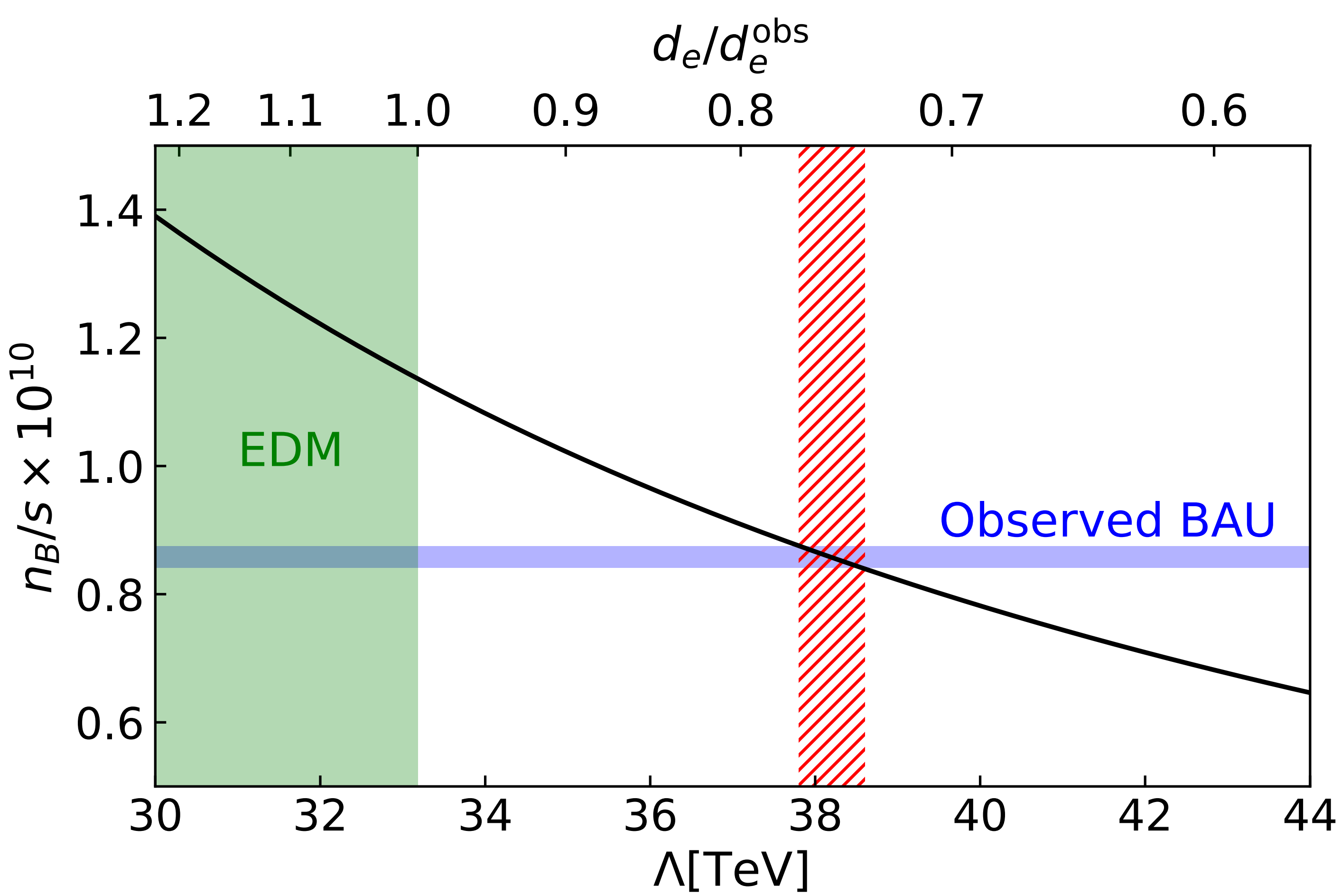
[Panico, Pomarol & Riembau, JHEP 09 (2019);
Deken & Stoffer, JHEP 10 (2019);
Kley, Theil, Venturini & Weiler, EPJC 82 (2022);
Abe, Sato & Yamanaka, JHEP 09 (2024);
Banno et al., JHEP 02 (2025)]

$$\frac{d_e}{e} = \frac{g^2 m_e}{96\pi^2\Lambda^2} = 3.1 \times 10^{-30}\,\mathrm{cm}\left(\frac{38\,\mathrm{TeV}}{\Lambda}\right)^2$$

- Current strongest constraint from JILA [Roussy et al., Science 381 (2023)]

$$\left|\frac{d_e}{e}\right| < 4.1 \times 10^{-30}\,\mathrm{cm} \equiv \frac{d_e^{\mathrm{obs}}}{e}$$

- Observed BAU can be explained if $\Lambda \simeq 38\,\mathrm{TeV}$ with satisfying the current EDM constraint from JILA



[MT, arXiv: 2505.09984]

Summary

- In sphalerogenesis, all Sakharov's conditions are simultaneously satisfied via the decay of EW sphaleron-like configurations

- Observed BAU can be explained by just adding the operator $\mathcal{O}_{\widetilde{W}}$

$$\mathcal{O}_{\widetilde{W}} = -\frac{g}{3\Lambda^2}\epsilon_{ijk}\widetilde{W}^i_{\mu\nu}W^{j\nu\rho}W^{k\mu}_{\rho}$$

  - No first order EW phase transition
  - No new fields and particles

Sphalerogenesis is a minimal baryogenesis

- The BAU can be explained while evading restrictions from electron EDM measurements if $\Lambda \simeq 38\,\mathrm{TeV}$

  - 73% improvement of EDM measurements is required
  - Completely testable at forthcoming EDM measurements