Nikhef

Radboud Universiteit

BARYOGENESIS

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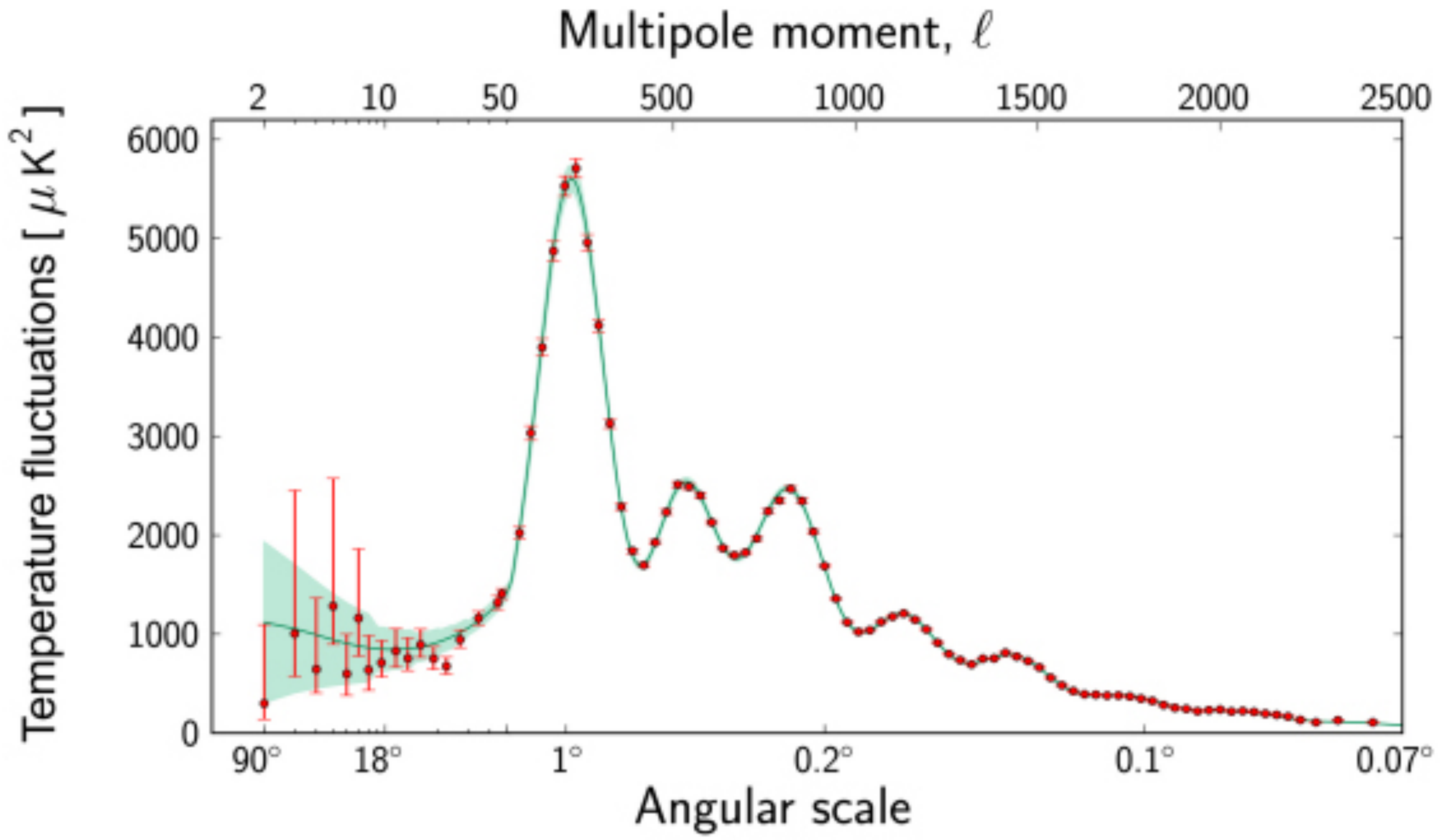
DRSTP June 2023

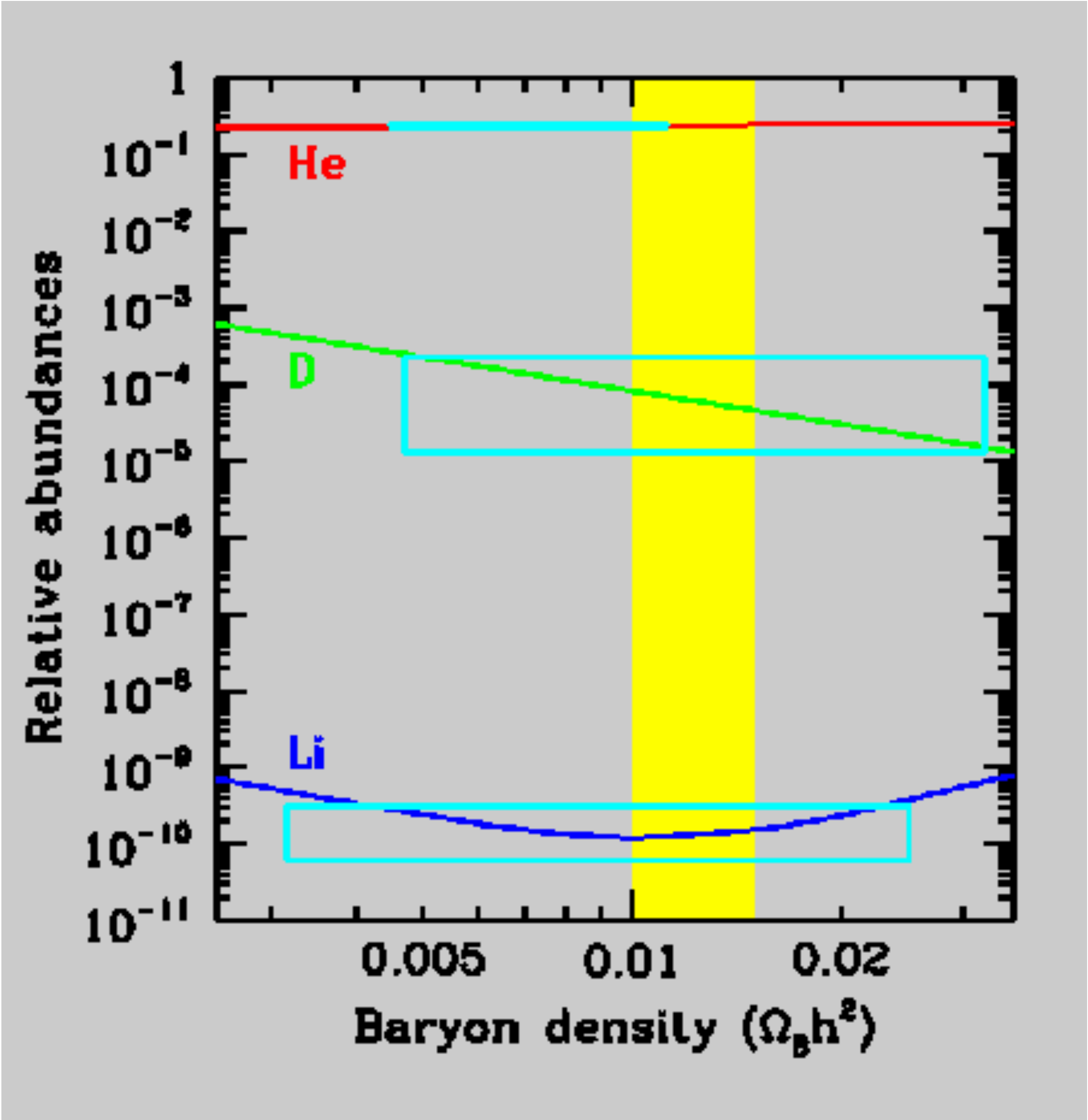
Why is everything made out of matter?

Why is everything made out of matter?

$$Y_b = \frac{n_b - n_{\bar{b}}}{s} \sim 10^{-10}$$



cosmic microwave background



nucleosynthesis

BARYOGENESIS SCENARIOS

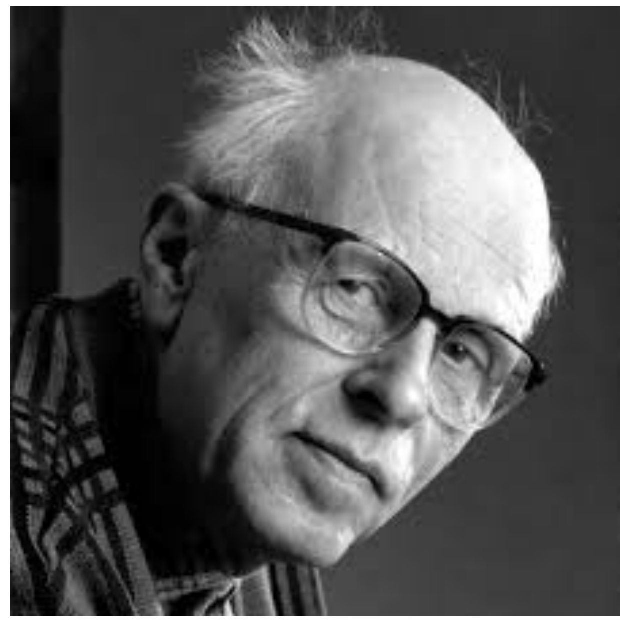
leptogenesis, Affleck-Dine baryogenesis, pangenesis, mesongenesis, Wimpy baryogenesis, electroweak baryogenesis, GUT baryogenesis, darkogenesis, cogenesis, gravitational baryogenesis, wash-in leptogenesis, axiogenesis, scotogenesis, spontaneous baryogenesis, …

PLAN

1. Sakharov conditions
2. Leptogenesis
3. Electroweak baryogenesis

SAKHAROV CONDITIONS

1. Baryon number violation
2. C- and CP-violation
3. Out of equilibrium



Sakharov 1976

C AND CP VIOLATION

$$q \to \mathrm{e}^{-i\epsilon/3} q$$

$$\bar{q} \to \mathrm{e}^{i\epsilon/3} \bar{q}$$

$\Rightarrow$ leaves $\mathcal{L}_{\mathrm{SM}}$ invariant

Noether:

baryon number

$$\partial_\mu j_B^\mu = \partial_\mu \frac{1}{3} \sum_q \bar{q} \gamma^\mu q = 0 \quad \Rightarrow \quad B = \int \mathrm{d}^3 x \, \frac{1}{3} \sum_q \bar{q} \gamma^0 q$$

C AND CP VIOLATION

$$B = \int \mathrm{d}^3x \, \frac{1}{3} \sum_q \bar{q}\gamma^0 q$$

$$q(\vec{x},t) \xrightarrow{P} \gamma^0 q(-\vec{x},t) \qquad q(\vec{x},t) \xrightarrow{C} -i\gamma^2 q^*(\vec{x},t)$$

$$q^\dagger(\vec{x},t)q(\vec{x},t) \xrightarrow{P} q^\dagger(-\vec{x},t)q(-\vec{x},t)$$

$$q^\dagger(\vec{x},t)q(\vec{x},t) \xrightarrow{C} (-i\gamma^2 q)^T(-i\gamma^2 q^*) = q^T q^* = (q^\dagger q)^T = -q^\dagger(\vec{x},t)q(\vec{x},t)$$

$$B \xrightarrow{P} B \quad \& \quad B \xrightarrow{C} -B$$

B odd under C and CP

OUT OF EQUILIBRIUM

$$\langle B(t)\rangle = \mathrm{Tr}(\mathrm{e}^{-\mathrm{H/T}}\mathrm{B(t)}) = \mathrm{Tr}(\mathrm{e}^{-\mathrm{H/T}}\mathrm{e}^{-\mathrm{iHt}}\mathrm{B(0)e^{iHt}}) = \langle \mathrm{B(0)}\rangle$$

time-independent in thermal equil.

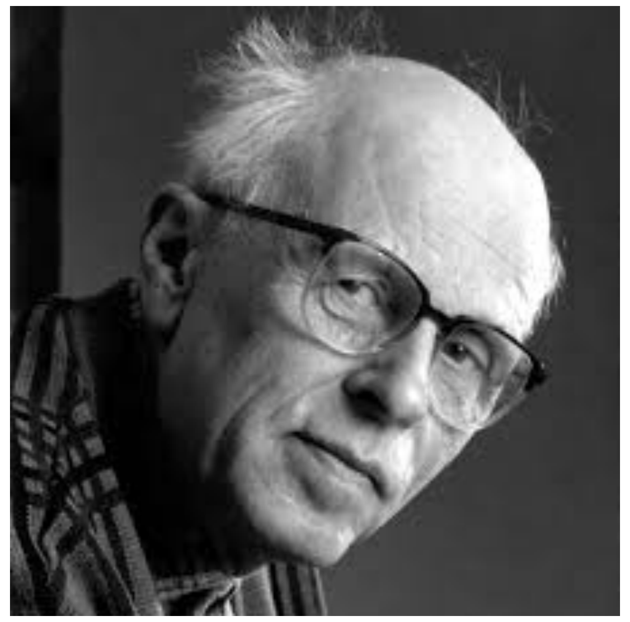
B even under $t \rightarrow -t$ and odd under $\Theta = \mathrm{CPT}$

$$\langle B(t)\rangle = \mathrm{Tr}(\Theta\Theta^{-1}\mathrm{e}^{-H/T}B(0)\rangle = \mathrm{Tr}(\mathrm{e}^{-H/T}\Theta^{-1}B(0)\Theta\rangle = -\langle B(t)\rangle$$

$$\Rightarrow \boxed{\langle B(t)\rangle = 0}$$

SAKHAROV CONDITIONS IN THE STANDARD MODEL

1. Baryon number violation
2. C- and CP-violation
3. Out of equilibrium



Sakharov 1976

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BARYON NUMBER VIOLATION IN THE SM

’t Hooft 1976

path integral measure not invariant under $U(1)_B$ and $U(1)_L$

$$\partial_\mu J^\mu_B = \partial_\mu J^\mu_L = \frac{n_F}{32\pi^2}\left(g^2 W^a_{\mu\nu}\tilde{W}^{a\mu\nu} + g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right) = \partial_\mu K^\mu$$

vacuum pure gauge at infinity $\vec{W}(\vec{x}) = \frac{i}{g}U(\vec{x})\vec{\nabla}U(\vec{x})^{-1}$ $\vec{B} = 0$

$S^3 \to S^3$ labeled by winding number N_{cs}

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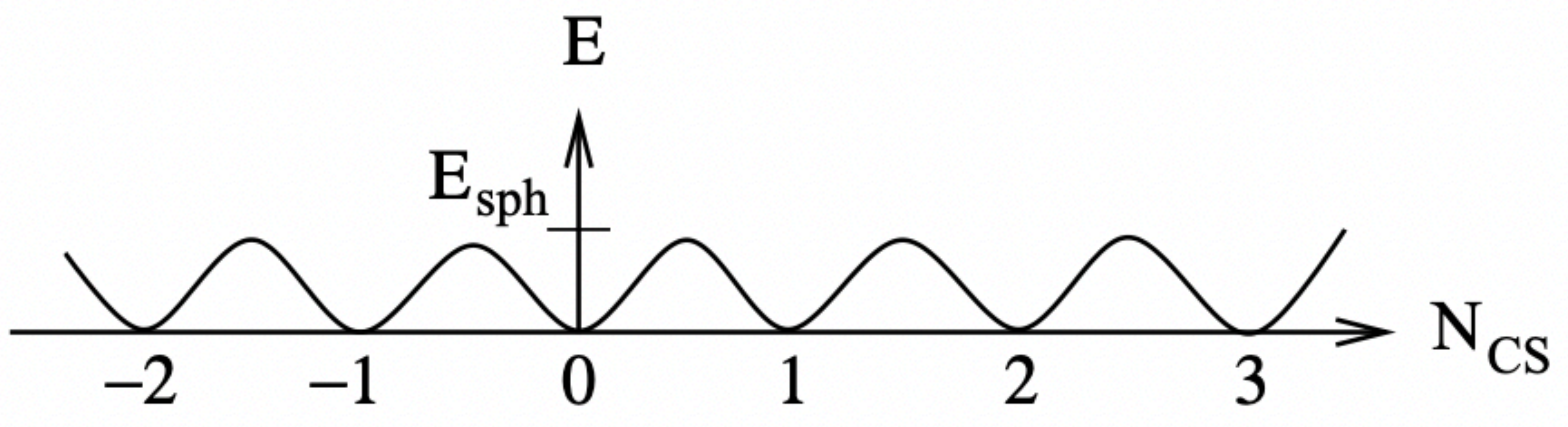
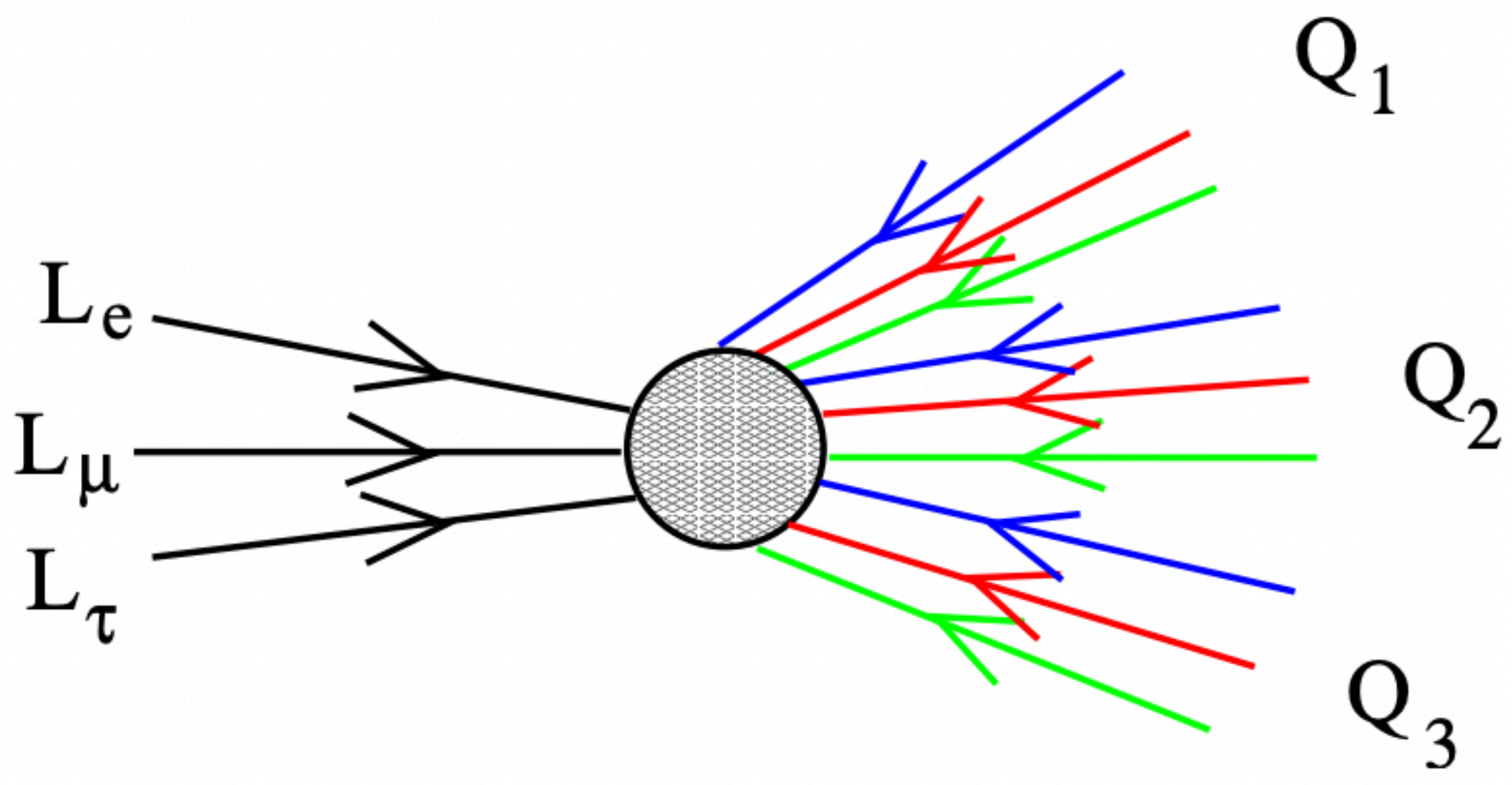
BARYON NUMBER VIOLATION IN THE SM

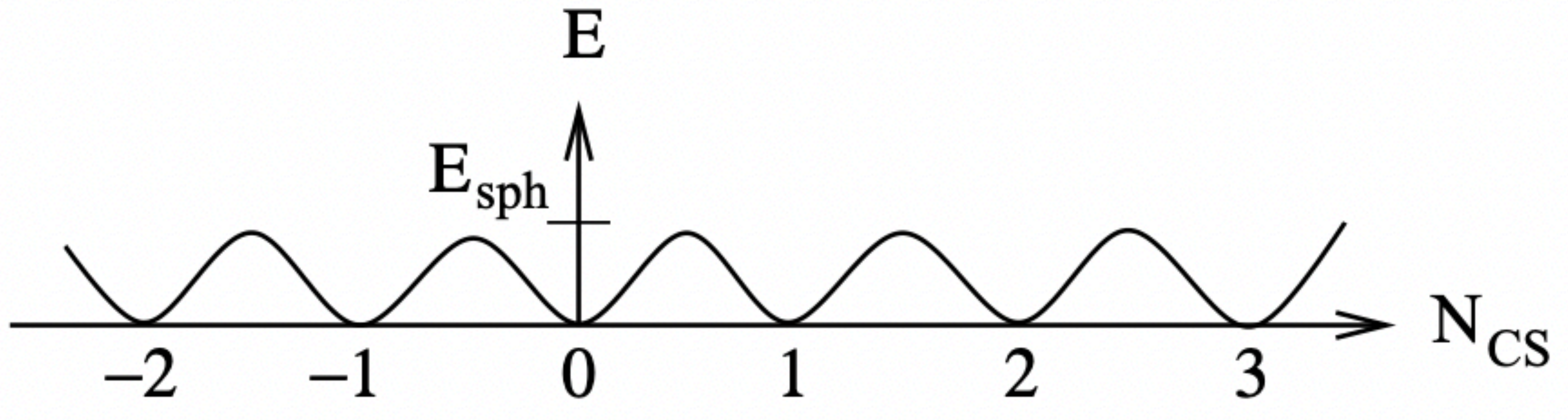


$$\Delta B = \Delta L = n_F \Delta N_{cs}$$



$$u + d \to \bar{d} + 2\bar{s} + \bar{c} + 2\bar{b} + \bar{t} + \bar{\nu}_e + \bar{\nu}_\mu + \bar{\nu}_\tau$$

BARYON NUMBER VIOLATION IN THE SM



$$E_{\rm sph} \sim 4M_W/\alpha_W$$

$$\frac{\Gamma}{V} \sim \begin{cases} \mathrm{e}^{-8\pi^2/g^2}, & T \ll m_W \\ \mathrm{e}^{-E_{\rm sph}/T}, & T \sim m_W \\ T^4, & T \gg m_W \end{cases}$$

C AND CP VIOLATION IN THE SM

weak interactions violate C

CP violation from phase in CKM matrix and QCD θ angle $\mathcal{L} \supset \theta \frac{g_s^2}{32\pi^2} F^{\mu\nu} \tilde{F}_{\mu\nu}$

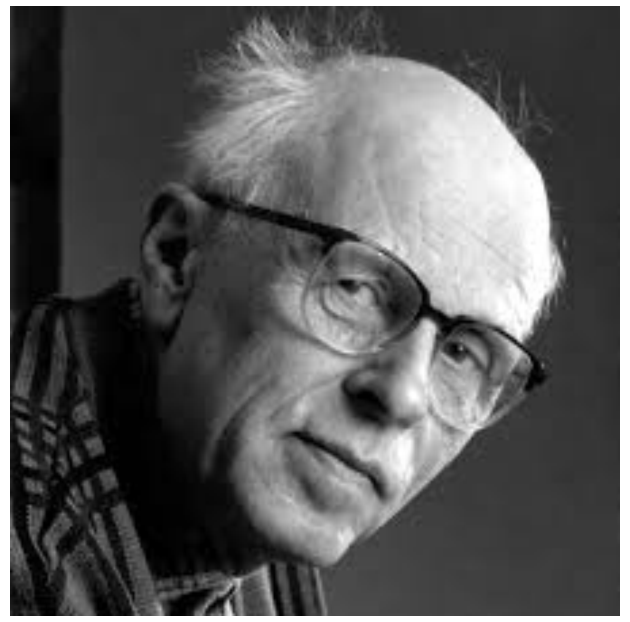
↓ ↓

Jarlskog invariant $\frac{J_{\rm CP}}{T_{\rm EW}^{12}} \sim 10^{-20}$

$\theta < 10^{-10}$ EDM of neutron

too small!

SAKHAROV CONDITIONS IN THE STANDARD MODEL



Sakharov 1976

sphalerons
B+L broken en B-L conserved

1. Baryon number violation ✔
2. C ✔- and CP-violation ✗
3. Out of equilibrium ✗

new ~~CP~~ sources

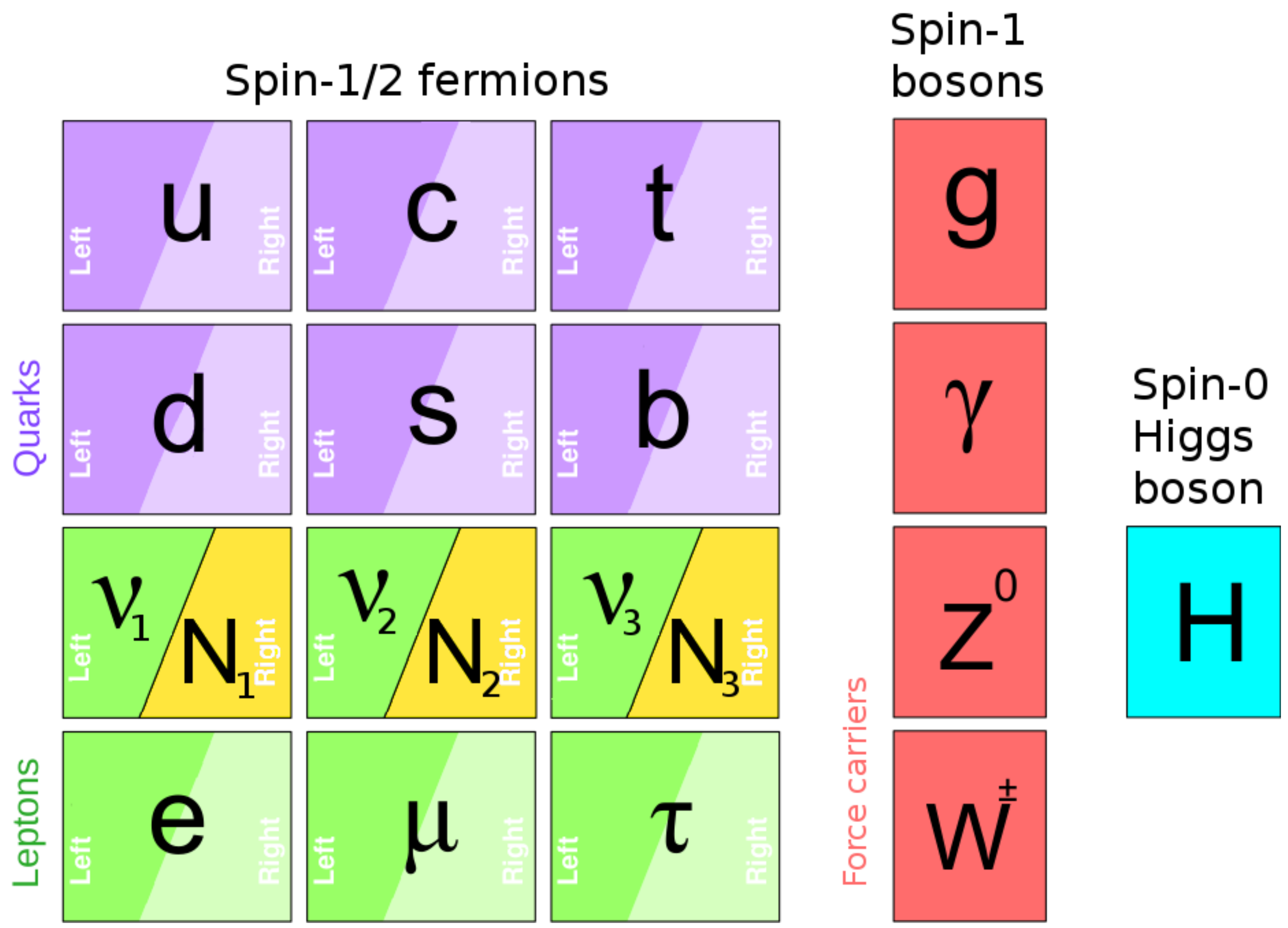
new dynamics

New physics beyond SM!

PLAN

1. Sakharov conditions
2. **Leptogenesis**
3. Electroweak baryogenesis

LEPTOGENESIS



1. Baryon number violation: majorana mass for N_i breaks L
2. C- and CP-violation: new phase in neutrino yukawa couplings
3. Out of equilibrium: production/decay of N_i

NEUTRINO MASS

$$\nu_L = \begin{pmatrix} \psi_L \\ 0 \end{pmatrix} \xrightarrow{C} \nu_L^c = \begin{pmatrix} 0 \\ (i\sigma^2 \psi_L^*) \end{pmatrix}$$

$$\psi \xrightarrow{C} -i\gamma^2\psi^* \qquad \Rightarrow \qquad \nu_R = \begin{pmatrix} 0 \\ \psi_R \end{pmatrix} \xrightarrow{C} \nu_R^c = \begin{pmatrix} (-i\sigma^2 \psi_R^*) \\ 0 \end{pmatrix}$$

ν_L, ν_R^c are left-handed, ν_R, ν_L^c are right-handed

dirac mass

$$m_D \bar{\nu}_L \nu_R + \text{h.c.} = \frac{1}{2} \begin{pmatrix} \overline{\nu_L^c} & \overline{\nu_R} \end{pmatrix} \begin{pmatrix} 0 & m_D^T \\ m_D & 0 \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} + \text{h.c.}$$

majorana mass

$$\frac{1}{2} m_R \overline{\nu_R^c} \nu_R + \text{h.c.} = \frac{1}{2} \begin{pmatrix} \overline{\nu_L^c} & \overline{\nu_R} \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} + \text{h.c.}$$

NEUTRINO MASS

$$\mathcal{L} \supset -\bar{l}_L Y_\nu \tilde{H}\, \nu_R - \tfrac{1}{2} m_R \overline{\nu_R^c} \nu_R + \text{h.c.}$$

$$M = \begin{pmatrix} 0 & m_D \\ m_D^T & m_R \end{pmatrix}$$

take diagonal

diagonalize mass matrix

$$M_D = V^\dagger M U \quad \Rightarrow \quad M_D = M_D^T = V^\dagger M U = U^T M V^* \quad \Rightarrow \quad U = V^*$$

$$U = \begin{pmatrix} 1 & \theta \\ -\theta^\dagger & 1 \end{pmatrix} \begin{pmatrix} U_\eta & 0 \\ 0 & 1 \end{pmatrix}$$

NEUTRINO MASS

$$\mathcal{L} \supset -\bar{l}_L Y_\nu \tilde{H}\, \nu_R - \frac{1}{2} m_R \overline{\nu_R^c} \nu_R + \text{h.c.}$$

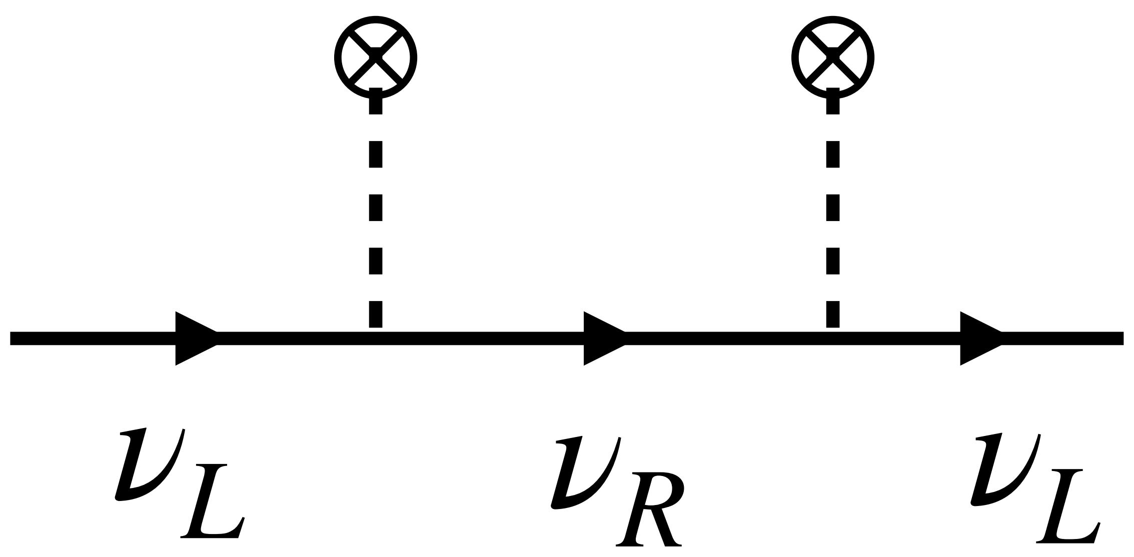
$$M = \begin{pmatrix} 0 & m_D \\ m_D^T & m_R \end{pmatrix}$$

light neutrinos

$$\eta = \eta_L + \eta_R = \nu_L + \nu_L^c - \theta(\nu_R + \nu_R^c)$$

see saw mechanism

$m_\eta =$



$$= -m_D \frac{1}{m_R} m_D^T = -\theta m_R \theta^T$$

$$\theta = m_D / m_R$$

SAKHAROV CONDITIONS IN LEPTOGENESIS

1. Baryon number violation: majorana mass for N_i breaks L
2. C- and CP-violation: new phase in neutrino yukawa couplings
3. Out of equilibrium: production/decay of N_i

BARYON NUMBER VIOLATION

$$\mathcal{L} \supset -\bar{l}_L Y_\nu \tilde{H}\, \nu_R - \frac{1}{2} m_R \overline{\nu_R^c} \nu_R + \text{h.c.}$$

$\Delta L = 2$

lepton number

$$l \to e^{-i\epsilon} l \qquad \bar{l} \to e^{i\epsilon} l$$

sphalerons

$$(B - L)_f = (B - L)_i = -L_i$$

$$(B + L)_f \sim 0 \qquad \Rightarrow \qquad B_f \sim -0.5 L_i$$

CP VIOLATION

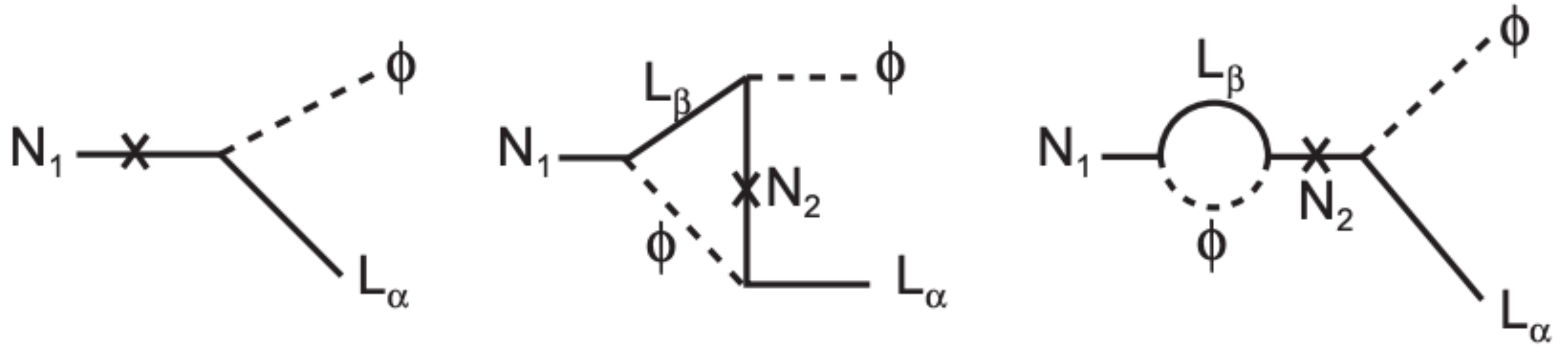
vanilla scenario $M_1 \ll M_2, M_3$

Fukugita and Yanagida 1986

$$\mathcal{L} \supset -\bar{l}_L Y_\nu \tilde{H}\, \nu_R - \tfrac{1}{2} m_R \overline{\nu_R^c} \nu_R + \text{h.c.}$$

phases

$$\epsilon_1 = \frac{\Gamma(N_1 \to lH) - \Gamma(N_1 \to \bar{l}H^*)}{\Gamma(N_1 \to lH) + \Gamma(N_1 \to \bar{l}H^*)}$$



$$\mathcal{M} = \mathcal{M}_0 + \mathcal{M}_1 = c_0 \mathcal{A}_0 + c_1 \mathcal{A}_1 \quad \Rightarrow \quad \epsilon_1 \propto \text{Im}(c_0 c_1^*) \text{Im}(\mathcal{A}_0 \mathcal{A}_1^*)$$

$$\frac{1}{p^2 - m^2 + i\epsilon} \to i\pi\delta(p^2 - m^2)$$

CP VIOLATION

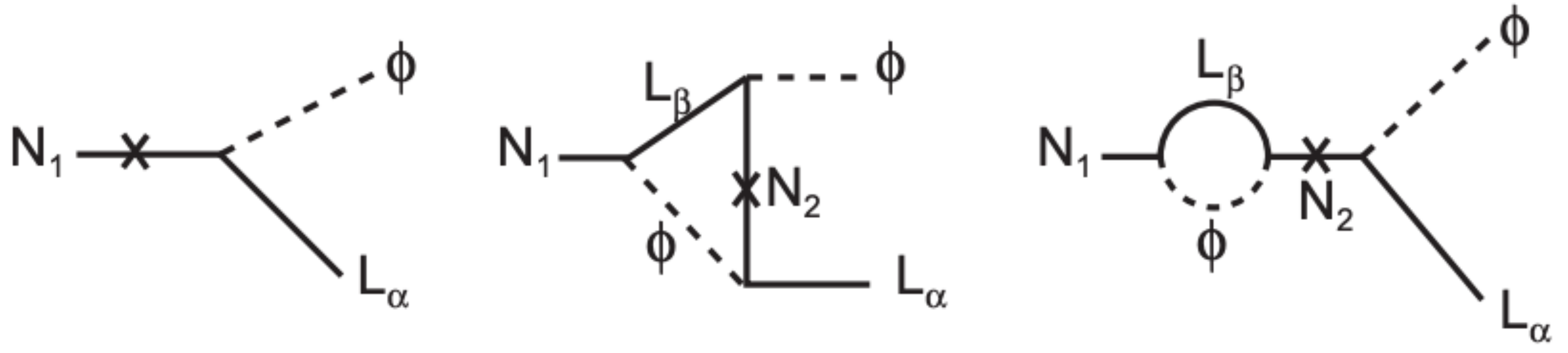
vanilla scenario $M_1 \ll M_2, M_3$

$$\mathcal{L} \supset -\bar{l}_L Y_\nu \tilde{H}\, \nu_R - \frac{1}{2} m_R \overline{\nu_R^c} \nu_R + \text{h.c.}$$

phases

$$\epsilon_1 = \frac{\Gamma(N_1 \to lH) - \Gamma(N_1 \to \bar{l}H^*)}{\Gamma(N_1 \to lH) + \Gamma(N_1 \to \bar{l}H^*)}$$

$$\sim \frac{M_1 m_\eta}{4\pi v^2}$$



scales with M_1

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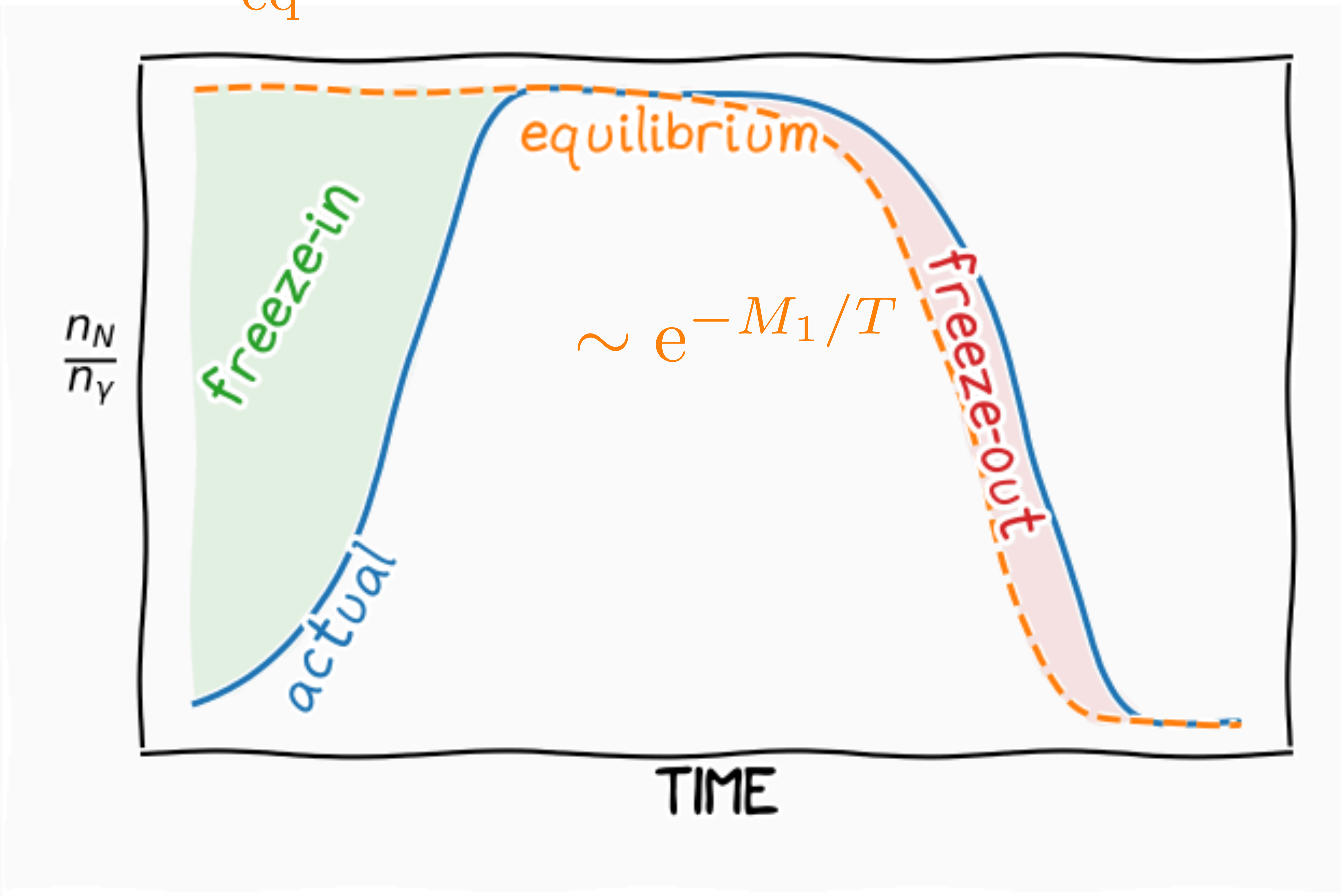
OUT OF EQUILIBRIUM DECAY

vanilla scenario $M_1 \ll M_2, M_3$

$n_{\rm eq} \sim T^3$

from Juraj Klaric



assumed $K = \frac{\Gamma_1}{H}\Big|_{T=M_1} \gtrsim 1$

SIMPLE ESTIMATE

vanilla scenario $M_1 \ll M_2, M_3$

total lepton number from decays

$$Y_b = \frac{n_b}{s} = \eta \, \frac{\epsilon_1 \, n_{N_1}^{\rm eq}}{s} \, K^{-1}$$

sphalerons $B_f = \eta L_i$

washout

$n_{N_1}^{\rm eq}/s \sim 10^{-3}$

SIMPLE ESTIMATE

vanilla scenario $M_1 \ll M_2, M_3$

$$Y_b = \frac{n_b}{s} = \eta \, \frac{\epsilon_1 \, n_{N_1}^{\mathrm{eq}}}{s} \, K^{-1} \overset{?}{\sim} 10^{-10}$$

$$M_1 \gtrsim 10^9 \text{ GeV}$$

TESTABILITY

vanilla scenario $M_1 \ll M_2, M_3$

- heavy RHN $M_1 \gtrsim 10^9\ \mathrm{GeV}$

- small mixing angle $\theta = \frac{m_D}{m_R}$

- 6 (2) phases at high energy, 3 (2) phases at low energies for $n_{\mathrm{RHN}} = 3$ (2)

LOW SCALE LEPTOGENESIS

$M_1 \sim M_2, M_3$

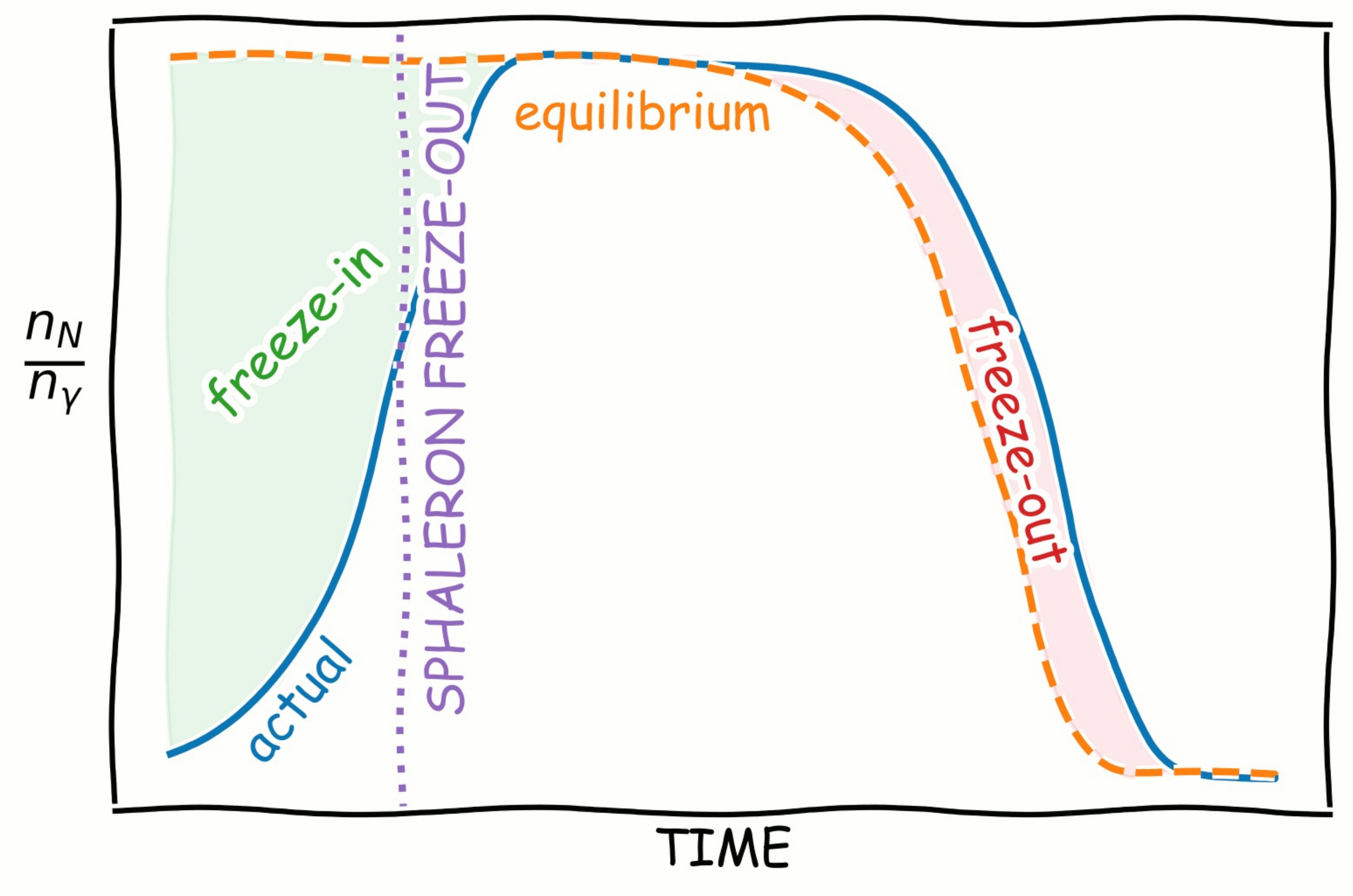
lower RHN mass

- flavor oscillations $M_1 \gtrsim 10^6 \mathrm{GeV}$
- resonant leptogenesis $M_1 \gtrsim 10^2 \mathrm{GeV}$
- ARS leptogenesis $M_1 \sim 10^{-1} - 10^2 \mathrm{GeV}$

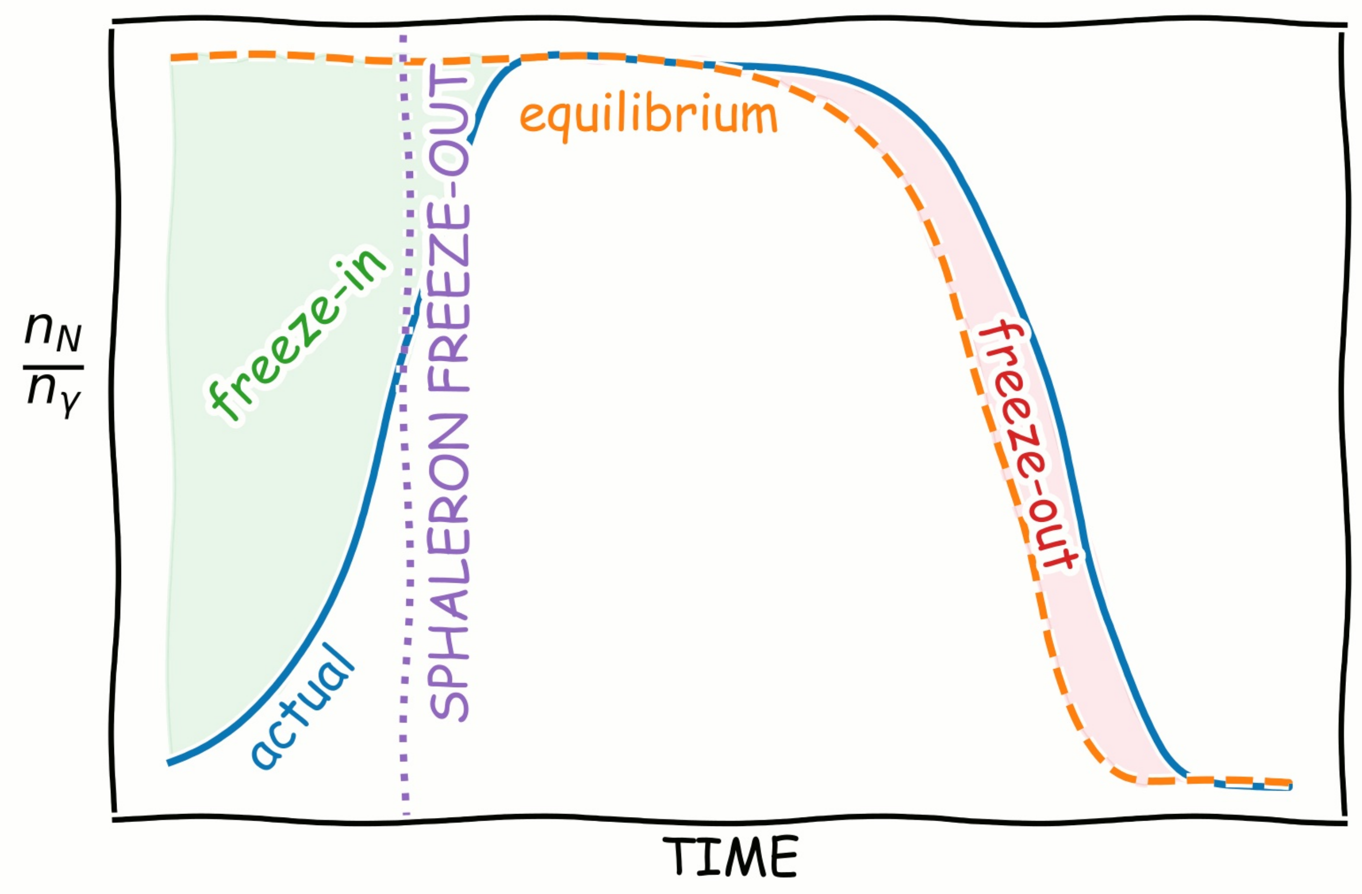
larger θ -approximate lepton number symmetry $m_\eta = -m_D m_R^{-1} m_D^T$

relate phases -zeros in the yukawa matrix

ARS LEPTOGENESIS



ARS LEPTOGENESIS



$\Gamma_1 > H \quad \& \quad \Gamma_2 < H \quad$ at $\quad T_{\rm EW}$

$L_2 \neq 0$

N_2

bath $\longrightarrow$ N_1 oscillations

$L_i = 0$

$\not{CP}$

N_1

$L_1 \neq 0$ $\longleftrightarrow$ bath $\longleftrightarrow$ $B \neq 0$

sphalerons

APPROXIMATE LEPTON SYMMETRY

RHNs combine in Dirac neutrino

$$Y = \begin{pmatrix} y_e & 0 \\ y_\mu & 0 \\ y_\tau & 0 \end{pmatrix} \qquad m_R = \begin{pmatrix} 0 & M \\ M & 0 \end{pmatrix}$$

- lepton number conserved
- degenerate RHN mass
- vanishing light neutrino mass

APPROXIMATE LEPTON SYMMETRY

RHNs combine in Dirac neutrino

$$Y = \begin{pmatrix} y_e & y'_e \\ y_\mu & y'_\mu \\ y_\tau & y'_\tau \end{pmatrix} \qquad m_R = \begin{pmatrix} \mu & M \\ M & \mu \end{pmatrix}$$

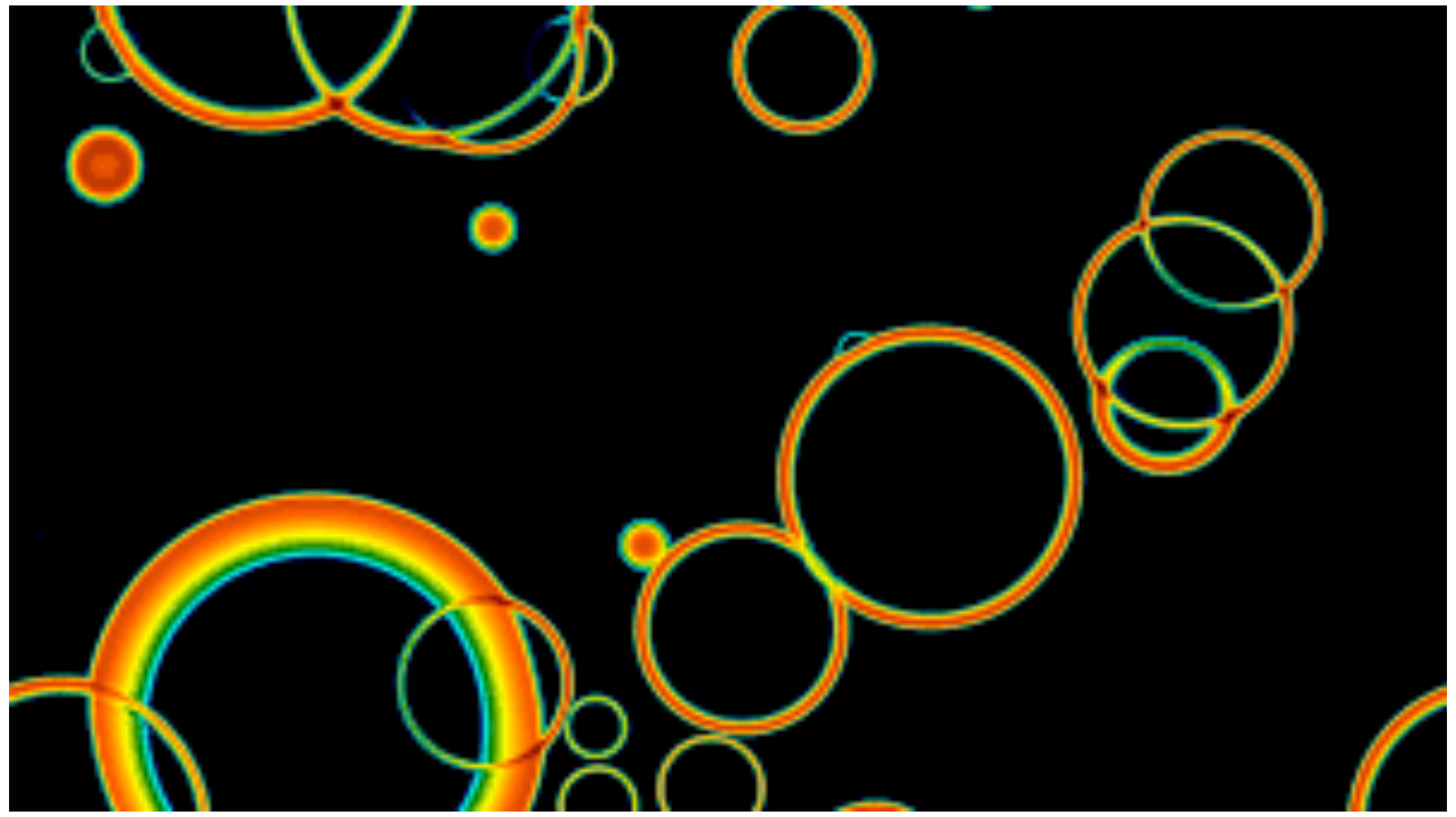
small symmetry breaking

- almost lepton number conserved
- almost degenerate RHN mass
- almost vanishing light neutrino

PLAN

1. Sakharov conditions
2. Leptogenesis
3. **Electroweak baryogenesis**

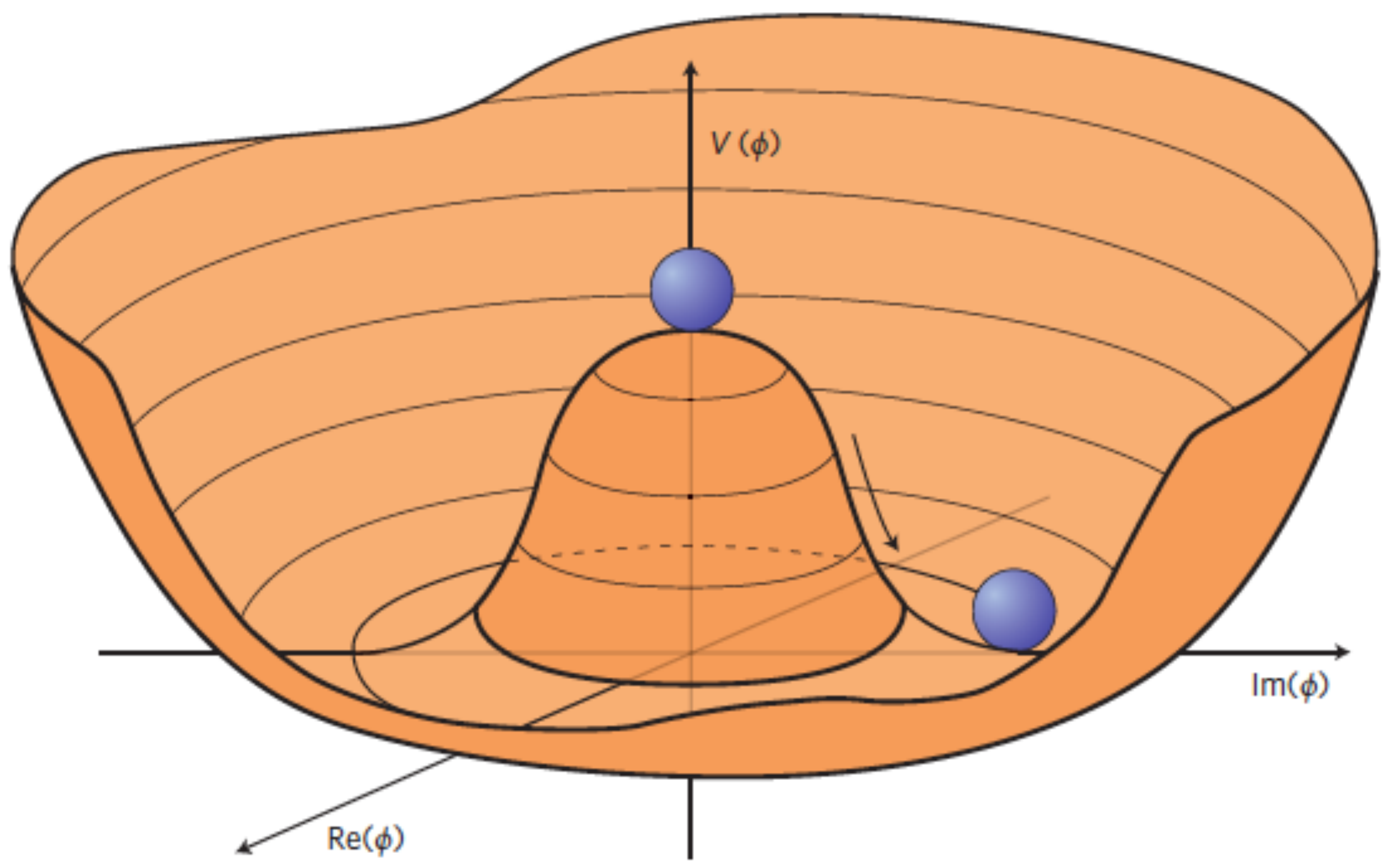
ELECTROWEAK BARYOGENESIS



1. Baryon number violation: sphalerons
2. C- and CP-violation: new CP violation at EW scale
3. Out of equilibrium: 1st order EW phase transition

EW PHASE TRANSITION

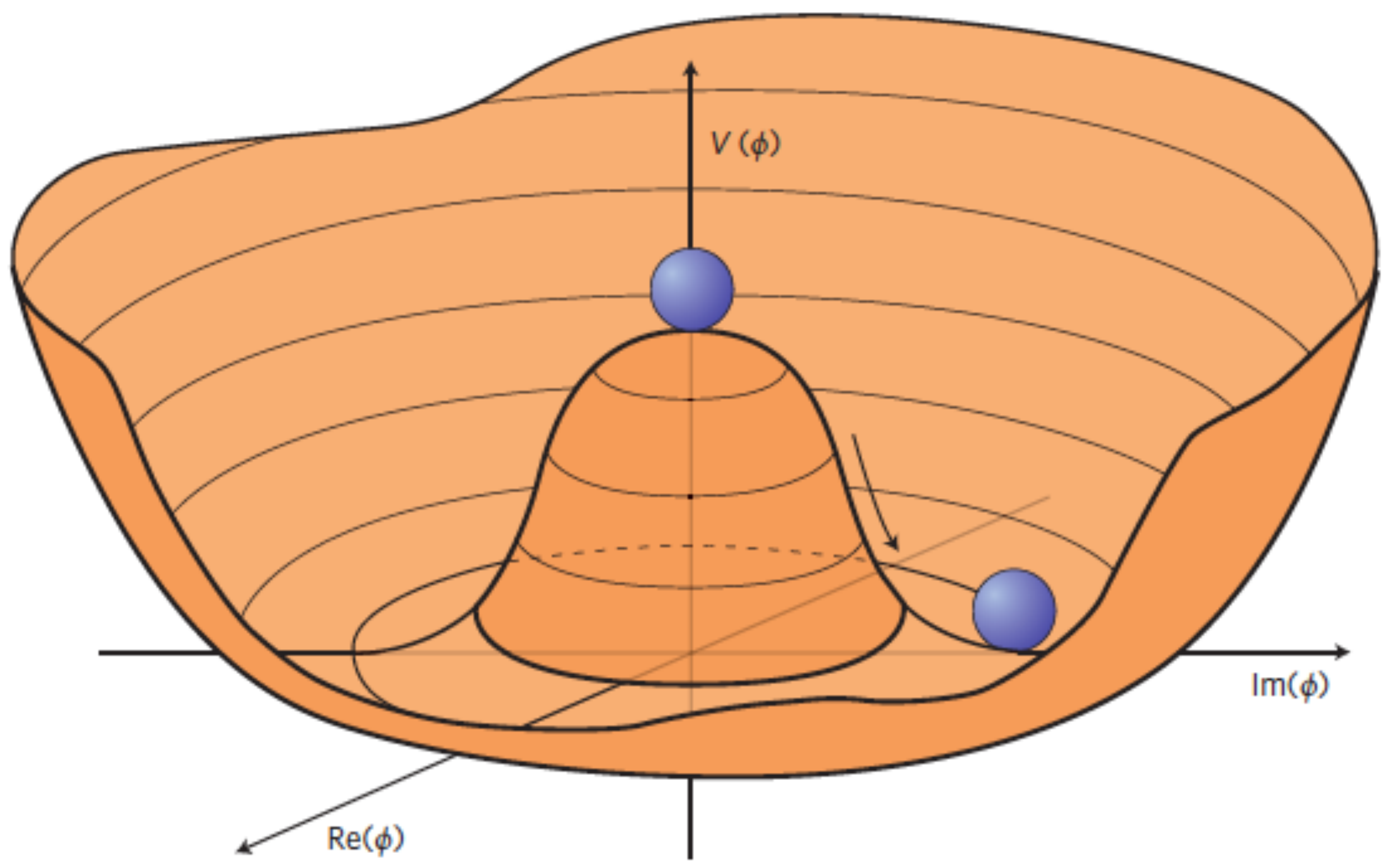
$T = 0$



$$V = \frac{\lambda}{4}(\phi^2 - v^2)^2$$

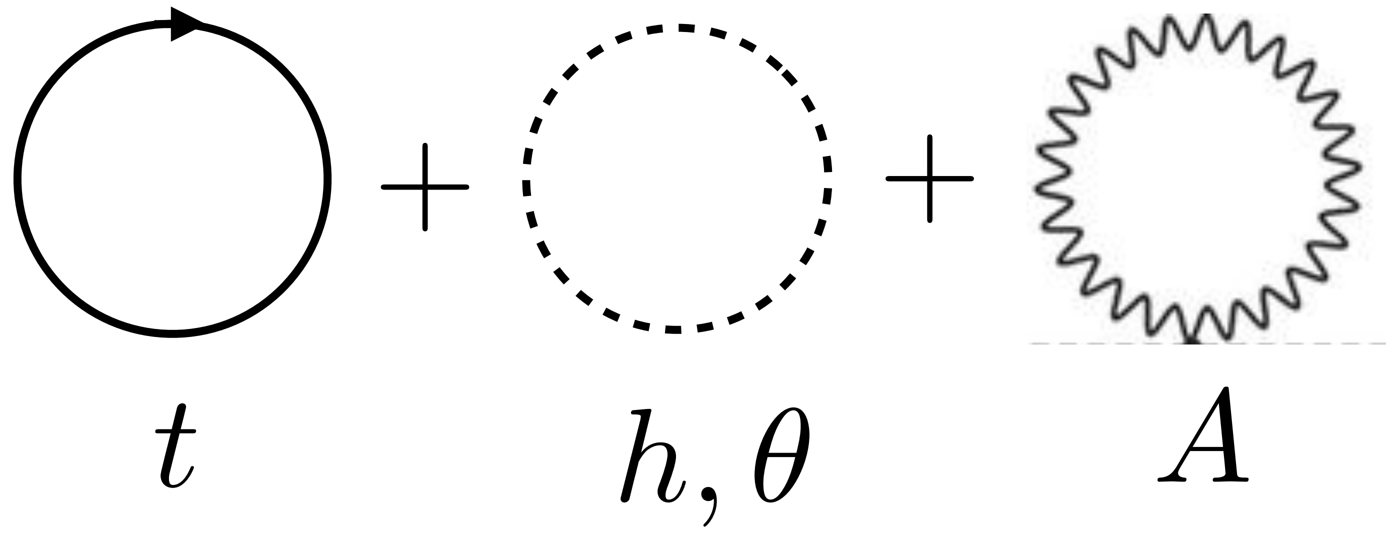
EW PHASE TRANSITION

$T = 0$



$$V = \frac{\lambda}{4}(\phi^2 - v^2)^2$$

$T \neq 0$



$$V_T = \bigcirc + \bigcirc + \bigcirc + \ldots$$

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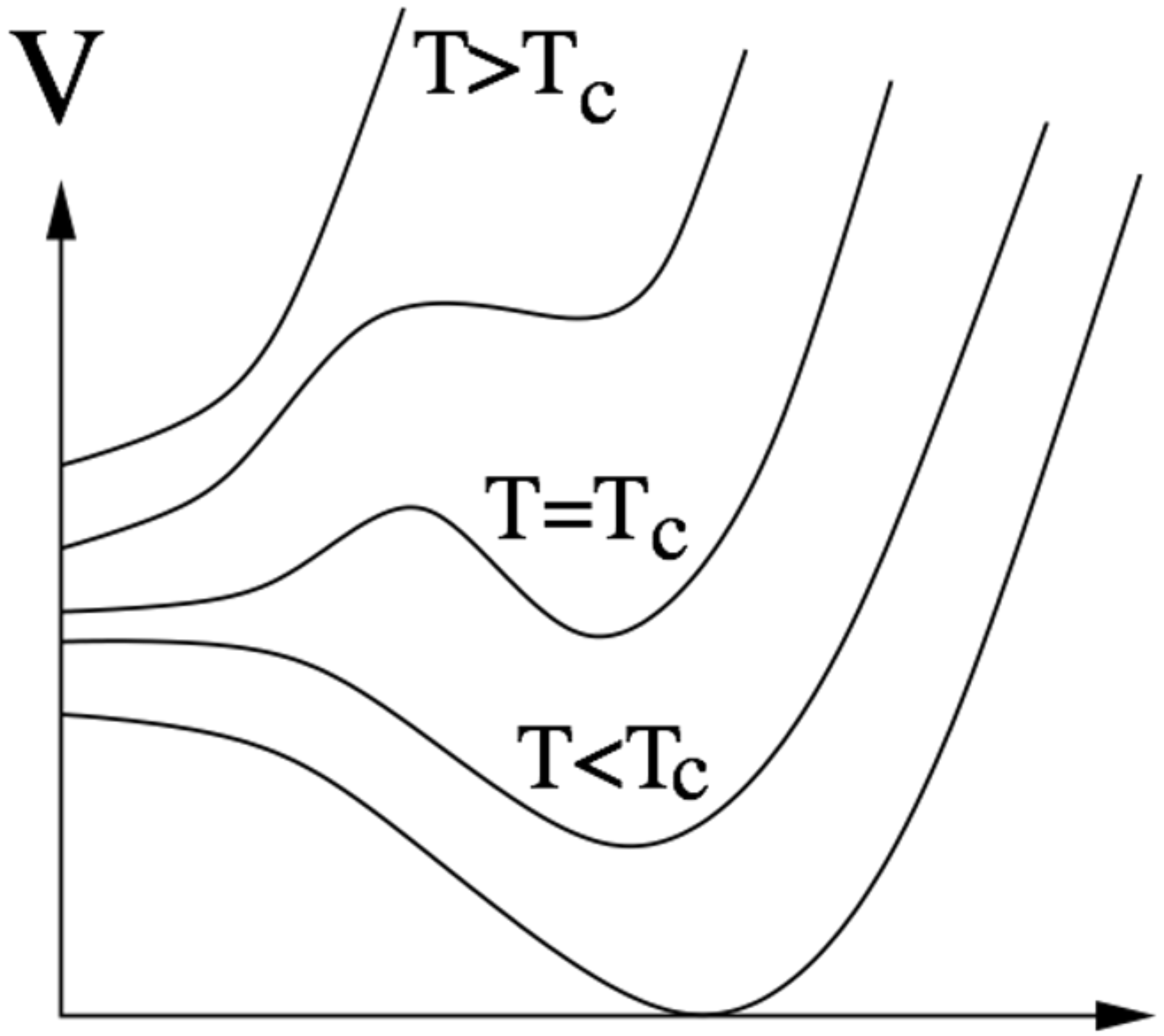
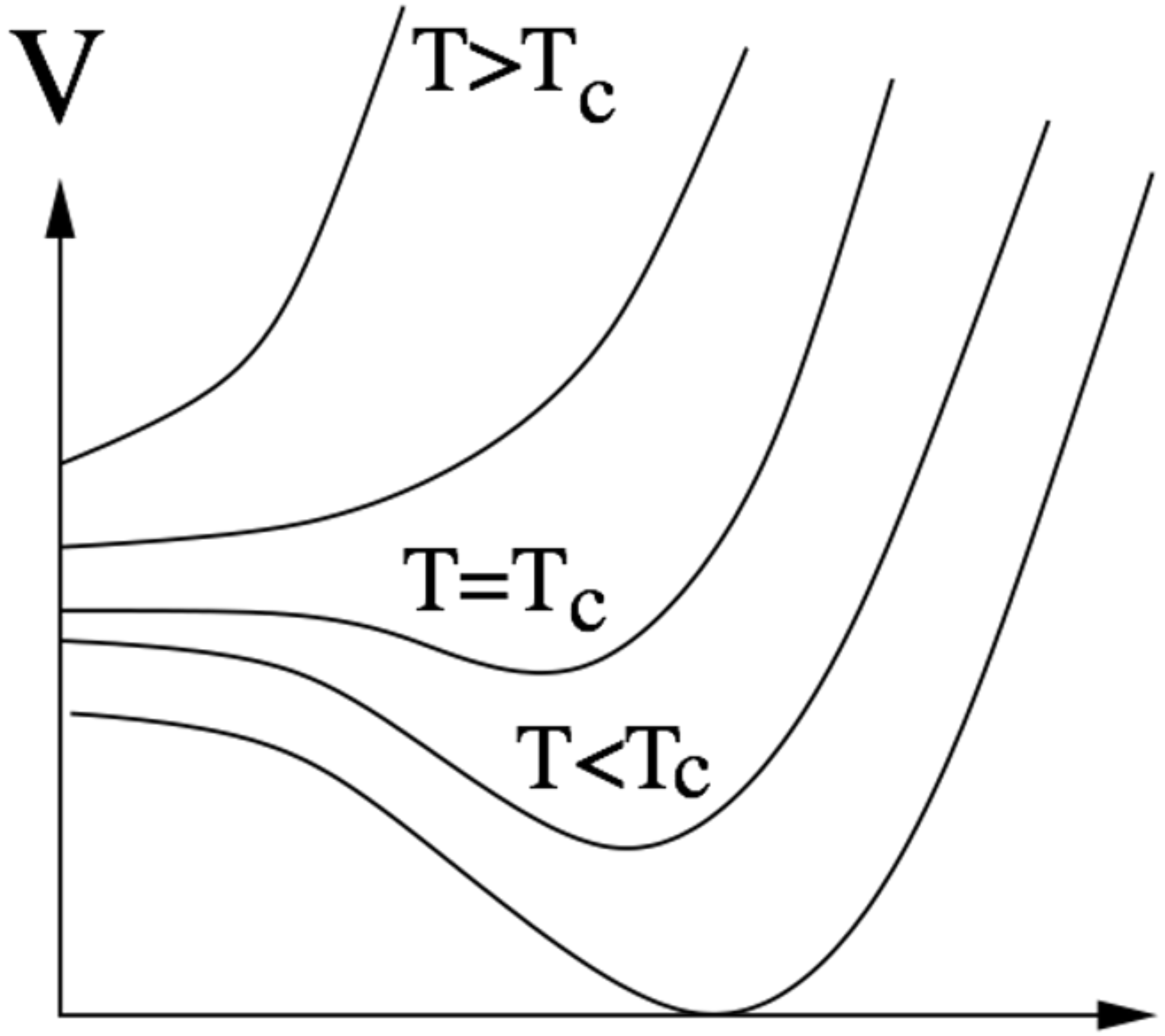
EW PHASE TRANSITION



from Cline ’06

1st order



2nd order/cross over

THERMAL CORRECTIONS

partition function in thermal equil. $Z = \mathrm{tr}\rho = \mathrm{tr}(\mathrm{e}^{-\beta H}), \quad \beta = 1/T$

$$\Rightarrow \quad V_{\text{eff}} = \frac{F}{\mathcal{V}} = -\frac{T}{\mathcal{V}} \ln Z$$

compare with generation function $Z = \int \mathrm{d}\phi_i \mathrm{d}\phi_f \langle \phi_f(\vec{x}, t) | \mathrm{e}^{-iHt} | \phi_i(\vec{x}, 0) \rangle$

QFT at finite T $\simeq$ euclidean QFT on a finite imaginary `time' interval.

$$\tau = it, \quad 0 < \tau < \beta = 1/T$$

THERMAL CORRECTIONS IN QM

harmonic oscillator for bosons

$$Z = \int \mathrm{d}q \, \langle q | \mathrm{e}^{-H\beta} | q \rangle = \int \mathrm{d}q \sum_n \mathrm{e}^{-\beta\omega(n+\frac{1}{2})} \langle n|q\rangle\langle q|n\rangle \propto \frac{\mathrm{e}^{-\beta\omega/2}}{1-\mathrm{e}^{-\beta\omega}},$$

$$H = \omega(N + \frac{1}{2})$$

free energy

$$F = -1/\beta \ln Z = \frac{1}{2}\omega + T \ln(1 - \mathrm{e}^{-\beta\omega})$$

THERMAL CORRECTIONS IN QM

harmonic oscillator for fermions

$$Z = \int \mathrm{d}q \, \langle q | \mathrm{e}^{-H\beta} | q \rangle = \int \mathrm{d}q \sum_{n=0,1} \mathrm{e}^{-\beta\omega(n-\frac{1}{2})} \langle n|q\rangle\langle q|n\rangle \propto \mathrm{e}^{\beta\omega/2}(1+\mathrm{e}^{-\beta\omega})$$

free energy

$$F = -\frac{1}{2}\omega - T\ln(1+\mathrm{e}^{-\beta\omega})$$

THERMAL CORRECTIONS IN QFT

free QFT ~ harmonic oscillator for each k $\qquad \omega_i = \sqrt{\vec{k}^2 + m_i(\phi)^2}$

$$V^{\text{loop}} = \sum_{\text{bosons}} n_i \int \frac{\mathrm{d}^3\vec{k}}{(2\pi)^3} \left(\frac{1}{2}\omega_i + T \ln(1 - \mathrm{e}^{-\beta\omega_i}) \right)$$

$$- \sum_{\text{fermions}} n_i \int \frac{\mathrm{d}^3\vec{k}}{(2\pi)^3} \left(\frac{1}{2}\omega_i + T \ln(1 + \mathrm{e}^{-\beta\omega_i}) \right)$$

$$V_T = \sum_i \left(c_i^{(2)} m_i^2 T^2 + c_i^{(3)} m_i^3 T + \ldots \right) \quad \text{for} \quad T^2 \gg m_i^2$$

THERMAL CORRECTIONS TO HIGGS POTENTIAL

free QFT ~ harmonic oscillator for each *k*

$$\omega_i = \sqrt{\vec{k}^2 + m_i(\phi)^2}$$

$$V_T = \sum_i \left(c_i^{(2)} m_i^2 T^2 + c_i^{(3)} m_i^3 T + ... \right)$$

$$\Phi = \{h, \theta, W^\pm, Z, t\}, \quad m^2/\phi^2 = \{3\lambda, \lambda, \frac{1}{4}g^2, \frac{1}{4}(g^2 + g'^2), \frac{1}{2}y_t^2\}, \quad n = \{1, 3, 6, 3, 12\}$$

THERMAL CORRECTIONS TO HIGGS POTENTIAL

Higgs potential $$V = \frac{1}{2}(-\lambda v^2 + aT^2)\phi^2 - \frac{1}{3}bT\phi^3 + \frac{\lambda}{4}\phi^4$$

at T_c degenerate minima at $\phi = 0$ and $\phi = v_c$

$$V(T_c) = \frac{\lambda}{4}\phi^2(\phi - v_c)^2 = \frac{\lambda}{4}v_c^2\phi^2 - \frac{\lambda}{2}v_c\phi^3 + \frac{\lambda}{4}\phi^4$$

strong 1st order PT

$$\frac{v_c}{T_c} = \frac{2b}{3\lambda} \approx \frac{3g^3}{16\pi\lambda} \gtrsim 1 \qquad \Rightarrow \qquad \boxed{m_h^2 \lesssim (30\,\mathrm{GeV})^2}$$

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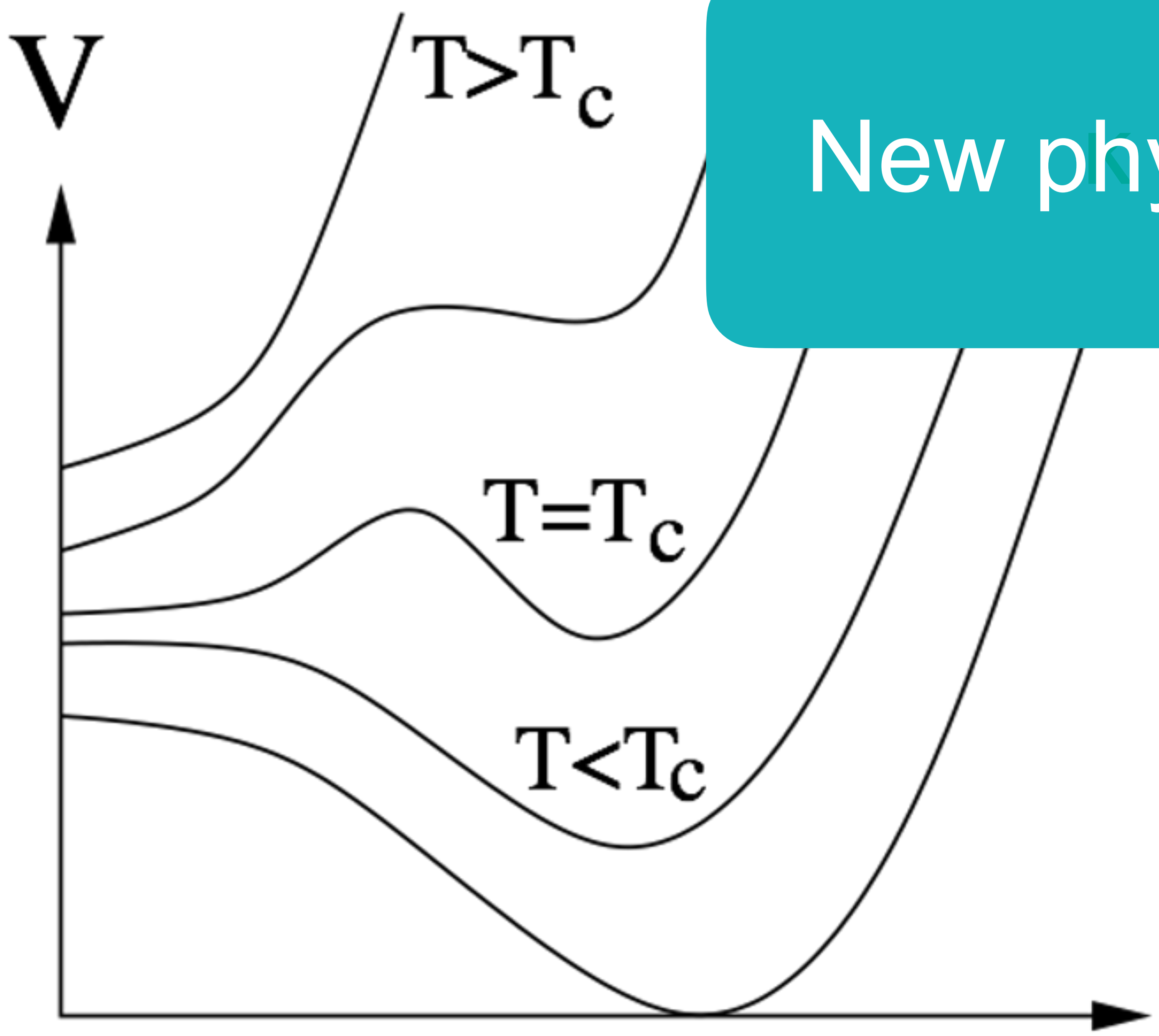
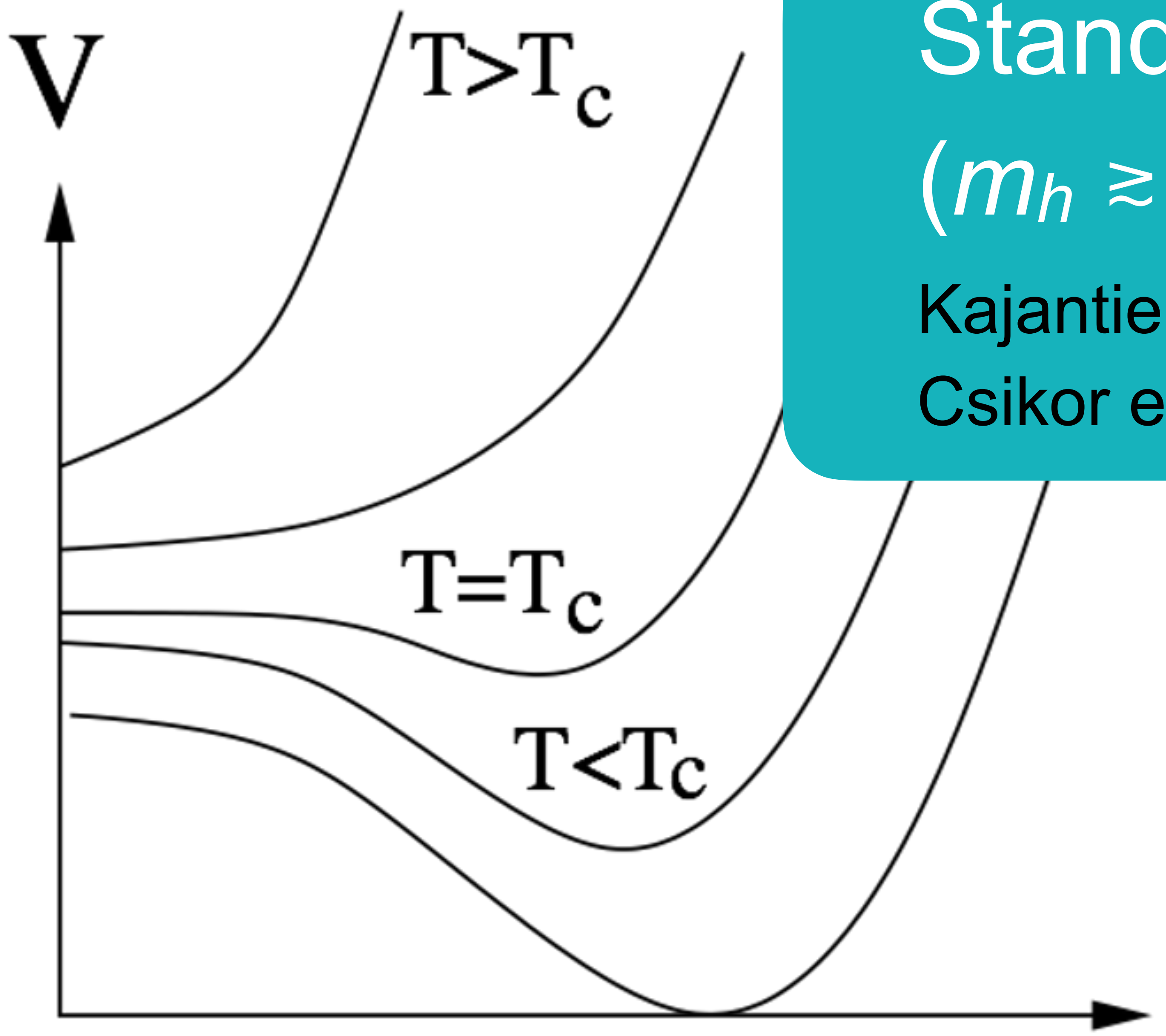
EW PHASE TRANSITION



New physics

from Cline ’06

1st order



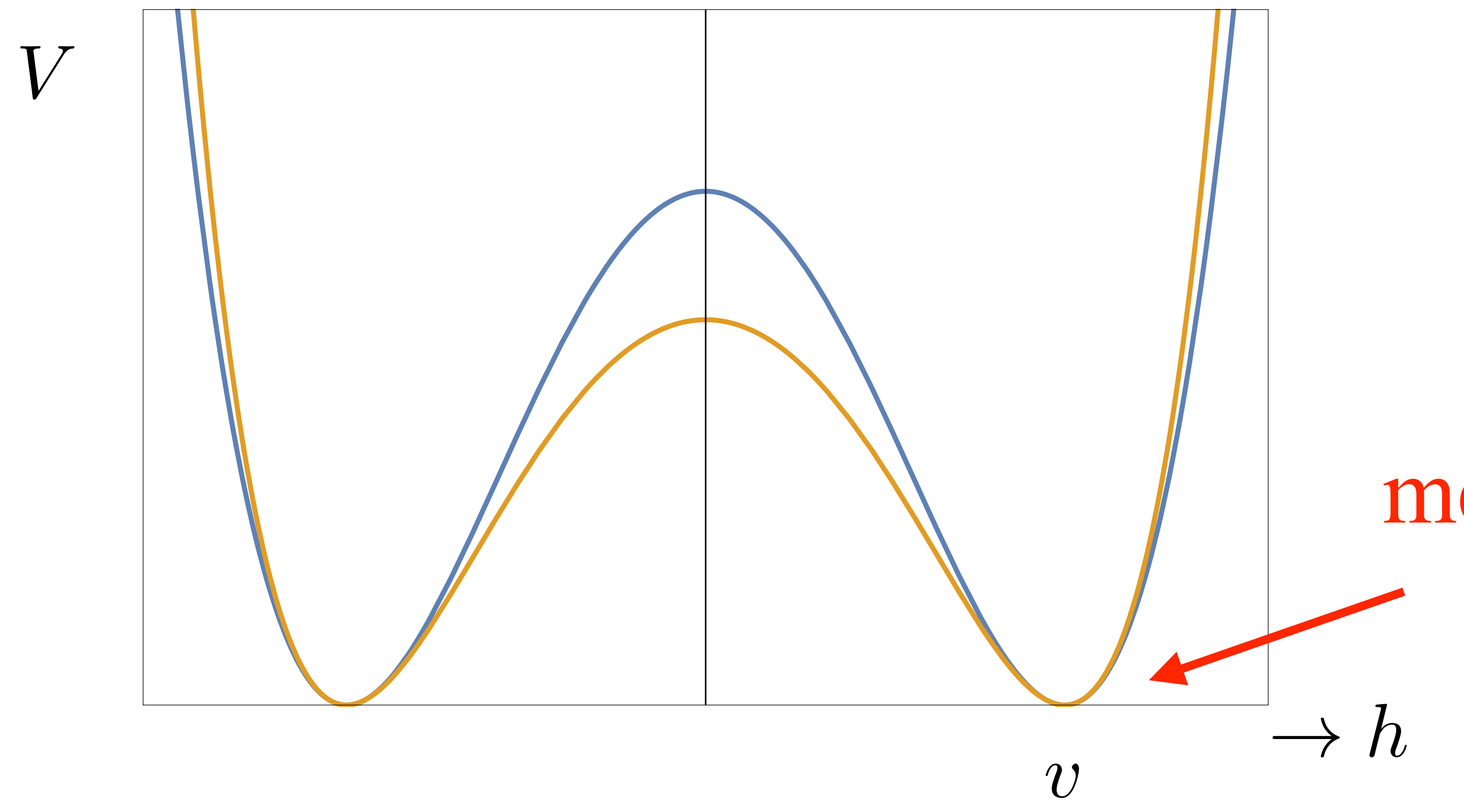
Standard Model
($m_h \gtrsim 65$ GeV)
Kajantie et al. ’96
Csikor et al. ‘98

2nd order/cross over

EW PHASE TRANSITION

how much room for new physics?

$$-1 \lesssim \frac{\lambda_{hhh}^{\text{BSM}}}{\lambda_{hhh}^{\text{SM}}} \lesssim 7$$



$$m_h = 125.3\,\text{GeV}$$

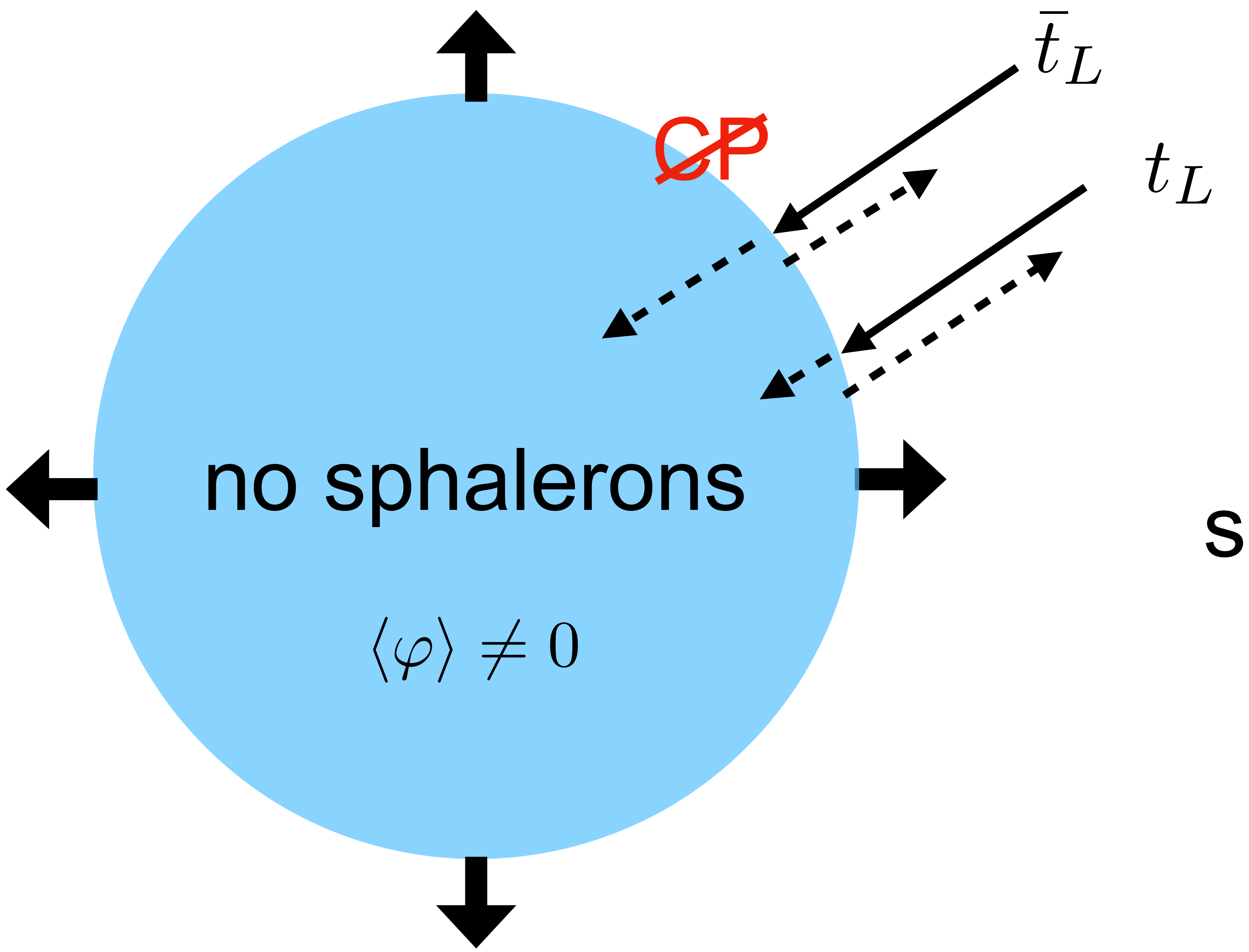
$$v = 246\,\text{GeV}$$

ELECTROWEAK BARYOGENESIS IN A NUTSHELL

Cohen, Kaplan and Nelson 1991

$$\mathcal{L} \supset \frac{y_t}{\sqrt{2}}\phi\left(1 + c\frac{\phi^2}{\Lambda^2}\right)\bar{t}_L t_R + \text{h.c.}$$

CP violation



sphalerons

$\langle\varphi\rangle = 0$

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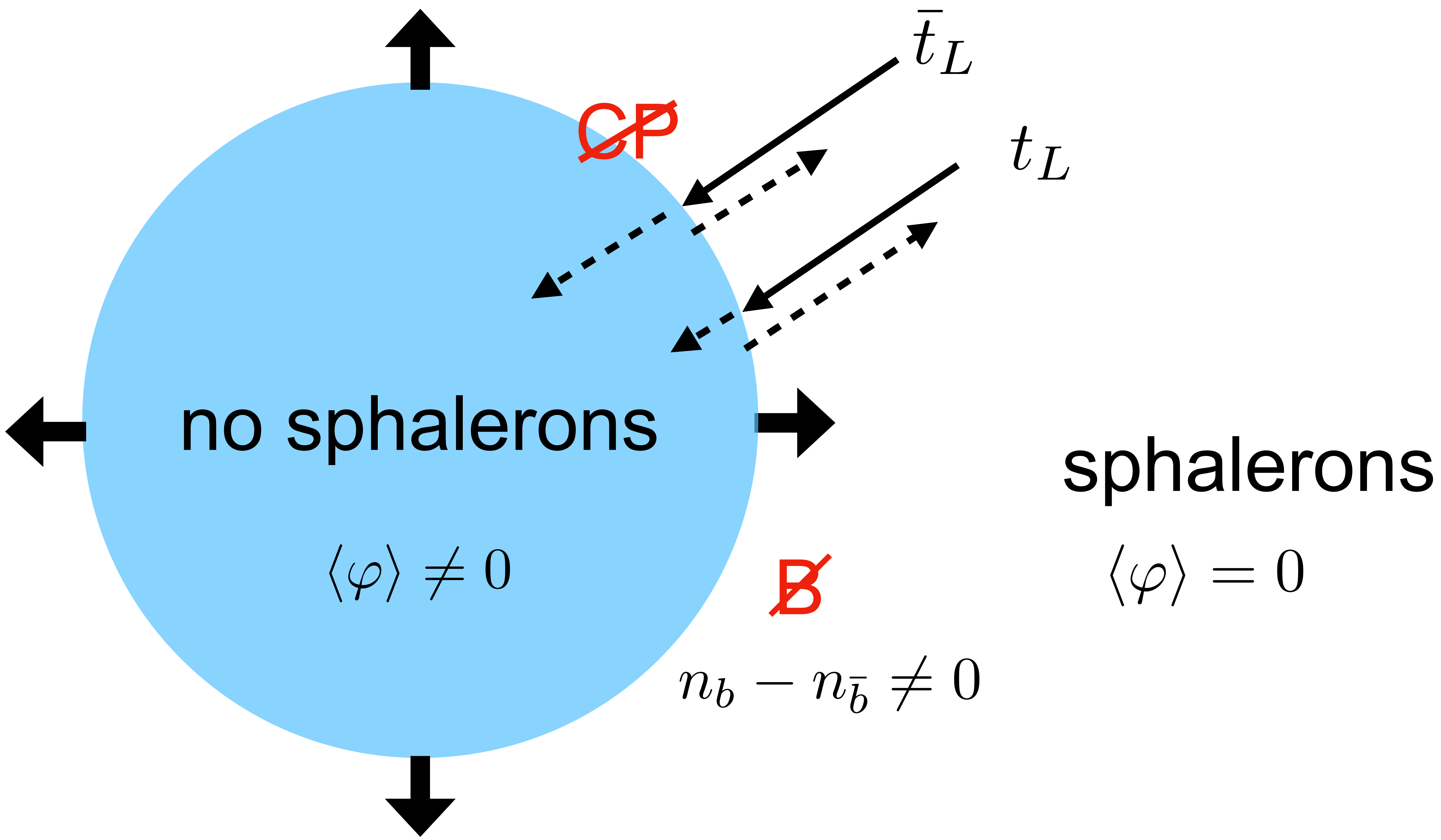

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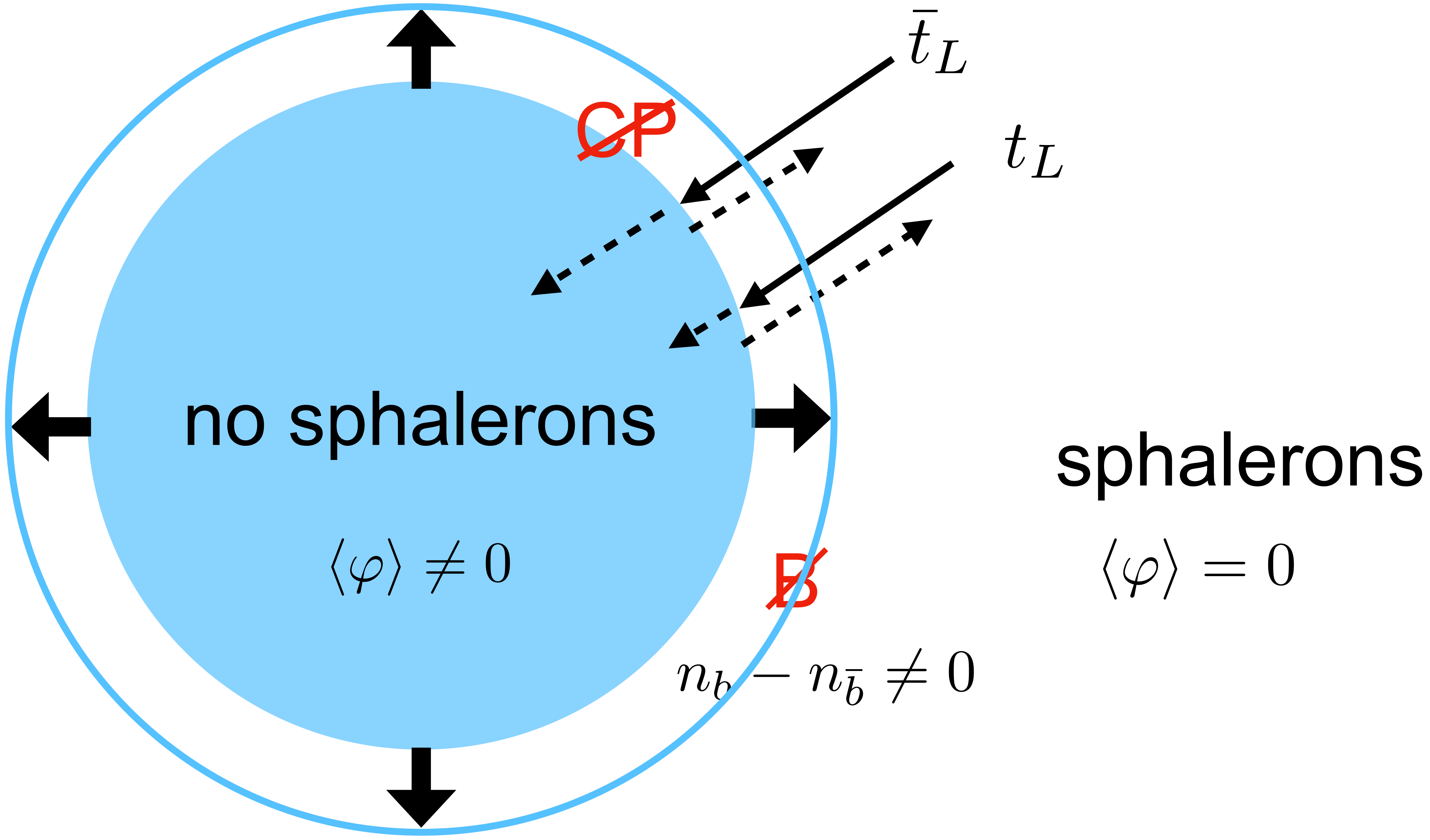


$$\frac{\Gamma_{\text{sph}}}{V} \sim \mathrm{e}^{-E_{\text{sph}}/T} \sim \mathrm{e}^{-8\pi v/(gT)}$$

BOLTZMANN EQUATIONS

phase space density

$$n(\vec{x},t) = g_s \int \frac{\mathrm{d}^3\vec{p}}{(2\pi)^3} f(\vec{x},\vec{p},t)$$

Boltzmann eq.

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{\partial f}{\partial t} + \frac{\mathrm{d}\vec{x}}{\mathrm{d}t} \cdot \nabla_{\vec{x}} f + \frac{\mathrm{d}\vec{p}}{\mathrm{d}t} \cdot \nabla_{\vec{p}} f = C[f]$$

force

collision term

Nikhef

SEMI-CLASSICAL FORCE

$$(i\gamma\cdot\partial - mP_L - m^* P_R)\psi = 0$$

subst. $\psi = \mathrm{e}^{-i\omega t}\begin{pmatrix} L_s \\ R_s \end{pmatrix} \otimes \chi_s$

gives:

$$\left[(\omega + is\partial_z)\frac{1}{m}(\omega - is\partial_z) - m^*\right] L_s = 0, \quad \left[(\omega - is\partial_z)\frac{1}{m^*}(\omega + is\partial_z) - m\right] R_s = 0$$

gradient expansion $L_s = \omega \mathrm{e}^{i\int^z p(z')\mathrm{d}z'}$ $\Rightarrow$ $\omega = \sqrt{(p+\theta'/2)^2 + |m|^2} - \frac{1}{2}s\theta'$

$m = |m|\mathrm{e}^{-i\theta}$

force $\Rightarrow$ $\dot{p} = -\left(\frac{\partial\omega}{\partial_z}\right)_p$

antiparticle $\theta \rightarrow -\theta$

TESTABILITY OF EW BARYOGENESIS

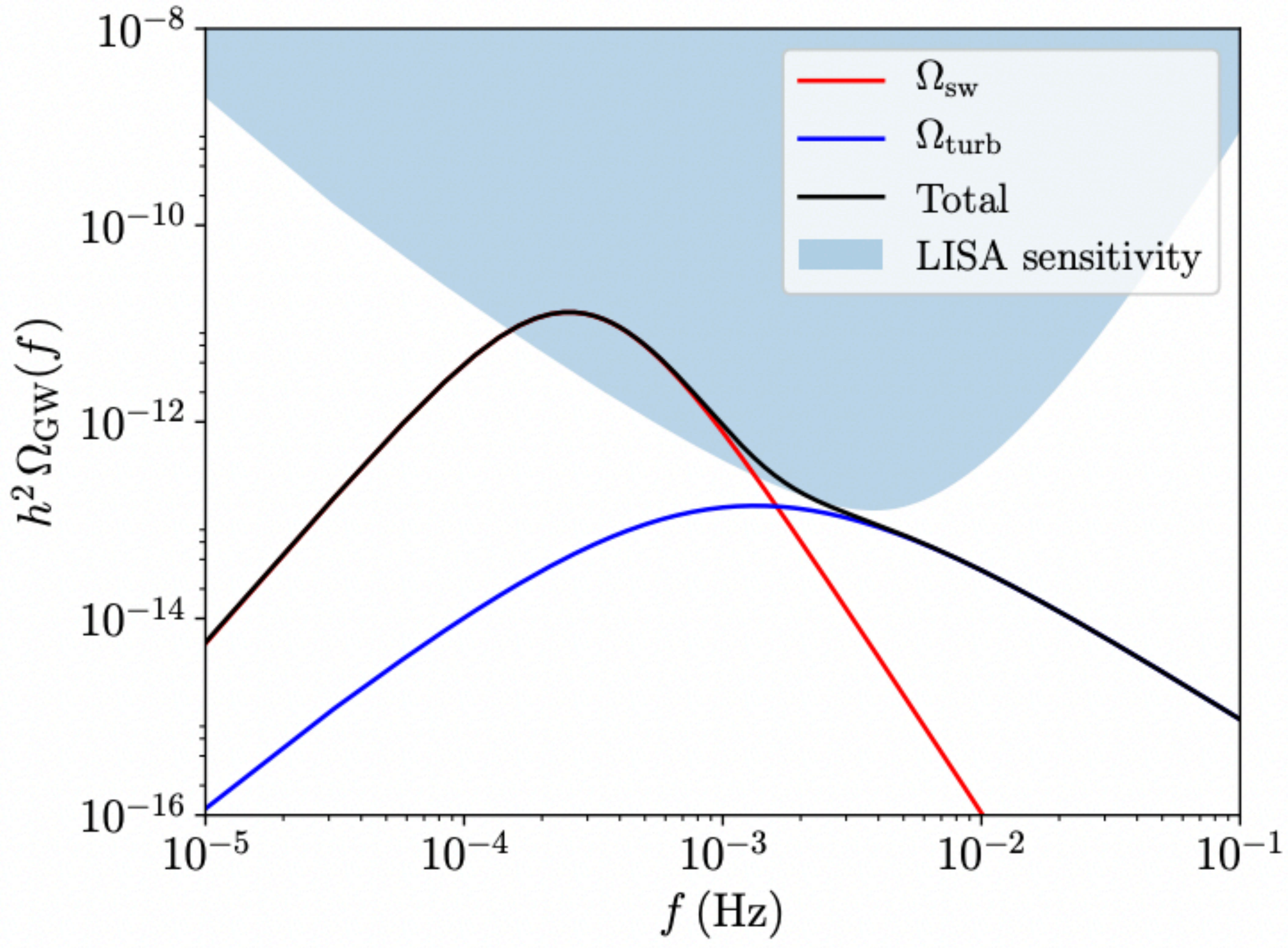
- triple higgs coupling at LHC $-1 \lesssim \frac{\lambda_{hhh}^{\mathrm{BSM}}}{\lambda_{hhh}^{\mathrm{SM}}} \lesssim 7$

- electric dipole moment of electron

- gravitational waves

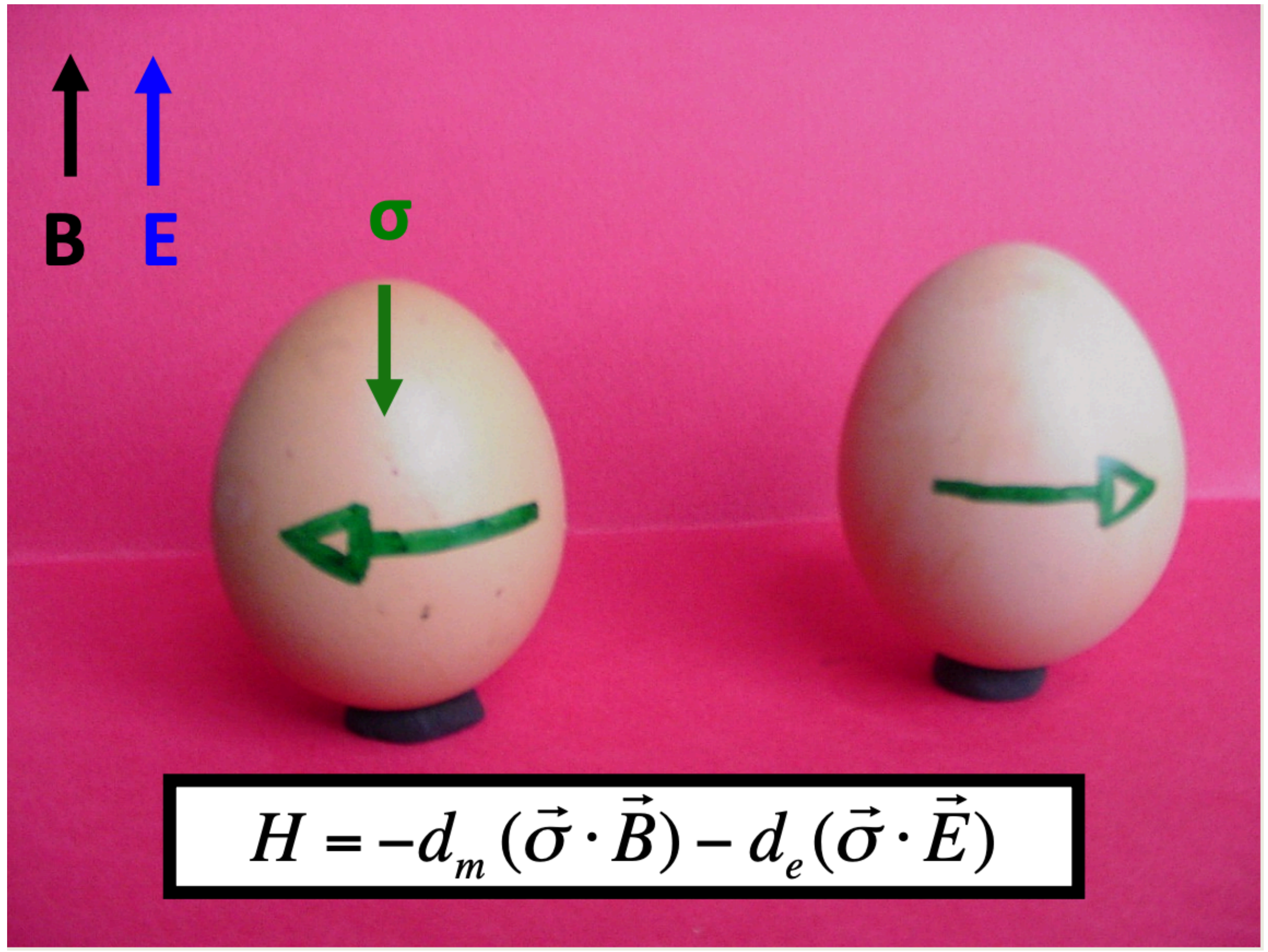
GRAVITATIONAL WAVES

- bubble collisions
- colliding sound waves
- turbulence

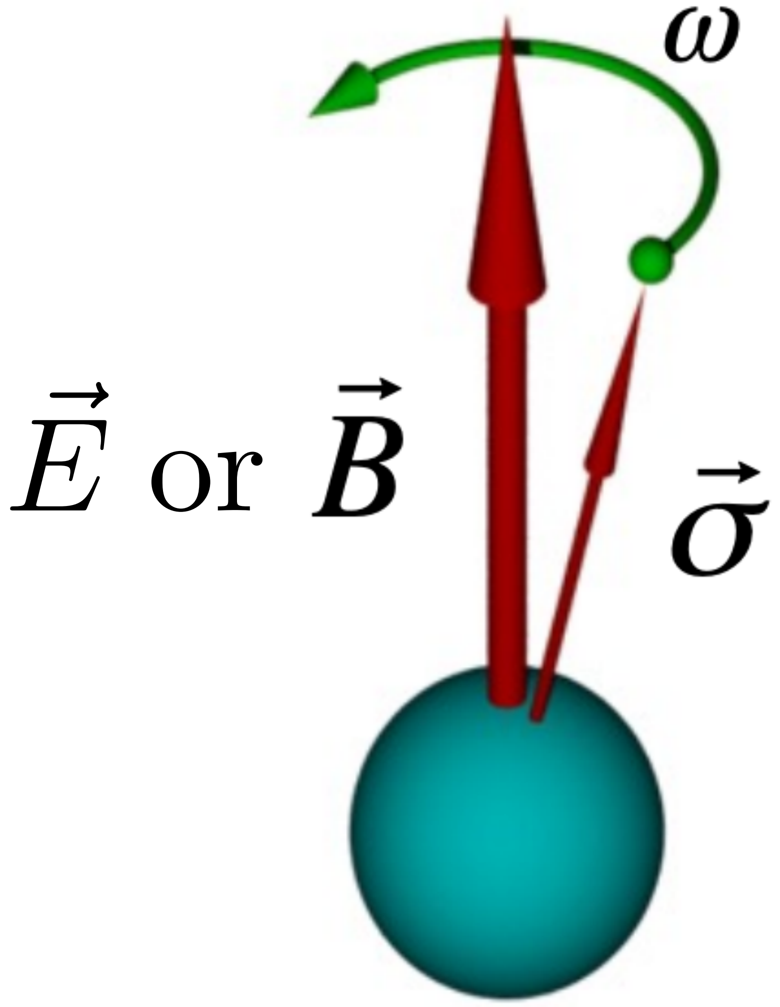


ELECTRIC DIPOLE MOMENT

from Jordy de Vries



$$H = -d_m(\vec{\sigma}\cdot\vec{B}) - d_e(\vec{\sigma}\cdot\vec{E})$$



spin $\vec{S} = \frac{1}{2}\vec{\sigma}$

magnetic dipole $\omega = d_m B \sin\theta$

electric dipole $\omega = d_e E \sin\theta$

ELECTRIC DIPOLE MOMENT

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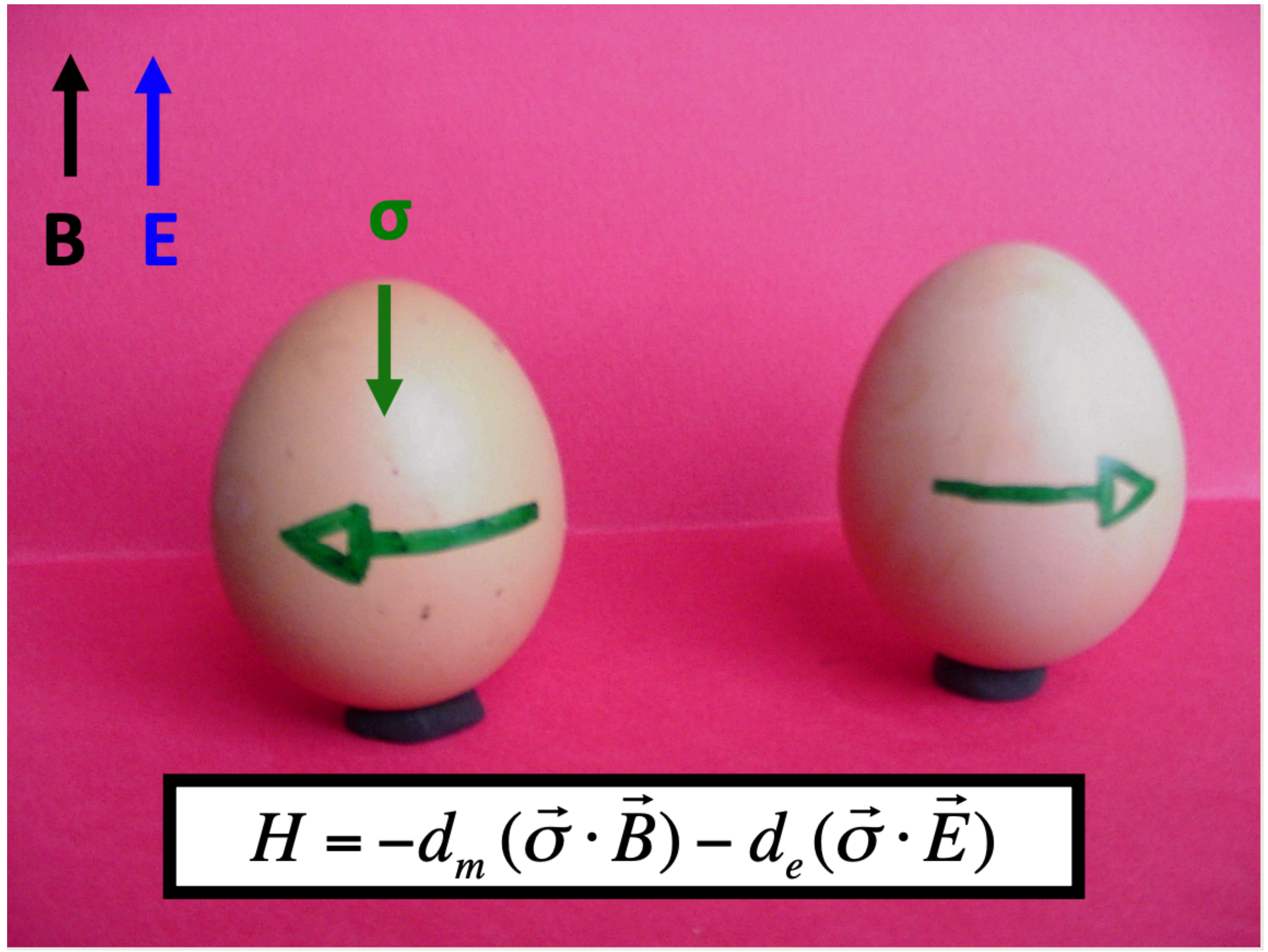
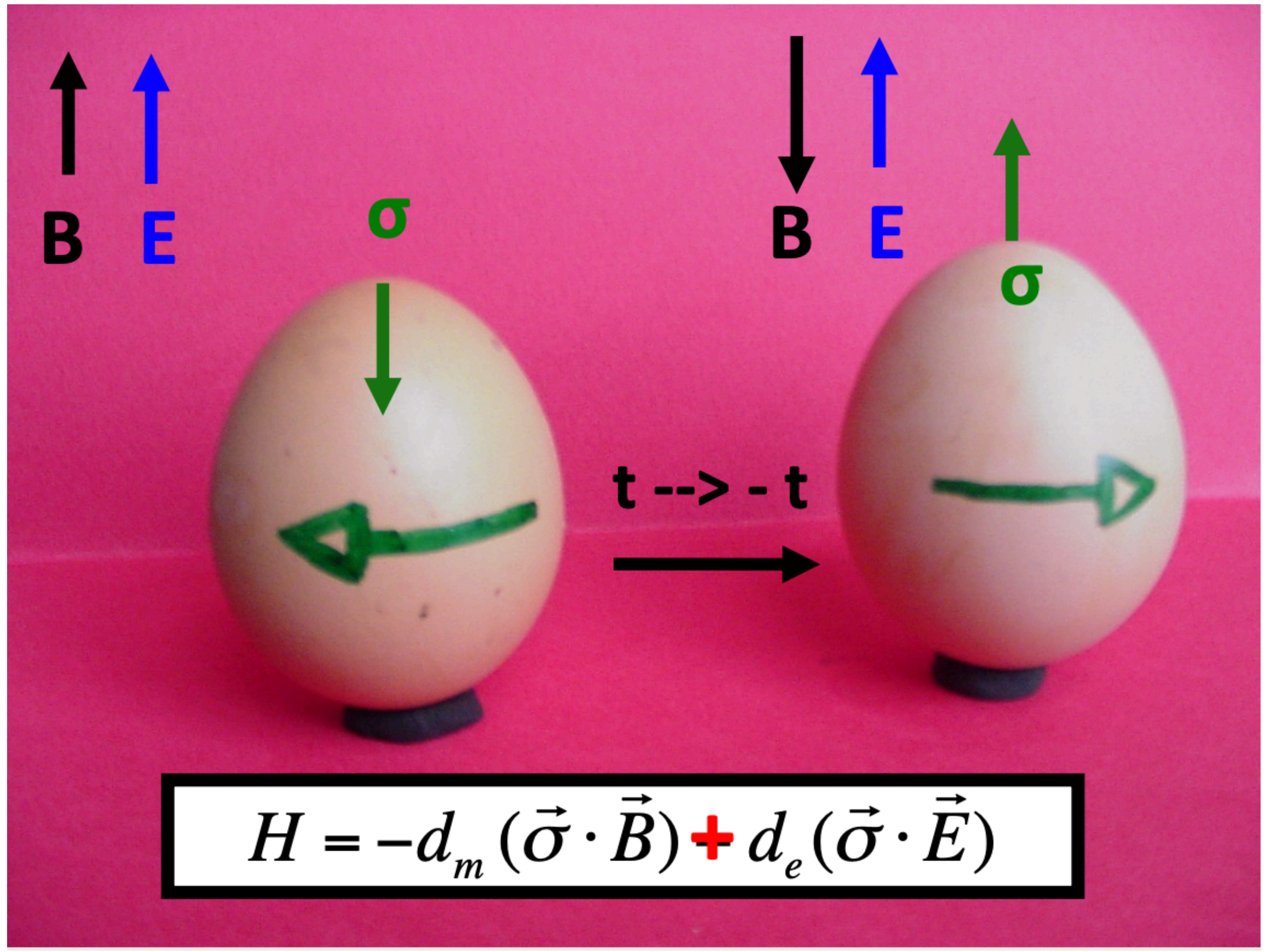




spin $\vec{S} = \frac{1}{2}\vec{\sigma}$

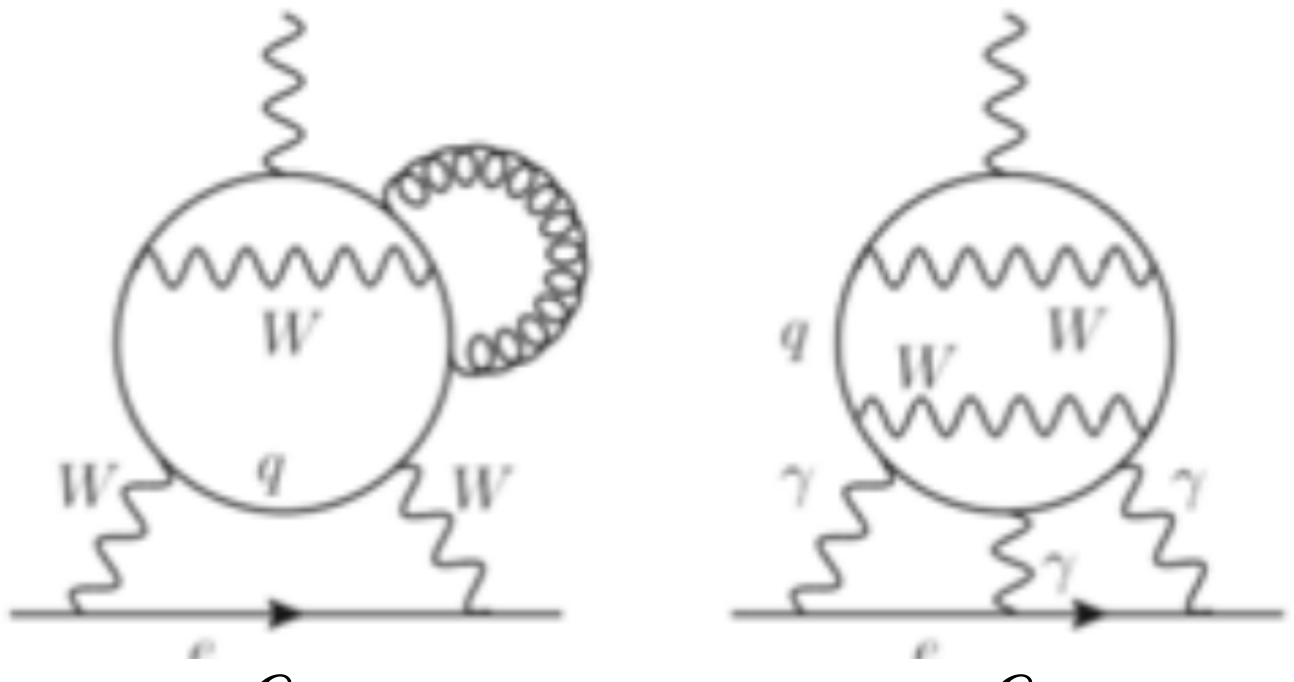
breaks CP

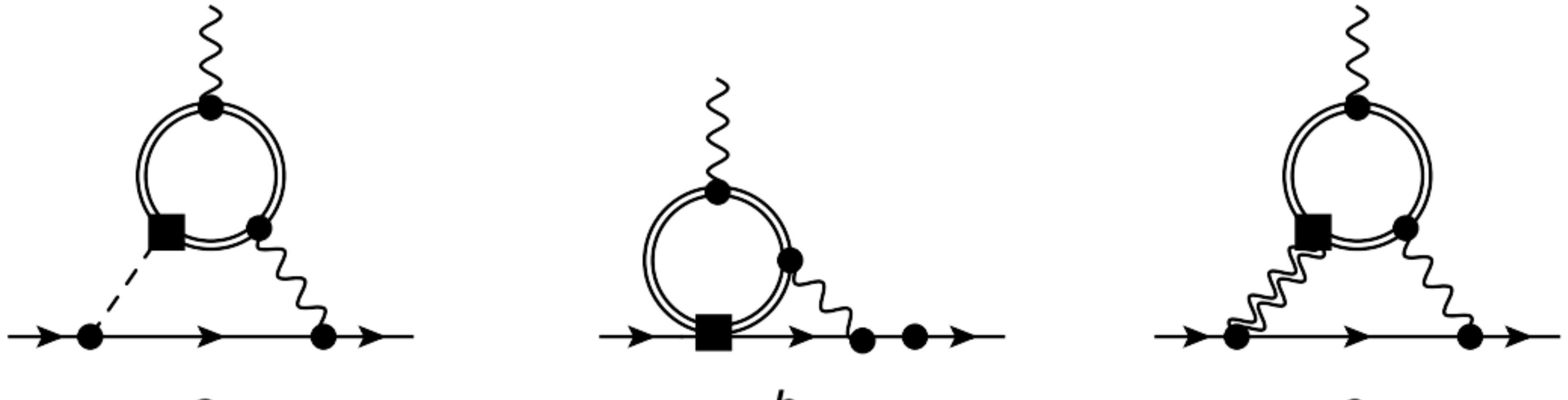
ELECTRIC DIPOLE MOMENT OF ELECTRON

measured $|d_e| \lesssim 4 \times 10^{-30}\, e\,\text{cm}$

new physics $\mathcal{L} \supset \frac{y_t}{\sqrt{2}} \phi \left(1 + c\frac{\phi^2}{\Lambda^2}\right) \bar{t}_L t_R + \text{h.c.}$

SM





$|d_e| \sim 10^{-44}\, e\,\text{cm}$

$\Lambda \gtrsim 10\,\text{TeV}$

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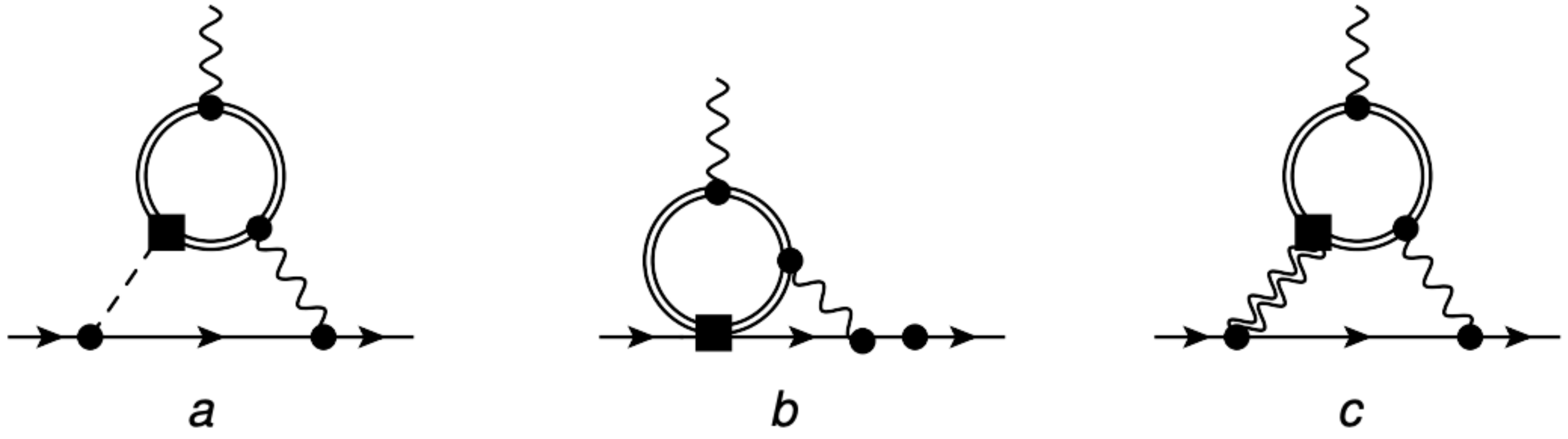

Rules out simplest scenarios

$\Lambda \gtrsim 10\,\text{TeV}$

RECENT WORK ON EW BARYOGENESIS

- triple higgs coupling at LHC
- electric dipole moment of electron
- gravitational waves

hide CP asymmetry
include flavor effects
new scenarios

thermal corrections
bubble wall velocity

PLAN

1. Sakharov conditions
2. Leptogenesis
3. Electroweak baryogenesis