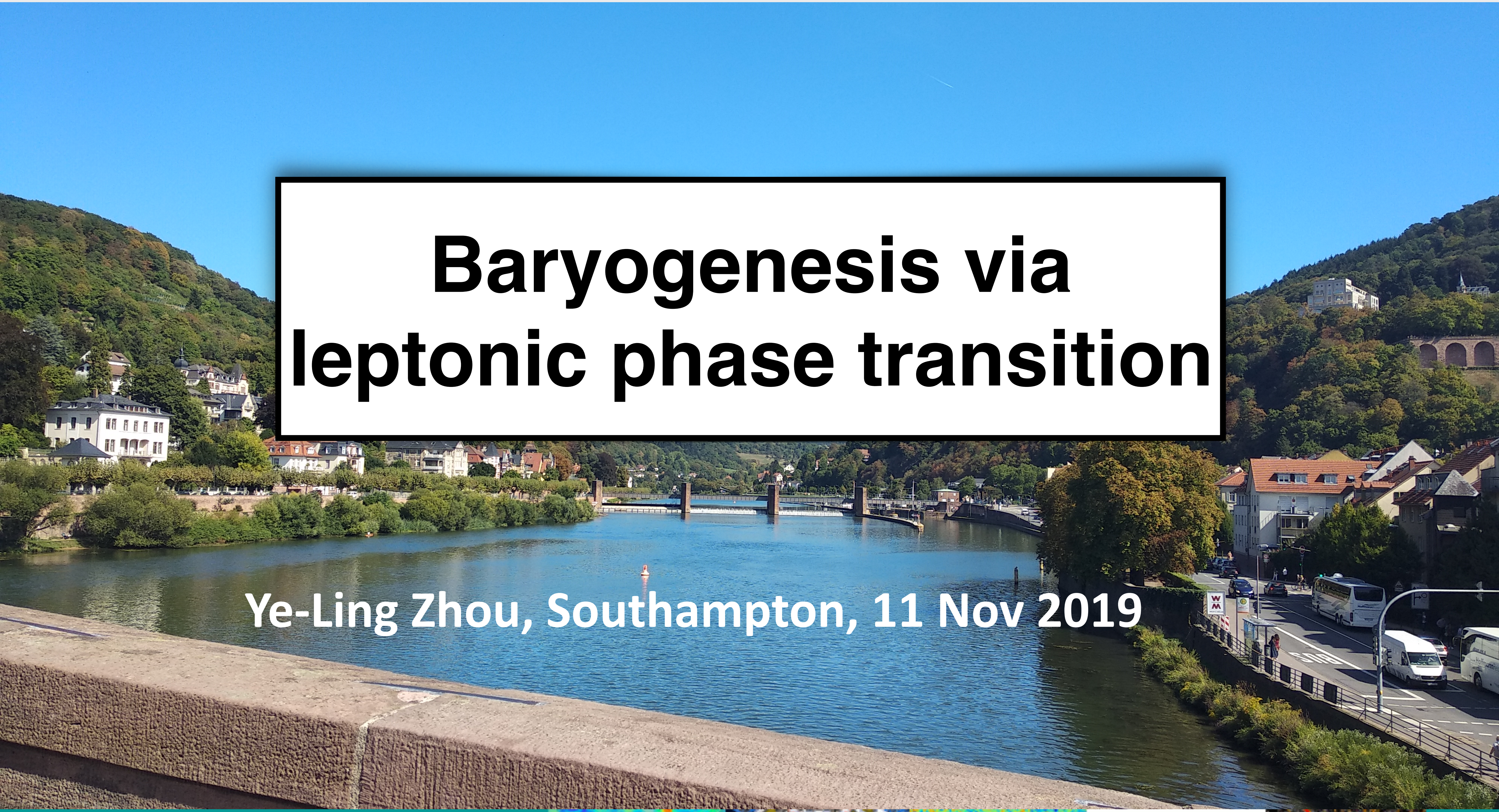
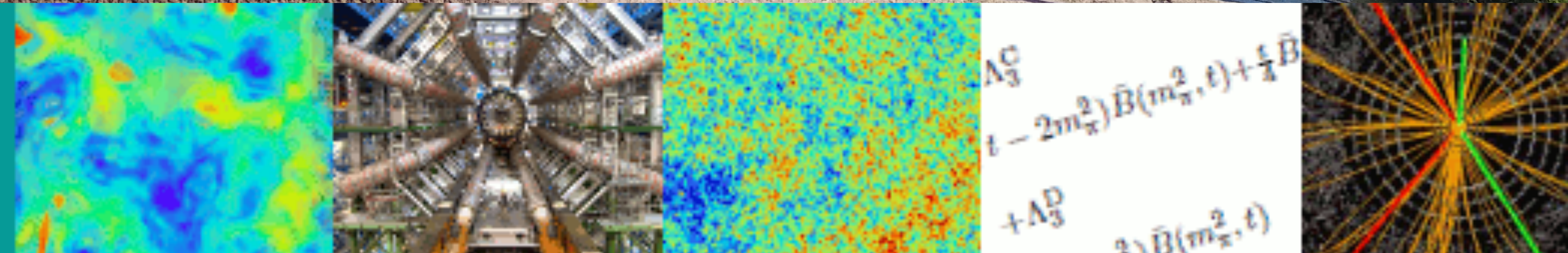
Max-Planck-Institut für Kernphysik Heidelberg



Baryogenesis via leptonic phase transition

Ye-Ling Zhou, Southampton, 11 Nov 2019

SHEP Southampton High Energy Physics

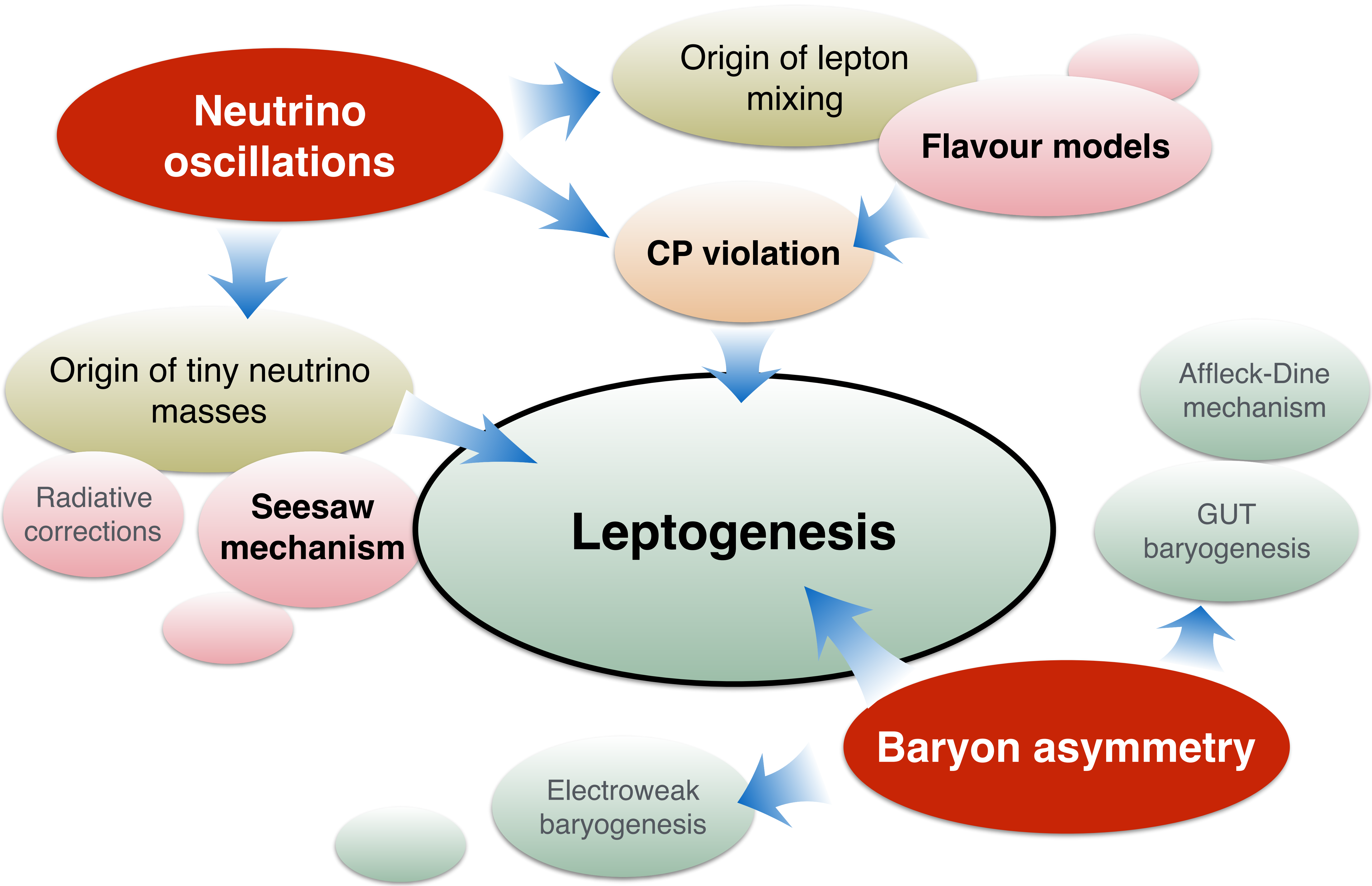


Introduction

Neutrino oscillations

Baryon asymmetry

Introduction



Outline

- *Review of neutrino mass and mixing*

  — —motivation of spacetime-varying Weinberg operator

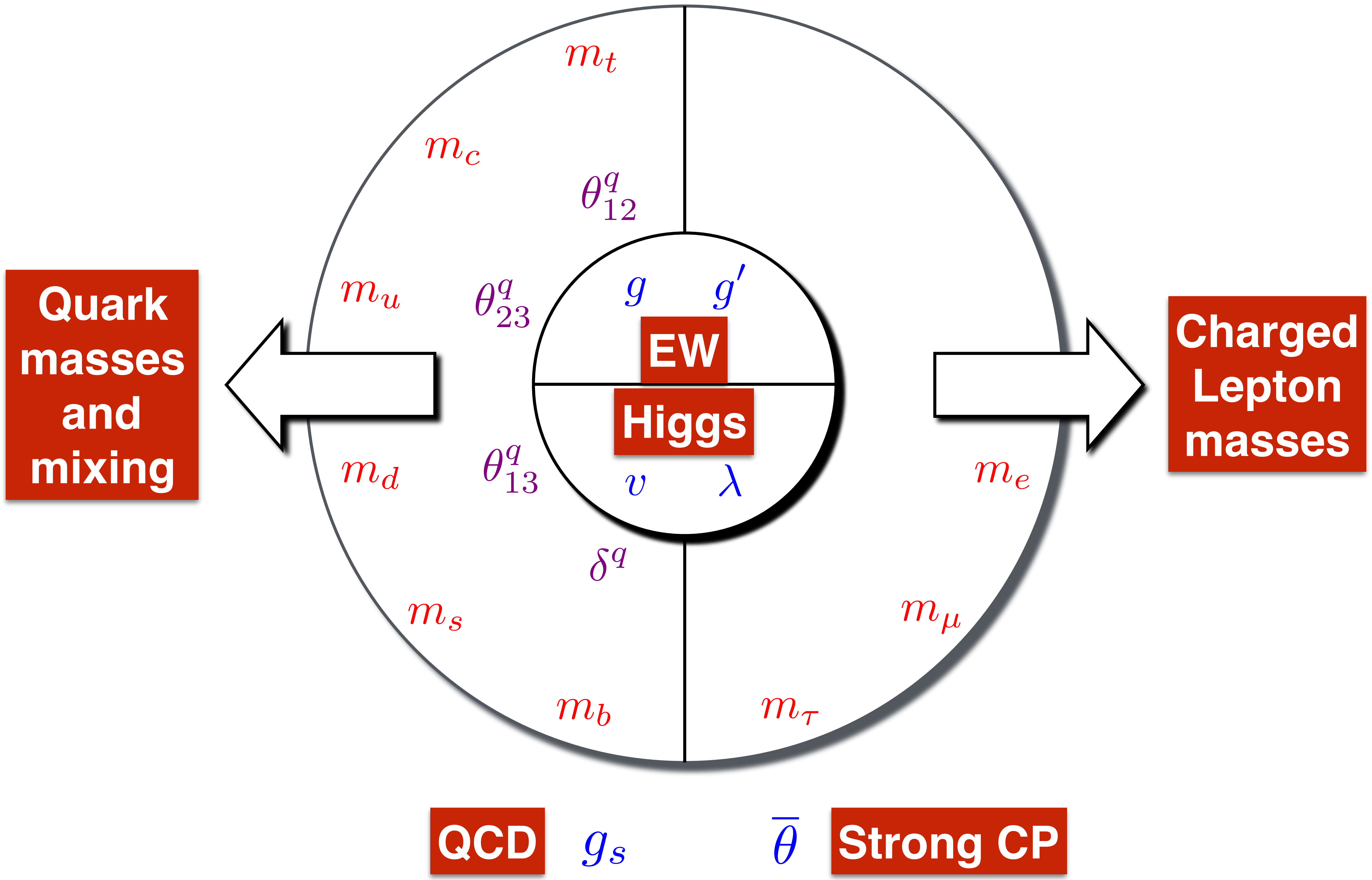
- *Leptogenesis via phase transition*

  — —intuitive picture based on semi-classical approach

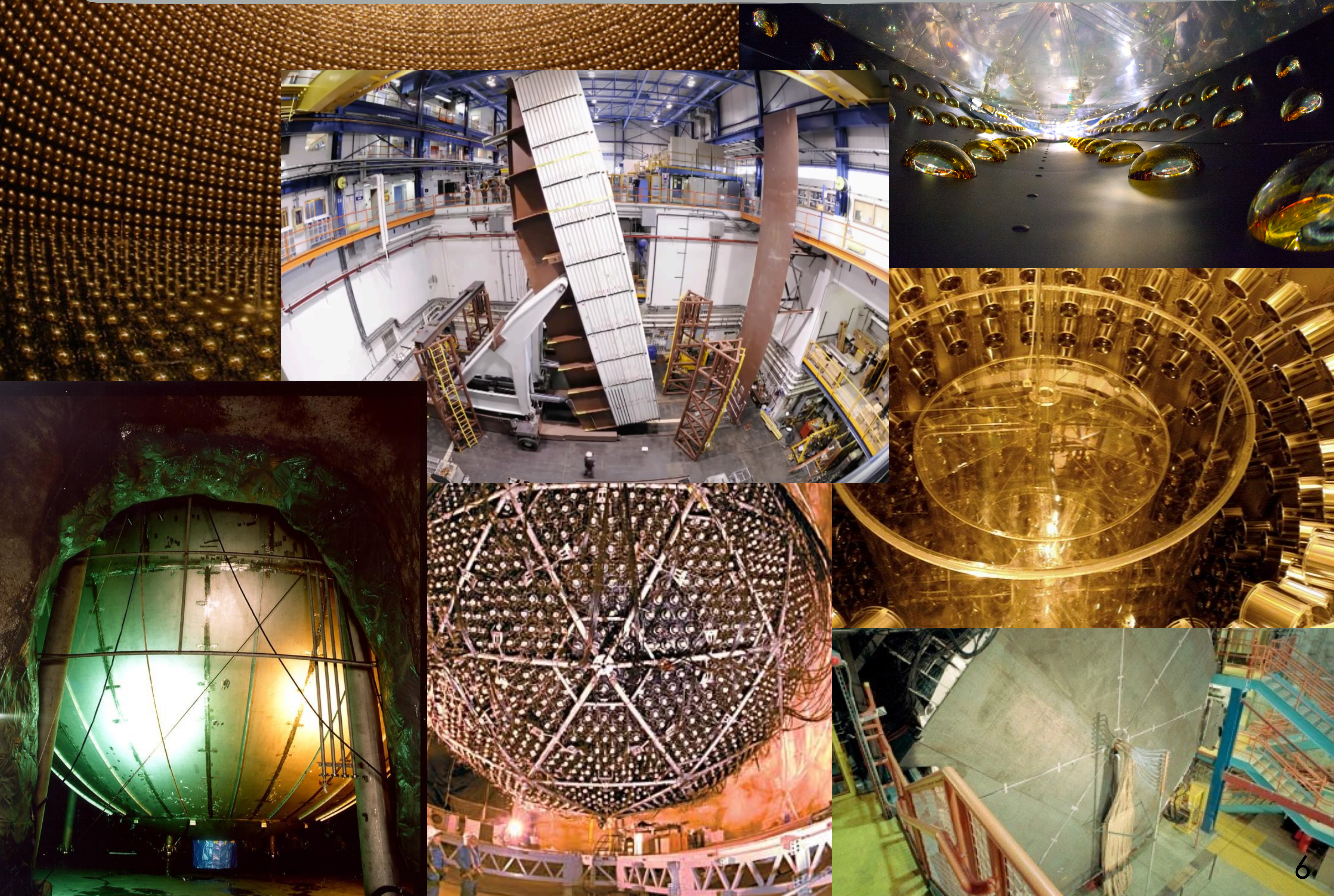
  — —quantitative result based on closed-time-path approach

SM (massless neutrinos)

17+2 free parameters



Neutrino oscillations confirmed neutrino masses and lepton mixing



Neutrino masses and lepton mixing

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

Flavour eigenstates **Mass eigenstates**

$$m_1, m_2, m_3$$

$$\Delta m^2_{21} = m^2_2 - m^2_1 \qquad \Delta m^2_{31} = m^2_3 - m^2_1$$

Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\frac{\alpha_{21}}{2}} & \\ & & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$$

Atmospheric **Reactor** **Solar** **Majorana**

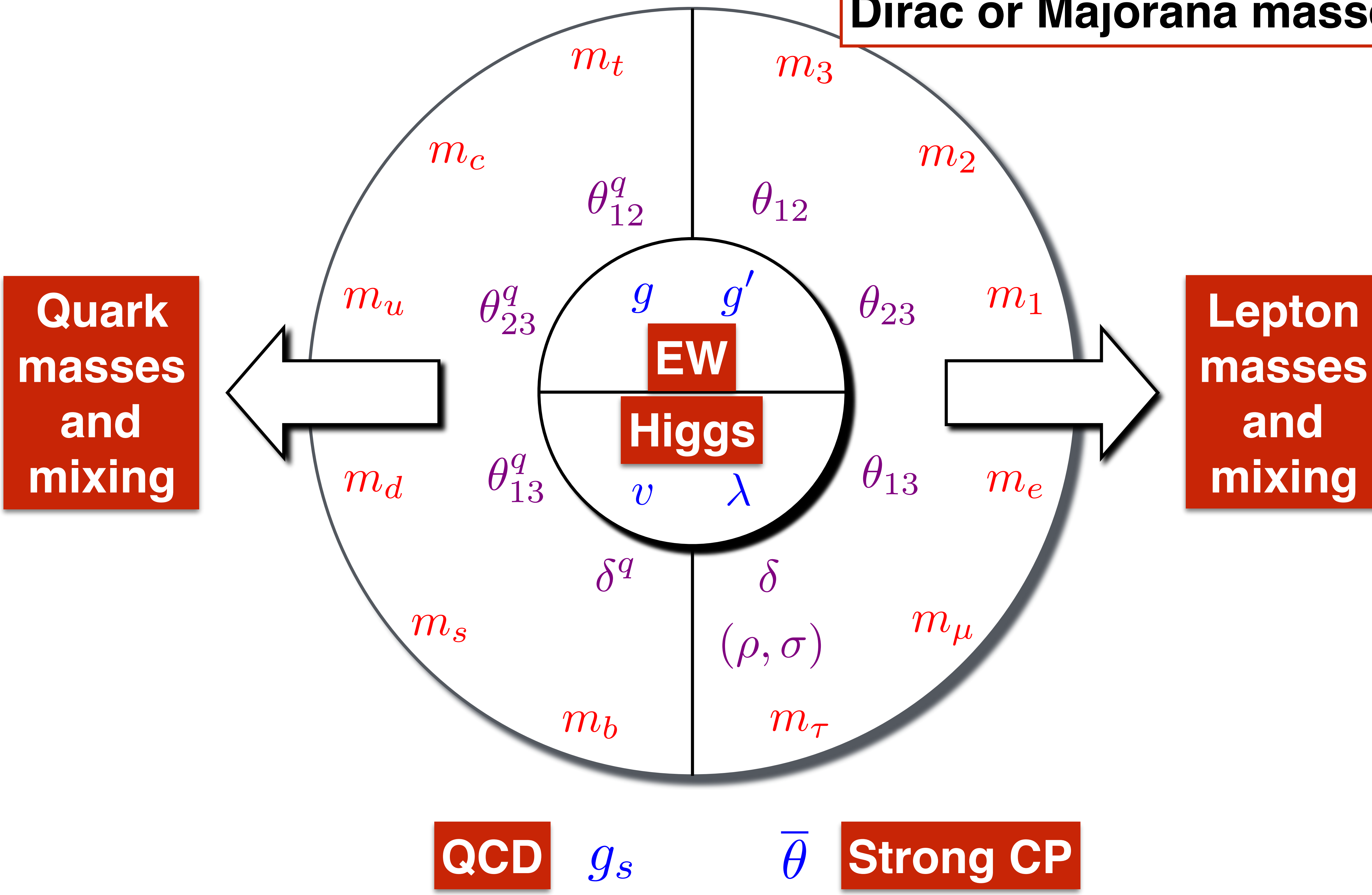
Mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$ $\quad c_{ij} = \cos\theta_{ij},\ s_{ij} = \sin\theta_{ij}$

CP-violating phases Dirac-type δ Majorana-type α_{21}, α_{31}

SM + massive neutrinos

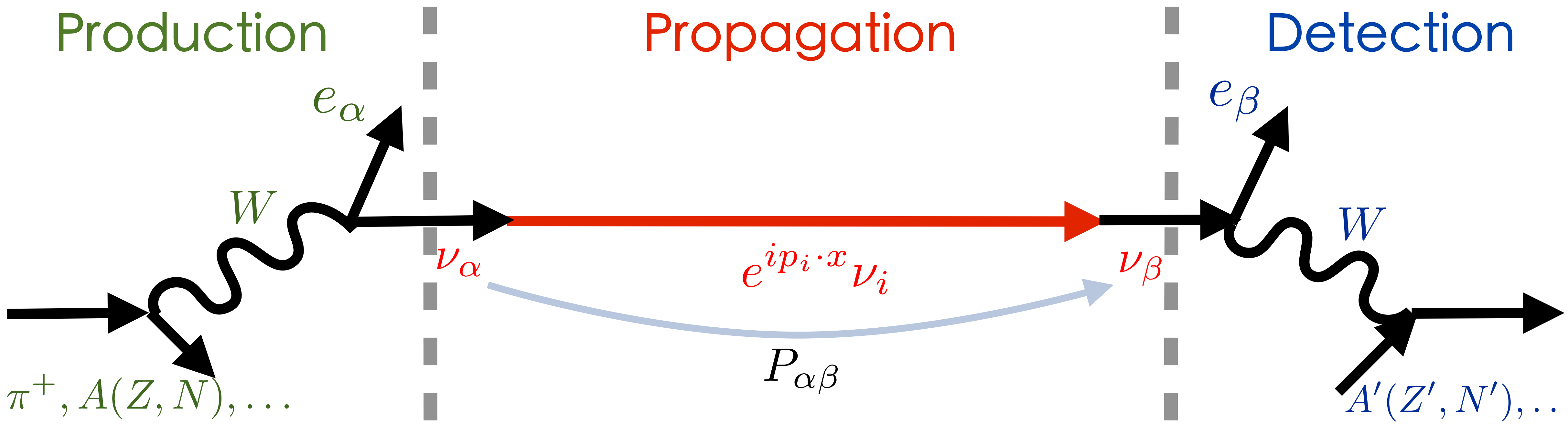
24(26)+2 free parameters

Neutrinos may take Dirac or Majorana masses



Neutrino oscillations

Active neutrino oscillation in neutrino oscillation experiments



$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \qquad |\nu_\alpha(x)\rangle = \sum_i U^*_{\alpha i} e^{ip_i \cdot x} |\nu_i\rangle \qquad \langle \nu_\beta | \nu_\alpha(x)\rangle = \sum_i U^*_{\alpha i} U_{\beta i} e^{ip_i \cdot x}$$

probability $P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(x)\rangle|^2$

$$P(\nu_\alpha \to \nu_\beta) - P(\overline{\nu}_\alpha \to \overline{\nu}_\beta) =$$

CP asymmetry

$$\sum_{i \neq j} \ \mathrm{Im}\{\exp(-i \int_0^t \frac{\Delta m^2_{ij}}{2E} dt)\} \times \mathrm{Im}\{U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}\}$$

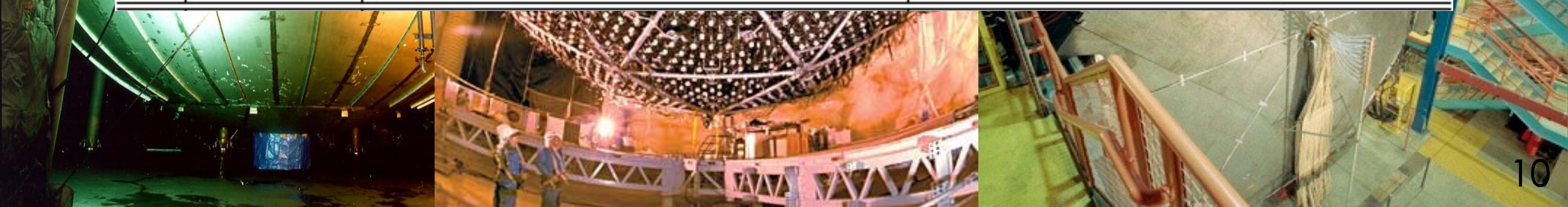
$\alpha \neq \beta$

Kinetic contribution **Interaction contribution**

Neutrino oscillations

NuFIT 4.1 (2019)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.2$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.558^{+0.020}_{-0.033}$	$0.427 \to 0.609$	$0.563^{+0.019}_{-0.026}$	$0.430 \to 0.612$
	$\theta_{23}/^\circ$	$48.3^{+1.1}_{-1.9}$	$40.8 \to 51.3$	$48.6^{+1.1}_{-1.5}$	$41.0 \to 51.5$
	$\sin^2\theta_{13}$	$0.02241^{+0.00066}_{-0.00065}$	$0.02046 \to 0.02440$	$0.02261^{+0.00067}_{-0.00064}$	$0.02066 \to 0.02461$
	$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.12}$	$8.26 \to 9.02$
	$\delta_{CP}/^\circ$	222^{+38}_{-28}	$141 \to 370$	285^{+24}_{-26}	$205 \to 354$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.523^{+0.032}_{-0.030}$	$+2.432 \to +2.618$	$-2.509^{+0.032}_{-0.030}$	$-2.603 \to -2.416$



Origin of neutrino masses

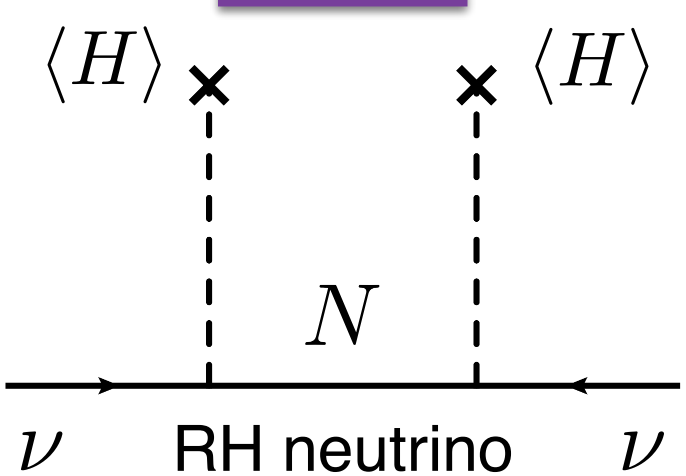
- **Weinberg Operator**

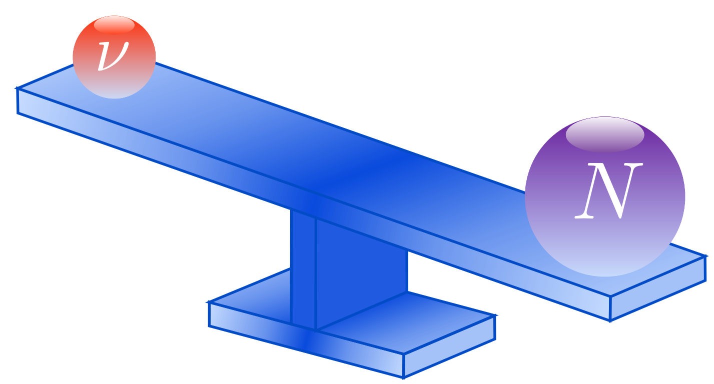
$$\mathcal{L}_W = \frac{\lambda_{\alpha\beta}}{\Lambda}\ell_{\alpha L} H C \ell_{\beta L} H + \text{h.c.}$$

Lepton number violation **Majorana masses**

- **Seesaw mechanism**

Type I



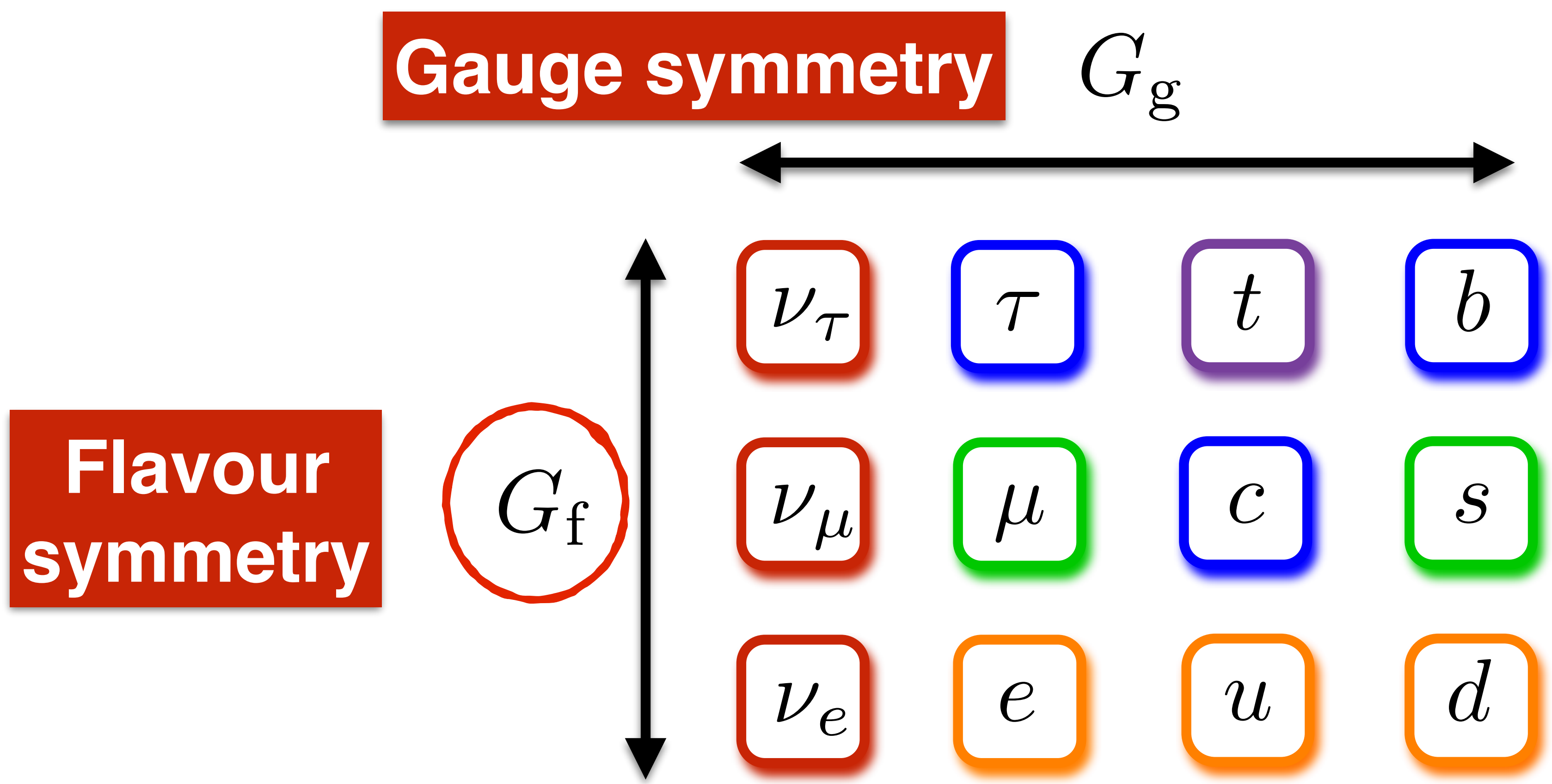


$$-\mathcal{L} = y\bar{\ell} H N + \frac{1}{2} m_N \overline{N^c} N + \text{h.c.}$$

$$m_D = y\langle H \rangle \qquad m_\nu = -\frac{m_D^2}{m_N}$$

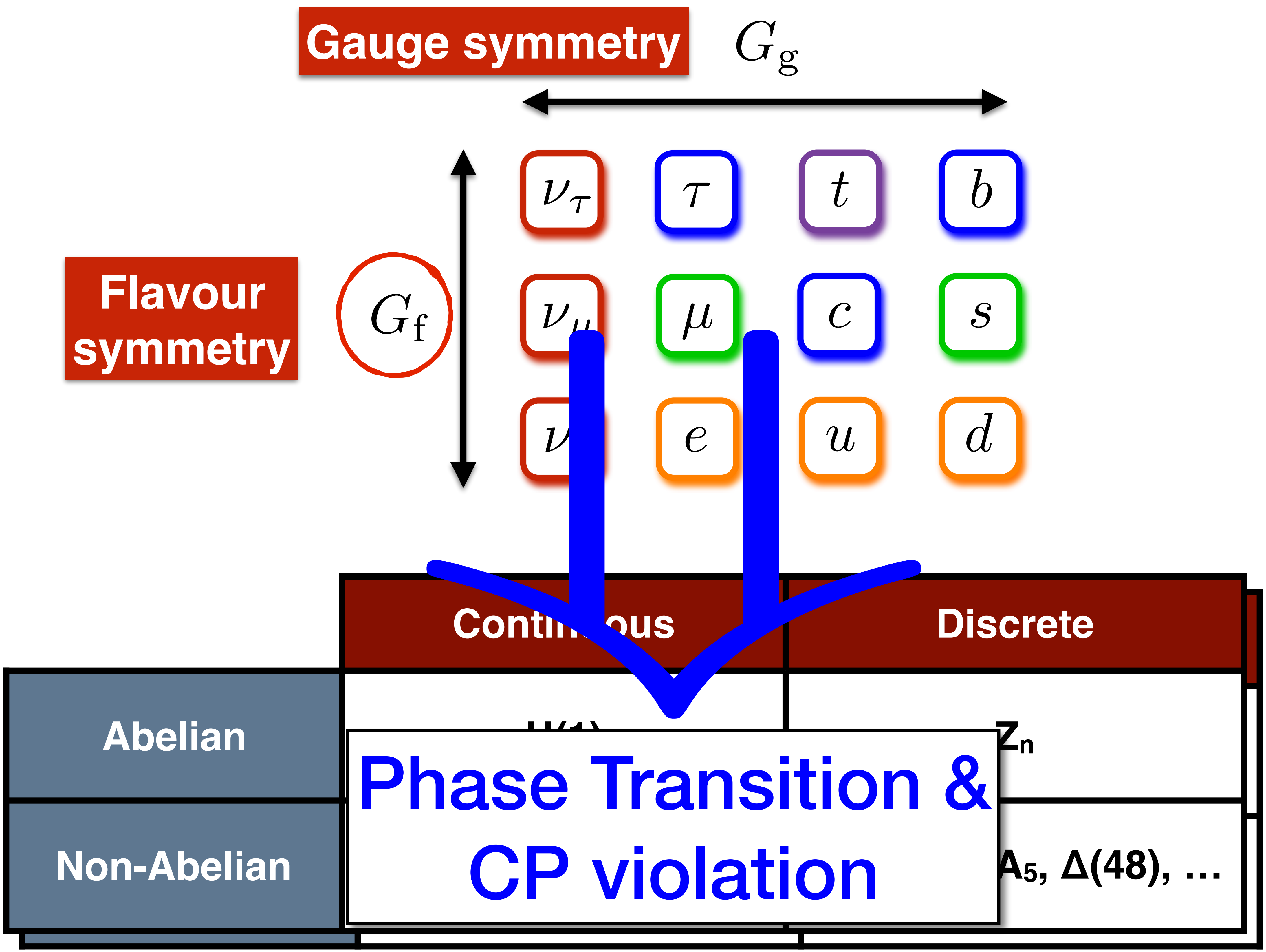
- **U(1)$_{B-L}$, Left Right Symm Model, GUT, …**

Origin of lepton flavour mixing



	Continuous	Discrete
Abelian	U(1)	Z_n
Non-Abelian	SU(3), SO(3),…	A_4, S_4, T', A_5, Δ(48), …

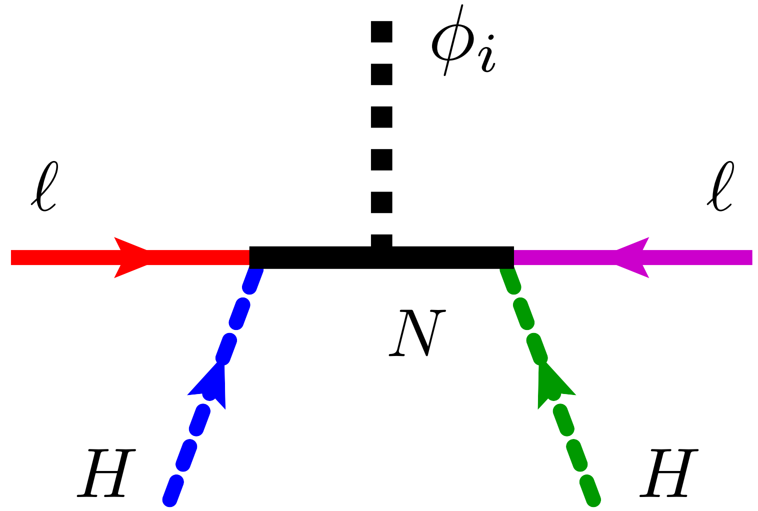
Origin of lepton flavour mixing



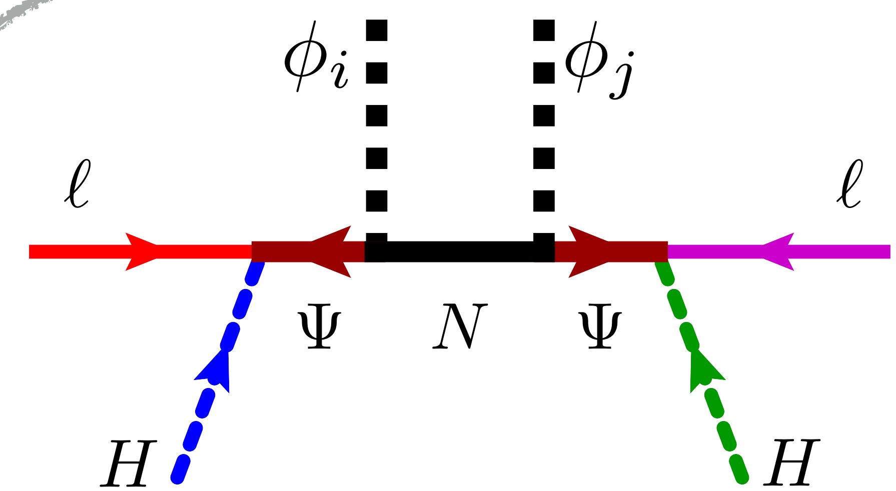
Spacetime-varying Weinberg operator

- UV completion

Option 1:
varying RH neutrino mass



Option 2:
varying Yukawa coupling



Ψ: vector-like fermion

- After the decouple of heavy fermions

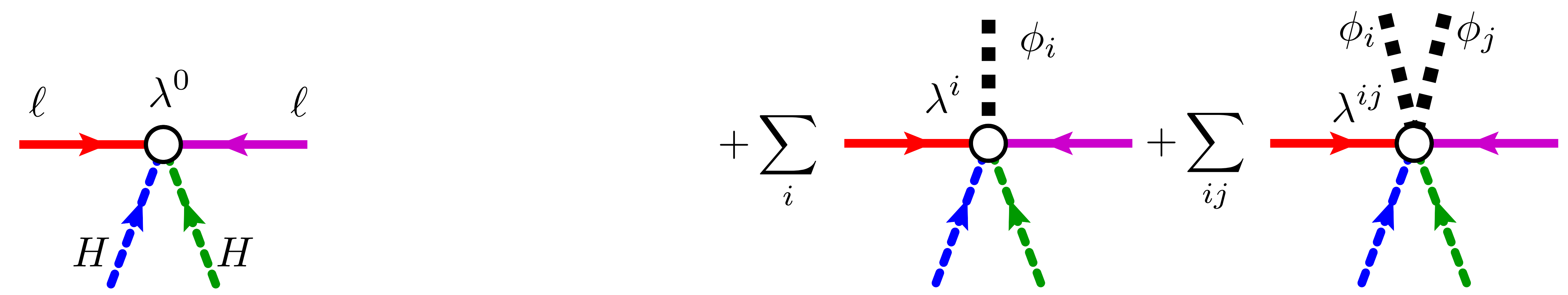
$$\mathcal{L}_{\rm W} = \frac{\lambda_{\alpha\beta}}{\Lambda}\ell_{\alpha L}HC\ell_{\beta L}H + \frac{\lambda^*_{\alpha\beta}}{\Lambda}\overline{\ell_{\alpha L}}H^*C\overline{\ell_{\beta L}}H^*\,,$$

$$\lambda_{\alpha\beta} = \lambda^0_{\alpha\beta} + \sum_{i=1}^{n}\lambda^i_{\alpha\beta}\frac{\phi_i}{v_{\phi_i}} + \sum_{i,j=1}^{n}\lambda^{ij}_{\alpha\beta}\frac{\phi_i}{v_{\phi_i}}\frac{\phi_j}{v_{\phi_j}} + \cdots$$

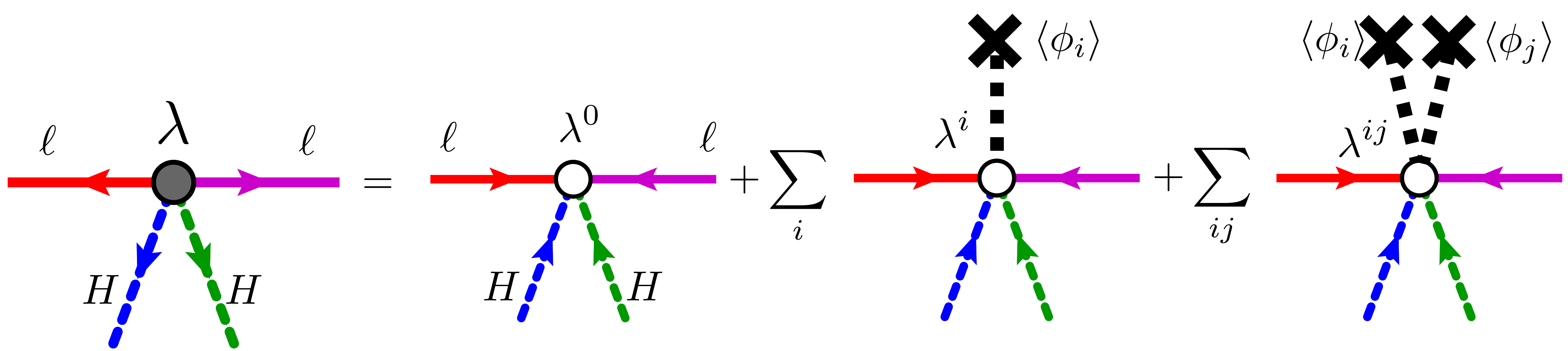
Assuming phase transition temperature lower than the mass scale of heavy fermions

Spacetime-varying Weinberg operator

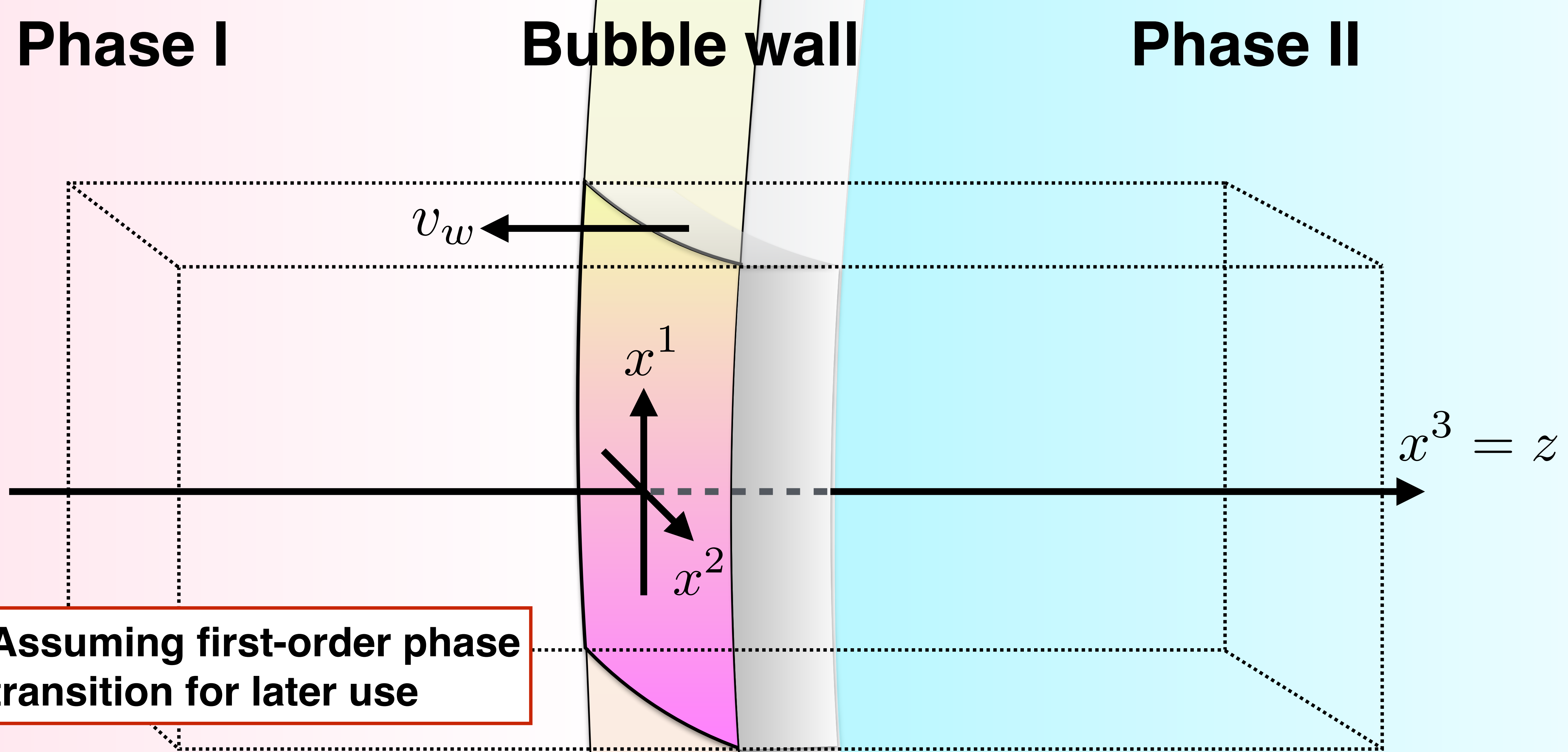
- Weinberg operator before phase transition



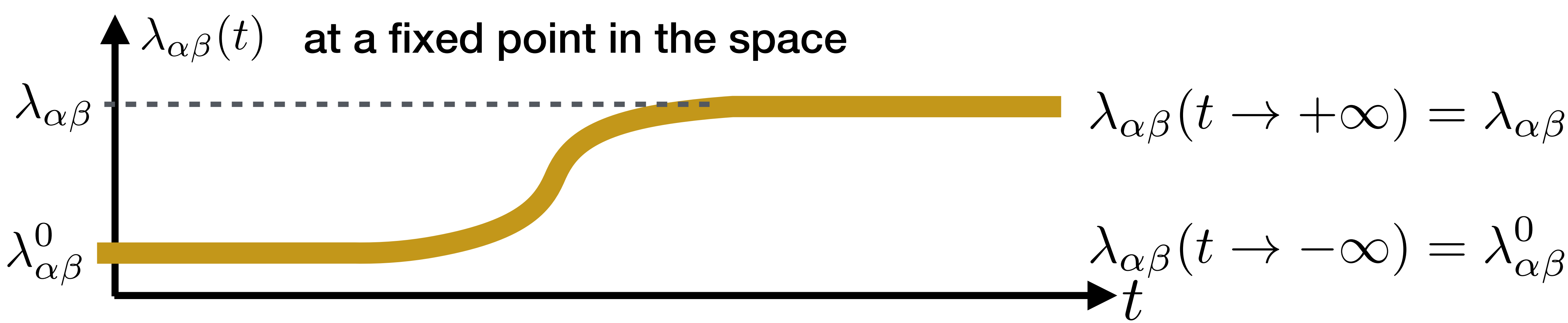
- Weinberg operator after phase transition



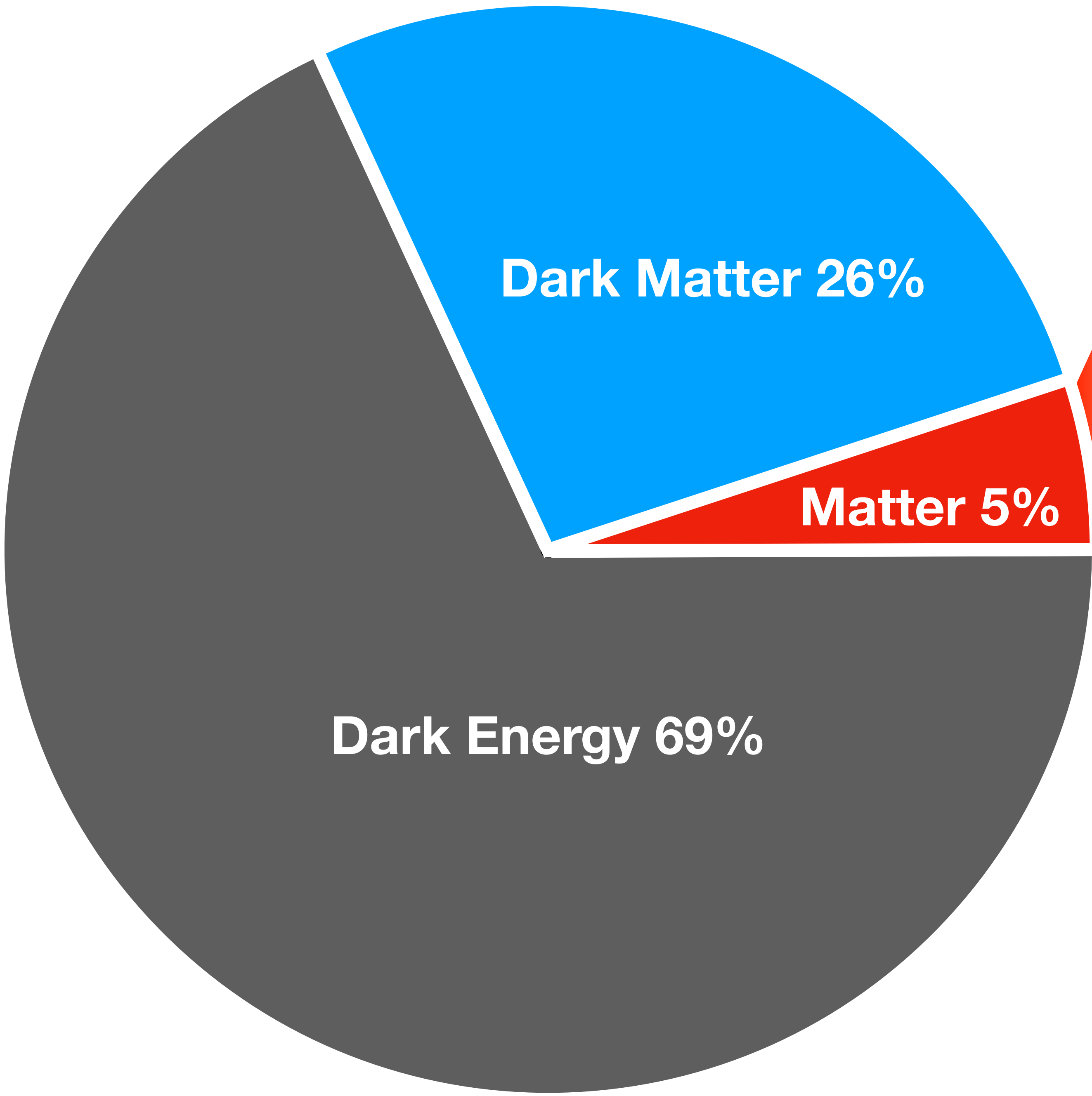
Spacetime-varying Weinberg operator



Assuming first-order phase transition for later use



Baryon-antibaryon asymmetry



Most matter is formed by baryon, not anti-baryon.

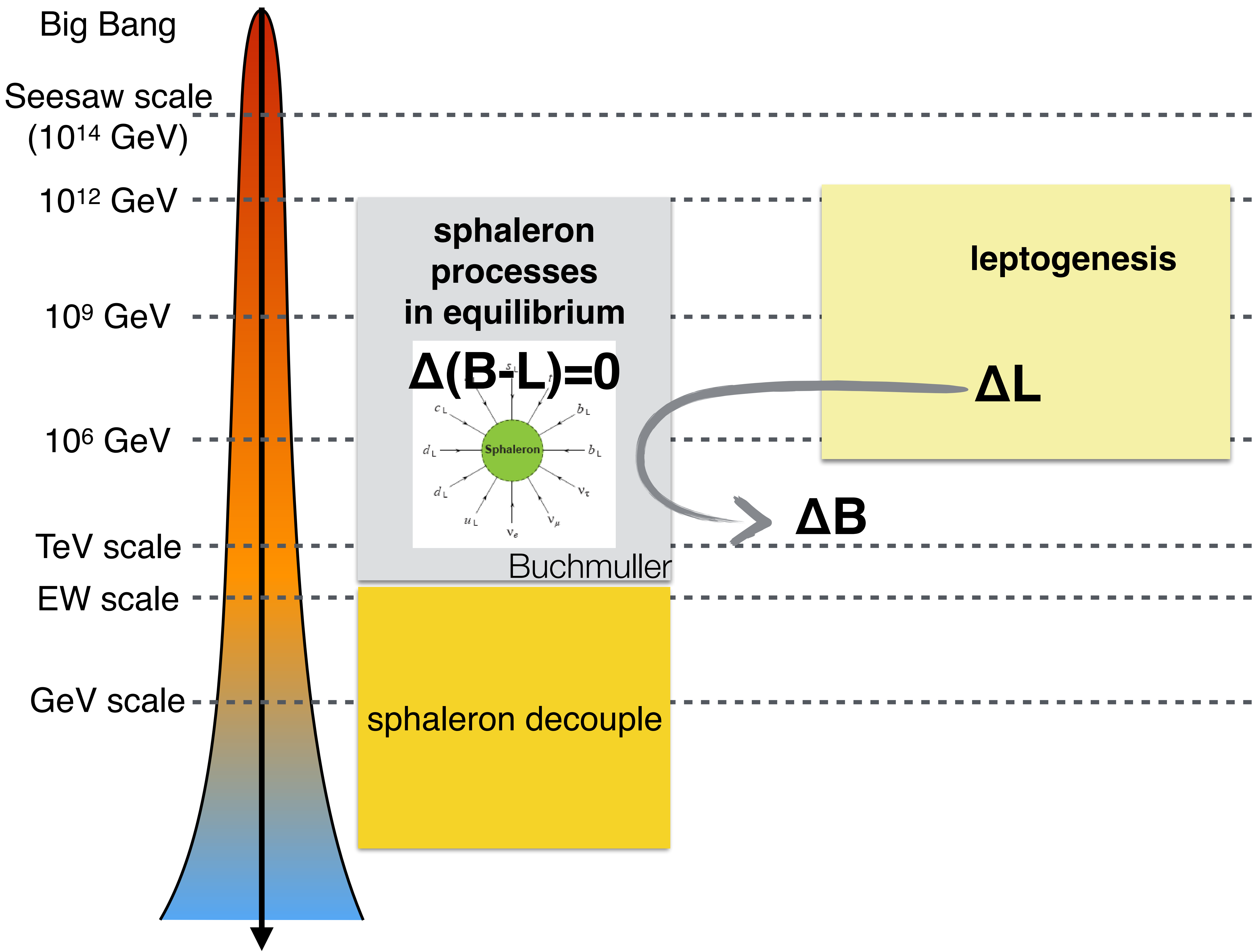
$$\eta_B \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma}$$
$$= (6.12 \pm 0.04) \times 10^{-10}$$

Planck 2018

The SM cannot provide strong out-of-equilibrium dynamics and enough CP violation.

Parameter(s)	$\Omega_b h^2$	$\Omega_c h^2$	$100\theta_{MC}$	H_0	n_s	$\ln(10^{10} A_s)$
Base ΛCDM	0.02237 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.54	0.9649 ± 0.0042	3.044 ± 0.014
r	0.02237 ± 0.00014	0.1199 ± 0.0012	1.04092 ± 0.00031	67.40 ± 0.54	0.9659 ± 0.0041	3.044 ± 0.014
$dn_s/d\ln k$	0.02240 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.53	0.9641 ± 0.0044	3.047 ± 0.015
$dn_s/d\ln k, r$	0.02243 ± 0.00015	0.1199 ± 0.0012	1.04093 ± 0.00030	67.44 ± 0.54	0.9647 ± 0.0044	3.049 ± 0.015
$d^2n_s/d\ln k^2, dn_s/d\ln k$.	0.02237 ± 0.00016	0.1202 ± 0.0012	1.04090 ± 0.00030	67.28 ± 0.56	0.9625 ± 0.0048	3.049 ± 0.015
N_{eff}	0.02224 ± 0.00022	0.1179 ± 0.0028	1.04116 ± 0.00043	66.3 ± 1.4	0.9589 ± 0.0084	3.036 ± 0.017

Baryogenesis via leptogenesis



Sakharov conditions for leptogenesis

B violation $\Longrightarrow$ **SM L/B-L violation**

(sphaleron processes)

C/CP violation

Out of equilibrium dynamics

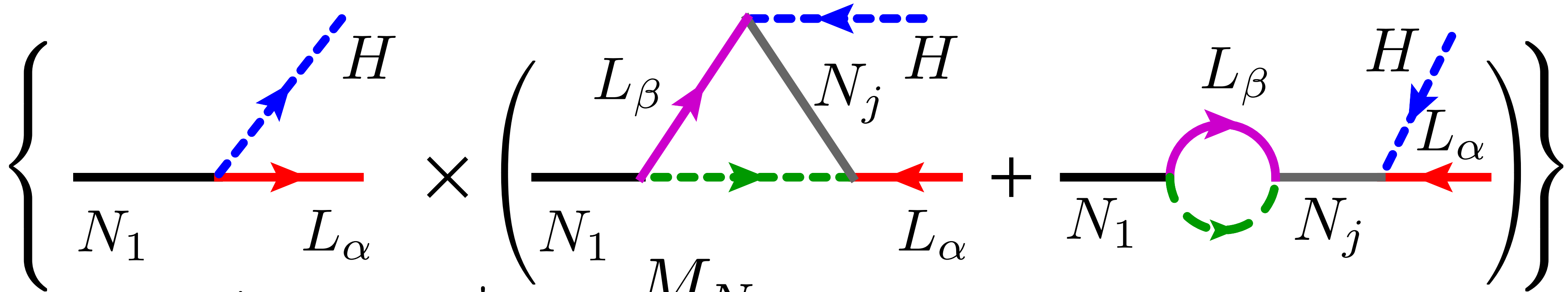
Leptogenesis via RH neutrinos

- **Classical thermal leptogenesis (in type-I seesaw)**

RH neutrino *N* | **Complex Yukawa couplings** | **Decay of lightest *N***

- **Lepton asymmetry** $\Delta f_{\ell_\alpha} \equiv f_{\ell_\alpha} - f_{\bar{\ell}_\alpha}$

$\Delta f_{\ell_\alpha} \propto \mathrm{Im}$



CP asymmetry

$$\propto \mathrm{Im}\{Y_{\alpha I}(Y^\dagger Y)_{IJ} Y^\dagger_{J\alpha}\} \times \frac{M_N}{16\pi} \cdots$$

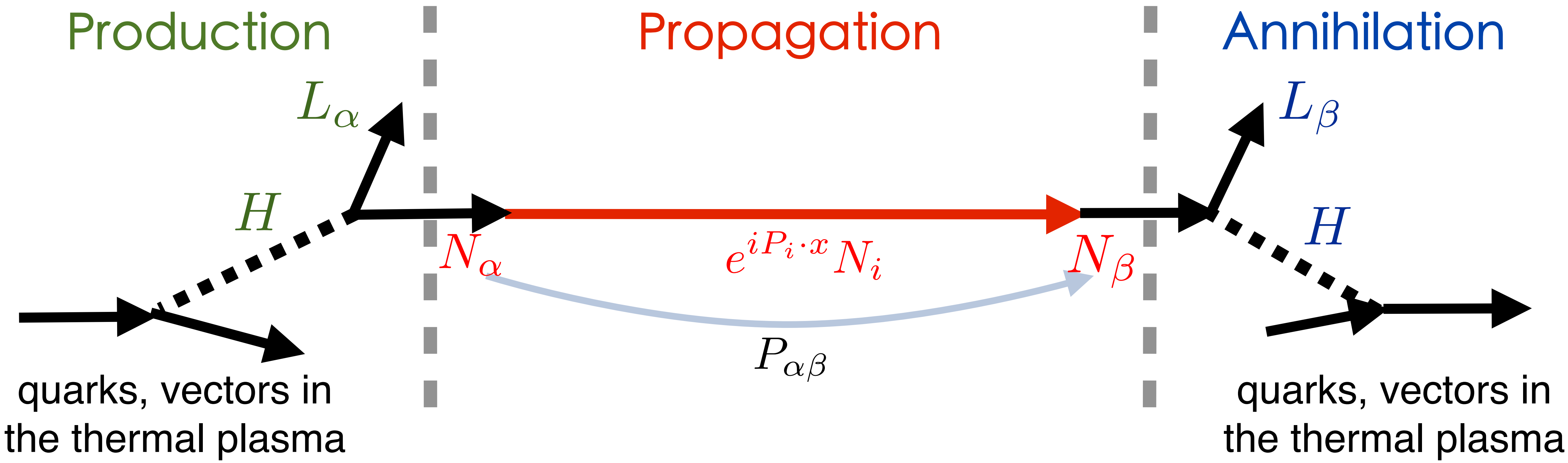
[Fukugita, Yanagida, 1986]

- **Flavour effects, Resonant leptogenesis, N_2 decay leptogenesis, …**

Pilaftsis, hep-ph/9702393, hep-ph/9707235; Pilaftsis, Underwood, hep-ph/0309342; Barbieri, Creminelli, Strumia, Tetradis, hep-ph/9911315; Vives, hep-ph/0512160; Nardi, Nir, Roulet, Racker, hep-ph/0601084; Abada, Davidson, Josse-Michaux, Losada, Riotto, hep-ph/0601083; Blanchet, Di Bari, hep-ph/0607330, ……

Leptogenesis via RH neutrinos

Sterile neutrino oscillation in early Universe



The "generalised" lepton number $\mathbf{L} = L + L_N$ is conserved.

$$\Delta_{\alpha\alpha} \propto \sum_\beta P(N_\beta \to N_\alpha) - P(\overline{N}_\beta - \overline{N}_\alpha) - P(N_\alpha \to N_\beta) + P(\overline{N}_\alpha - \overline{N}_\beta)$$

CP asymmetry

$$\propto \mathrm{Im}\{\exp(-i\int_0^t \frac{\Delta M^2_{IJ}}{2E}\mathrm{d}t)\} \times \mathrm{Im}\{Y_{\alpha I}(Y^\dagger Y)_{IJ} Y^\dagger_{J\alpha}\}$$

Akhmedov, Rubakov, Smirnov, hep-ph/9803255

Asaka and Shaposhnikov, hep-ph/0505013; Drewes, et al, 1606.06690, 1609.09069; Hernández, et al, 1606.06719; Drewes et al, 1711.02862, ……

Leptogenesis via leptonic phase transition

Weinberg operator + **leptonic phase transition**

1. Baryogenesis via leptonic CP-violating phase transition
   S Pascoli, J Turner, **YLZ**, arXiv:1609.07969
2. Leptogenesis via Varying Weinberg Operator: the Closed-Time-Path Approach,
   J Turner, **YLZ**, arXiv:1808.00470
3. Leptogenesis via Varying Weinberg Operator: a Semi-Classical Approach
   S Pascoli, J Turner, **YLZ**, arXiv:1808.00475

Role of Weinberg operator

A consistent Weinberg operator provides two Sakharov conditions

- The Weinberg operator violates lepton number and leads to LNV processes in the thermal universe.

$$H^*H^* \leftrightarrow \ell\ell\,,\quad \bar{\ell}H^* \leftrightarrow \ell H\,,\quad \bar{\ell}H^*H^* \leftrightarrow \ell\,,$$
$$\bar{\ell} \leftrightarrow \ell H H\,,\quad H^* \leftrightarrow \ell\ell H\,,\quad 0 \leftrightarrow \ell\ell H H$$

and their CP-conjugate processes

- The Weinberg operator is very weak and can directly provide out of equilibrium dynamics in the early Universe.

$$T < 10^{12}\,\mathrm{GeV}$$

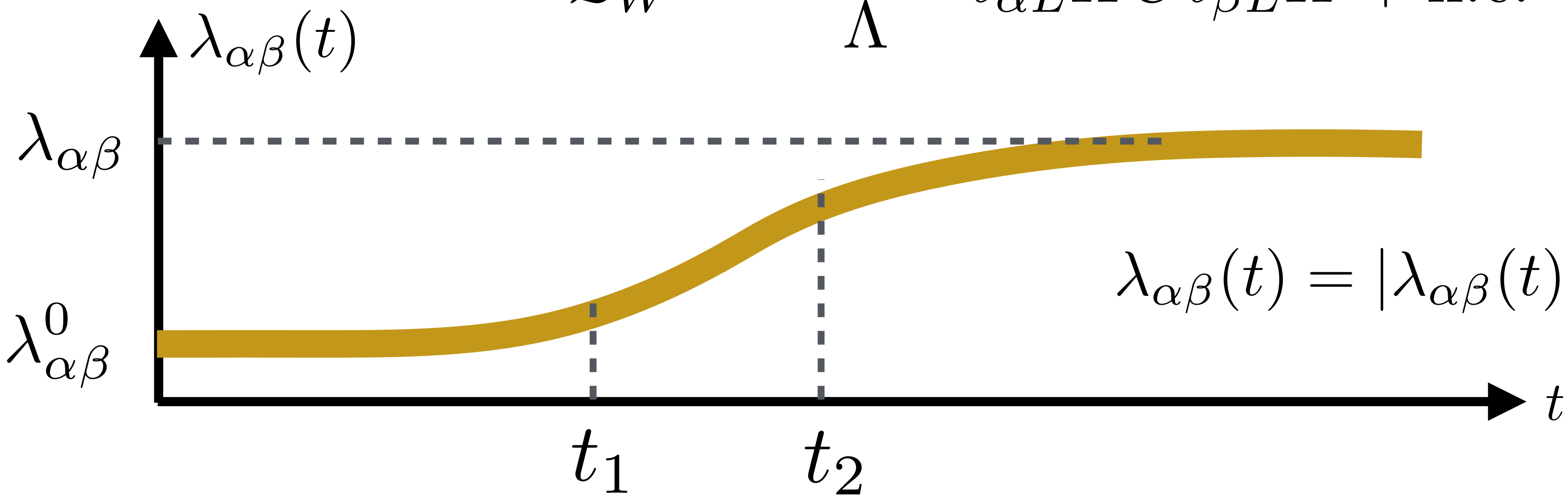
$$\Gamma_{\mathrm{W}} \sim \langle \sigma n \rangle \sim \frac{3}{(4\pi)^3}\frac{\lambda^2}{\Lambda^2}T^3 \sim \frac{3}{(4\pi)^3}\frac{m_\nu^2 T^3}{v_H^4} < H_u \sim 10\frac{T^2}{m_{\mathrm{pl}}}$$

No washout if there are no other LNV sources.

CP violation induced by varying Weinberg operator

- The coefficient of the Weinberg operator is varying

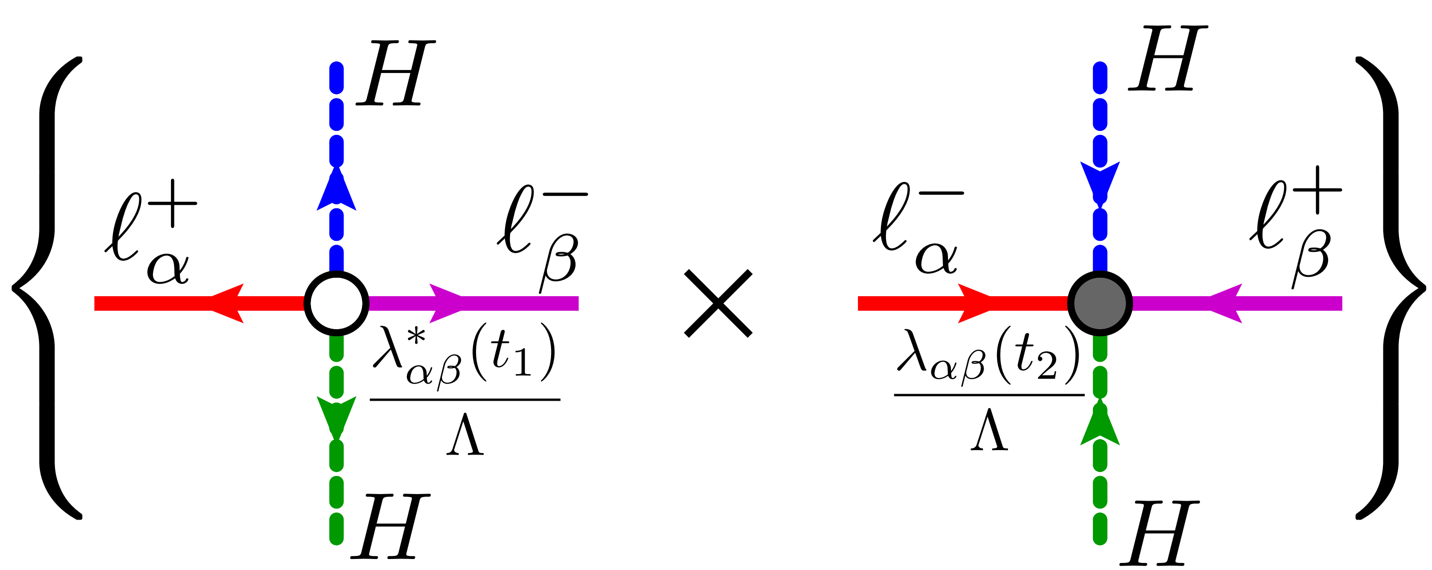
$$\mathcal{L}_W = \frac{\lambda_{\alpha\beta}(t)}{\Lambda}\ell_{\alpha L} H C \ell_{\beta L} H + \text{h.c.}$$



$$\lambda_{\alpha\beta}(t) = |\lambda_{\alpha\beta}(t)| e^{i\phi_{\alpha\beta}(t)}$$

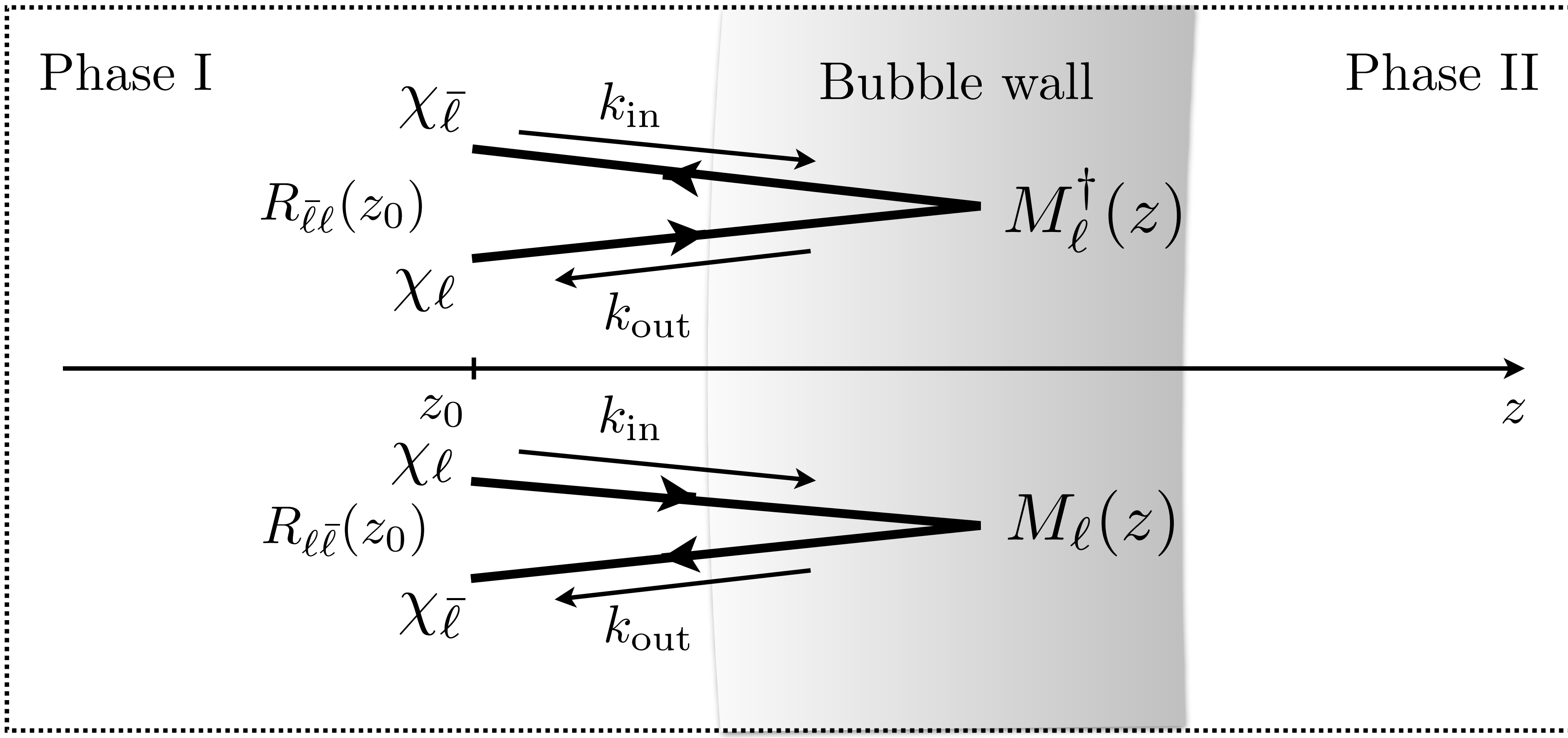
- Including spacetime-varying effect, the CP violation can be satisfied, and the lepton asymmetry is generated by the interference of the Weinberg operators at different times

$$\Delta f_{\ell_\alpha} \propto \text{Im}\left\{ \quad \right\}$$



Lepton asymmetry in Semi-classical approach

In the rest wall frame



wave functions of lepton and anti lepton

$$\chi_{\bar{\ell}}(x) = \begin{pmatrix} -\chi_{\bar{\nu}}(x) \\ \chi_{\bar{l}}(x) \end{pmatrix}$$

$$\chi_\ell(x) = \begin{pmatrix} \chi_\nu(x) \\ \chi_l(x) \end{pmatrix}$$

Majorana-like mass matrix

$$M_\ell^\dagger(x) = \frac{\lambda(x)}{\Lambda} \begin{pmatrix} 2\left[H^0(x)\right]^2 & -2H^0(x)H^+(x) \\ -2H^0(x)H^+(x) & 2\left[H^+(x)\right]^2 \end{pmatrix}$$

- We treating the Higgs as a background field in the thermal bath

$$\langle H^{0*}H^0\rangle = \langle H^{+*}H^+\rangle = \frac{1}{2}\langle H^\dagger H\rangle = 2\int \frac{d^3k}{(2\pi)^3}\frac{1}{2\omega}\frac{1}{e^{\beta\omega}-1} = \frac{T^2}{12},$$

Lepton asymmetry in Semi-classical approach

- The "EOM" of lepton and antilepton

$$i\partial\!\!\!/ \ell_L + M_\ell C \overline{\ell_L}^T = 0$$

$$\ell_L = \begin{pmatrix} \exp[-i(\omega t - k_{\rm in} z)]\chi_{1\ell}(z) \\ \exp[-i(\omega t + k_{\rm out} z)]\chi_{2\ell}(z) \\ 0 \\ 0 \end{pmatrix}$$

$$\overline{\ell_L}^T = \begin{pmatrix} 0 \\ 0 \\ \exp[+i(\omega t - k_{\rm in} z)]\chi_{1\bar\ell}(z) \\ \exp[+i(\omega t + k_{\rm out} z)]\chi_{2\bar\ell}(z) \end{pmatrix}$$

- We further include the decoherence effect is included by replacing the incoming and outgoing momentums

$$k_{\rm in} \to K_{\rm in} = k_{\rm in} + \frac{i}{2L}, \quad k_{\rm out} \to K_{\rm out} = k_{\rm out} - \frac{i}{2L}$$

$L = \frac{1}{6\gamma}$ decoherence length, avoiding interference between infinite distance

- EOM of lepton-antilepton propagating along the z direction is given by

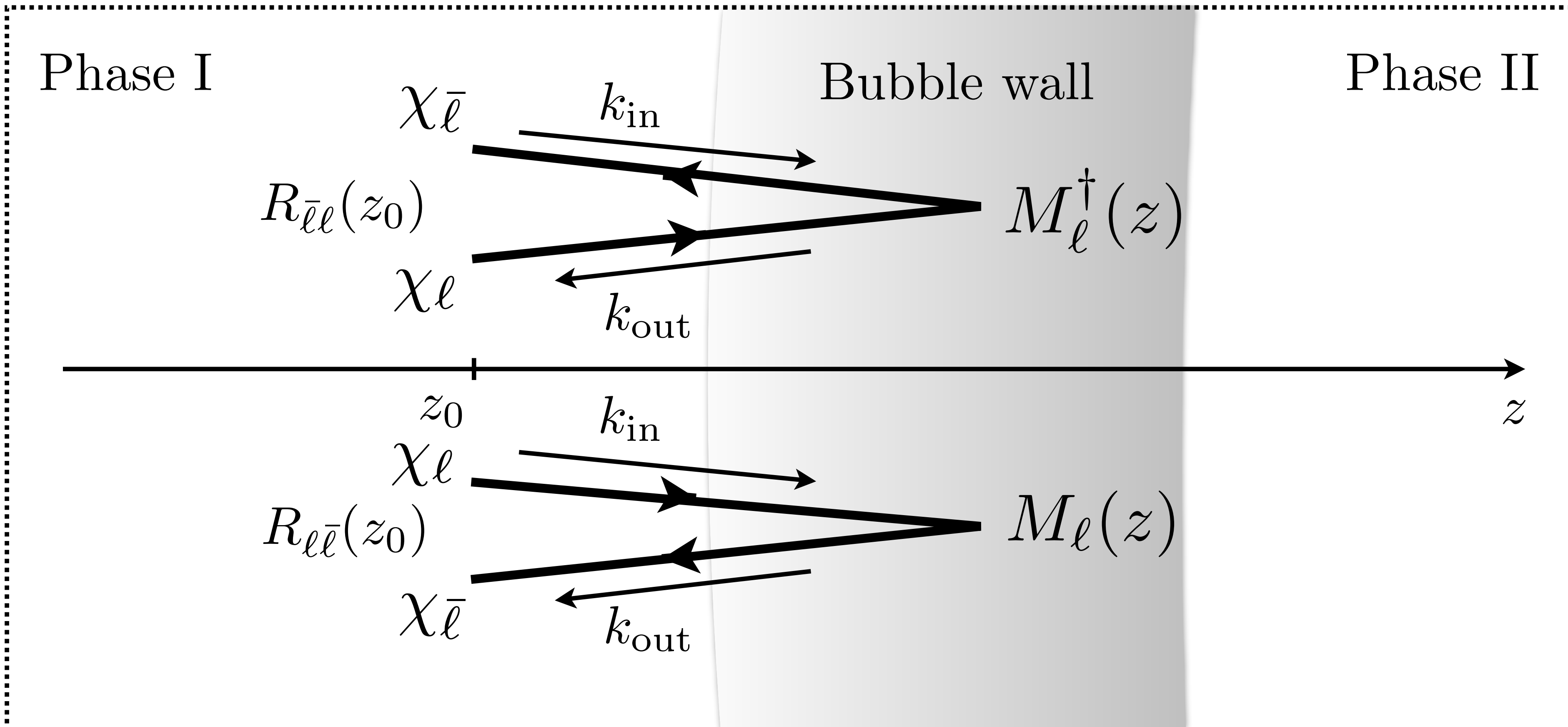
$$\left[(-i\partial_z + \omega)\mathbb{1}_2 - \begin{pmatrix} -K_{\rm in} & M_\ell^\dagger(z) \\ -M_\ell(z) & -K_{\rm out} \end{pmatrix}\right] \begin{pmatrix} \chi_{1\ell}(z) \\ \chi_{2\bar\ell}(z) \end{pmatrix} = 0. \qquad j_z = +\frac{1}{2}$$

$$\left[(-i\partial_z - \omega)\mathbb{1}_2 - \begin{pmatrix} K_{\rm in} & -M_\ell(z) \\ M_\ell^\dagger(z) & K_{\rm out} \end{pmatrix}\right] \begin{pmatrix} \chi_{1\bar\ell}(z) \\ \chi_{2\ell}(z) \end{pmatrix} = 0. \qquad j_z = -\frac{1}{2}$$

[The semi-classical approximation follows the technique of varying mass for left-right chirality transition developed for electroweak baryogenesis in Huet, Sather, hep-ph/9404302]

Lepton asymmetry in Semi-classical approach

In the rest wall frame



$$\chi_{\bar\ell}(x) = \begin{pmatrix} -\chi_{\bar\nu}(x) \\ \chi_{\bar l}(x) \end{pmatrix}$$

$$\chi_\ell(x) = \begin{pmatrix} \chi_\nu(x) \\ \chi_l(x) \end{pmatrix}$$

$$z_1 = z - z_0$$

antilepton to lepton $R_{\bar\ell\ell}(z_0) = i\int_0^{+\infty} dz_1 e^{-z_1/L} e^{ik_{\rm out}z_1} M_\ell^\dagger(z_0+z_1) e^{-ik_{\rm in}z_1}$

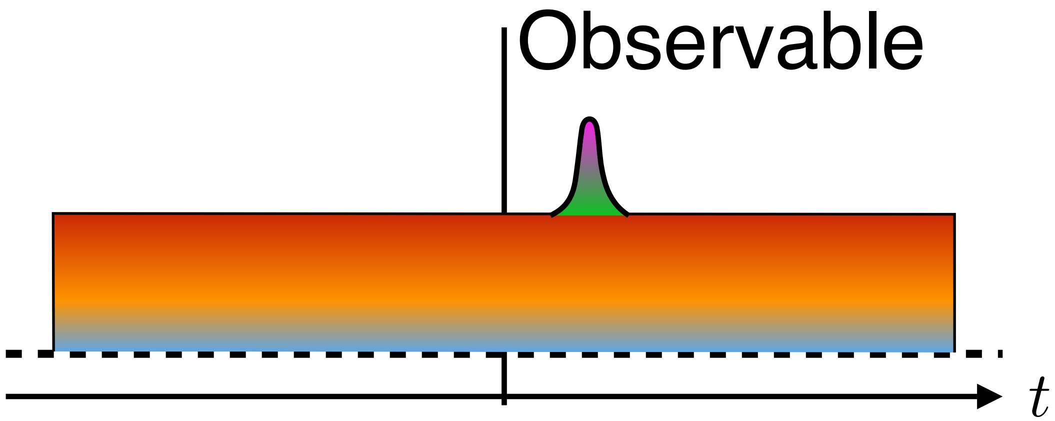
lepton to antilepton $R_{\ell\bar\ell}(z_0) = i\int_0^{+\infty} dz_1 e^{-z_1/L} e^{ik_{\rm out}z_1} M_\ell(z_0+z_1) e^{-ik_{\rm in}z_1}$

$$\Delta_{CP}(z_0) \equiv |R_{\bar\ell\ell}(z_0)|^2 - |R_{\ell\bar\ell}(z_0)|^2 = 2\int_0^{+\infty} dz_1 dz_2 e^{-(z_1+z_2)/L} \sin[(k_{\rm out}-k_{\rm in})(z_1-z_2)] \times {\rm Im}[M_\ell(z_0+z_1) M_\ell^\dagger(z_0+z_2)]$$

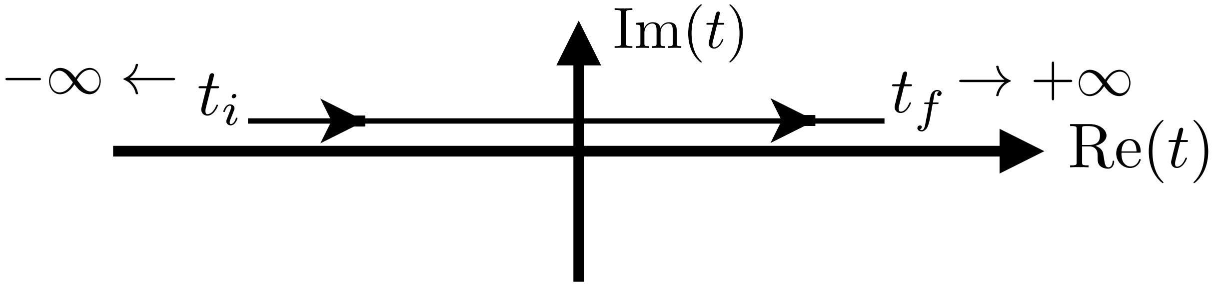
Asymmetry

The closed-time-path approach

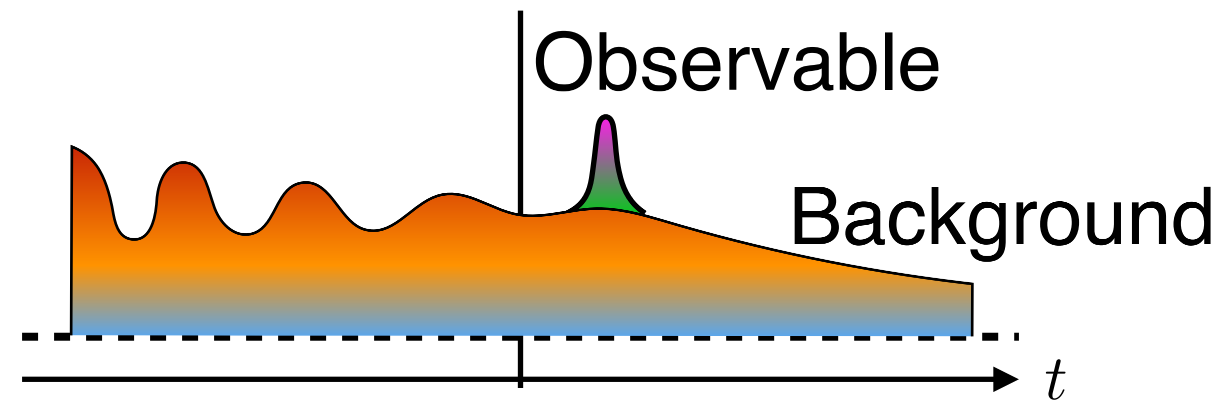
- **Classical QFT**
  at zero temperature,
  or theomal equilibrium



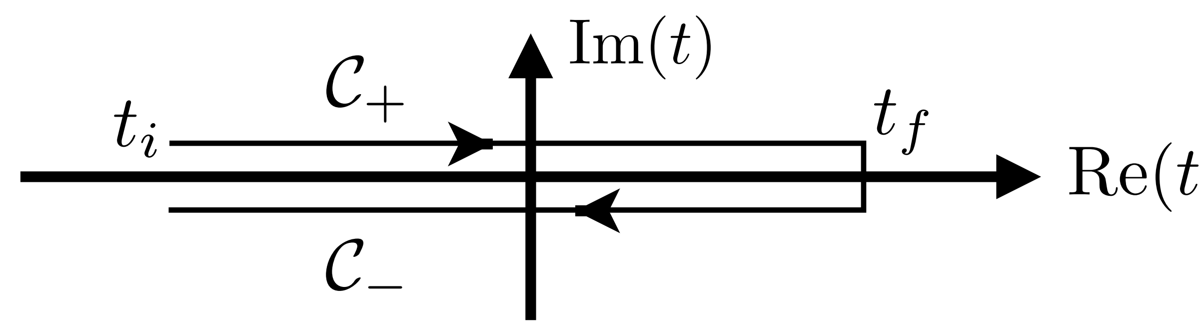
Vacuum/background is in thermal equilibrium, time-dependent



- **QFT in non-equilibrium case**



Background is time-dependent.
We have to specify a time.



$$\mathcal{C} = \mathcal{C}_+ \cup \mathcal{C}_-$$

$$\langle \Omega(t) | \mathcal{O} | \Omega(t) \rangle$$

In-out formalism $\langle \Omega(t_f | \mathcal{O} | \Omega(t_i) \rangle$

In-in formalism $\langle \Omega(t_i) | \mathcal{O} | \Omega(t_i) \rangle$

The closed-time-path approach

- **Propagators**

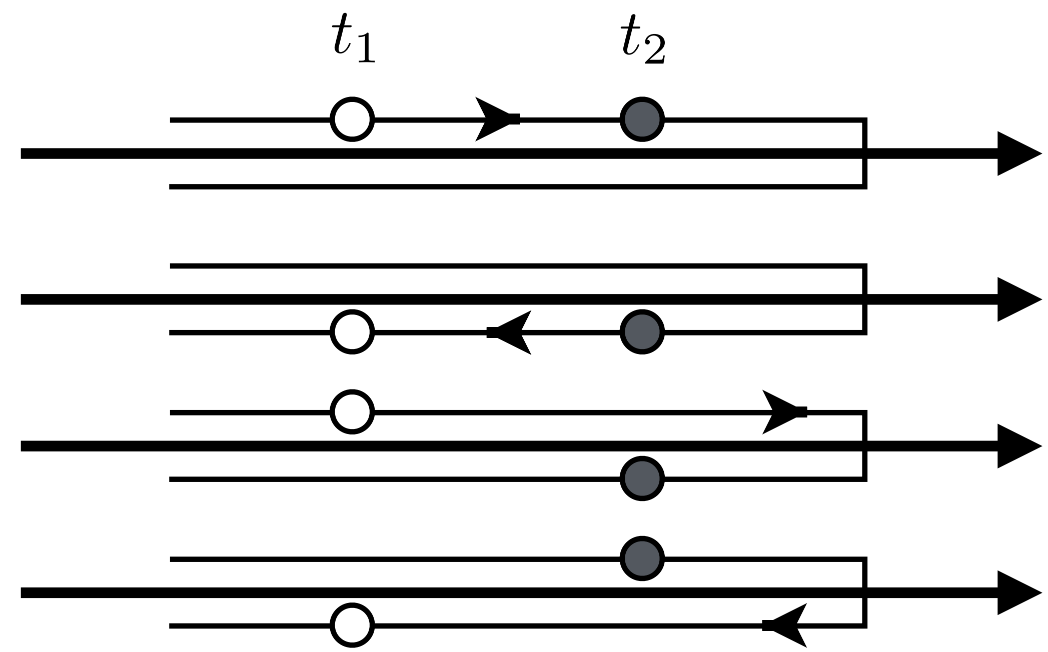
Feynman $S^{T}_{\alpha\beta}(x_1,x_2) = \langle T[\ell_\alpha(x_1)\bar{\ell}_\beta(x_2)]\rangle$

Dyson $S^{\bar{T}}_{\alpha\beta}(x_1,x_2) = \langle \bar{T}[\ell_\alpha(x_1)\bar{\ell}_\beta(x_2)]\rangle$

Wightman

$S^{<}_{\alpha\beta}(x_1,x_2) = -\langle \bar{\ell}_\beta(x_2)\ell_\alpha(x_1)\rangle$

$S^{>}_{\alpha\beta}(x_1,x_2) = \langle \ell_\alpha(x_1)\bar{\ell}_\beta(x_2)\rangle$



$x_1^\mu = (t_1, \vec{x}_1)$ $x_2^\mu = (t_2, \vec{x}_2)$

- **Kadanoff-Baym equation**

$$i\partial\!\!\!/ S^{<,>} - \Sigma^H \odot S^{<,>} - \Sigma^{<,>} \odot S^H = \frac{1}{2}\left[\Sigma^> \odot S^< - \Sigma^< \odot S^>\right]$$

Lepton asymmetry | **Self energy correction** | **Dispersion relations** | **Collision term**

$$\Delta n_{\ell\alpha}(x) = -\frac{1}{2}\mathrm{tr}\left\{\gamma^0\left[S^<_{\alpha\alpha}(x,x) + S^>_{\alpha\alpha}(x,x)\right]\right\}$$

$$\Delta f_{\ell_\alpha}(k) = -\int_{t_i}^{t_f} dt_1 \partial_{t_1} \mathrm{tr}[\gamma_0 S^<_{\vec{k}}(t_1,t_1) + \gamma_0 S^>_{\vec{k}}(t_1,t_1)]$$

$$S^H = S^T - \frac{1}{2}(S^> + S^<)$$

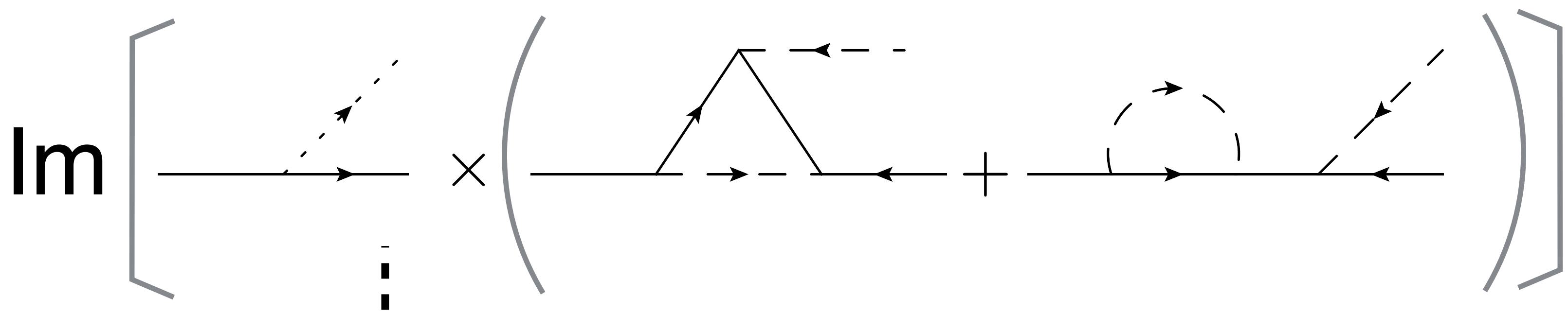
$$\Sigma^H = \Sigma^T - \frac{1}{2}(\Sigma^> + \Sigma^<)$$

CPV source

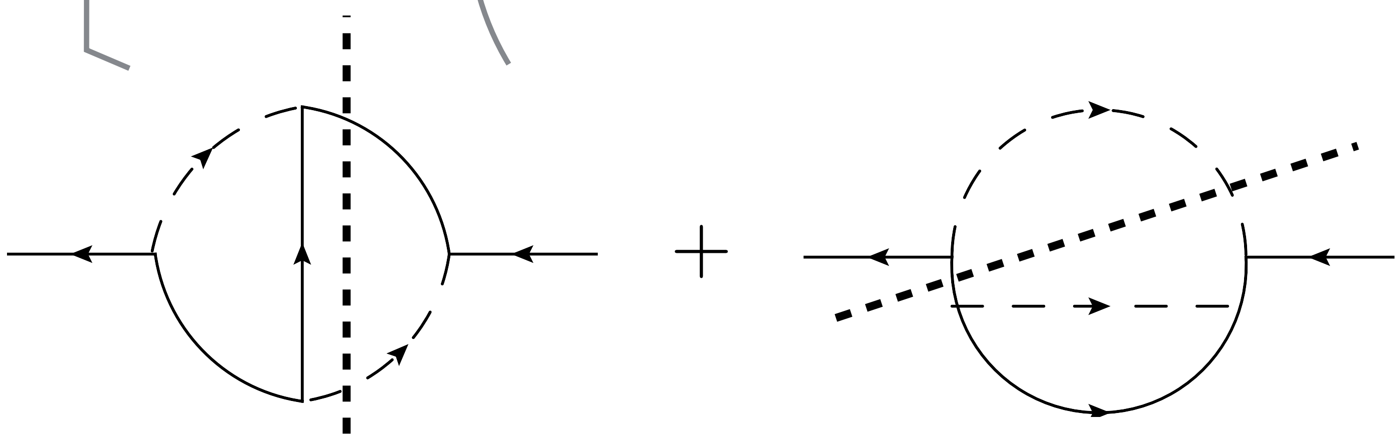
Classical QFT vs CTP formalism

- Leptogenesis via RH neutrino decay

e.g., Anisimov, Buchmuller, Drewes, Mendizabal, 1012.5821



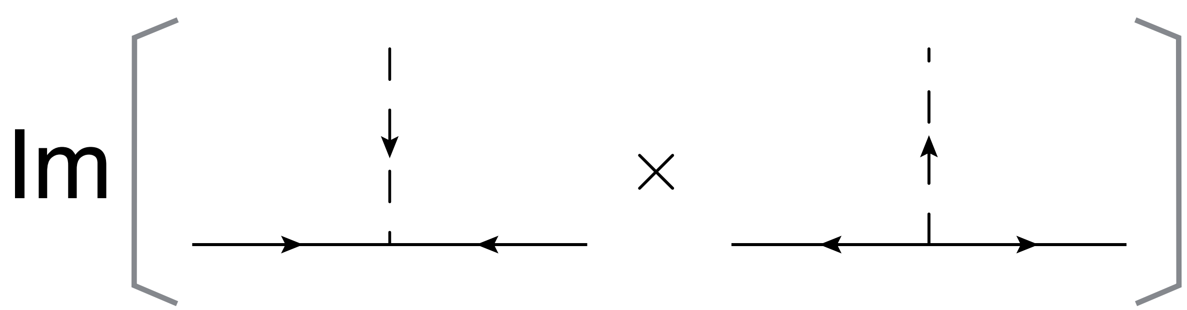
CPV source in classical formalism

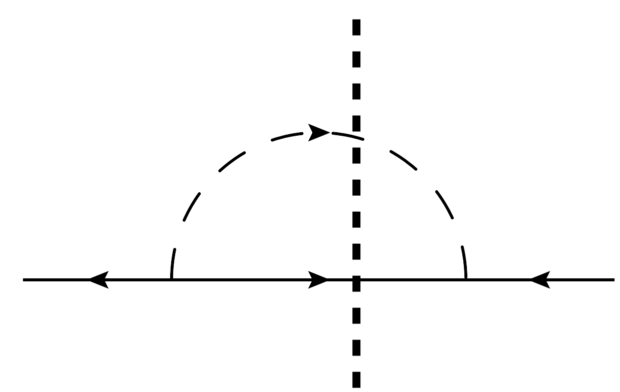


Self energies including CPV source in CTP formalism

- Leptogenesis via RH neutrino oscillation

Drewes, et al, 1711.02862

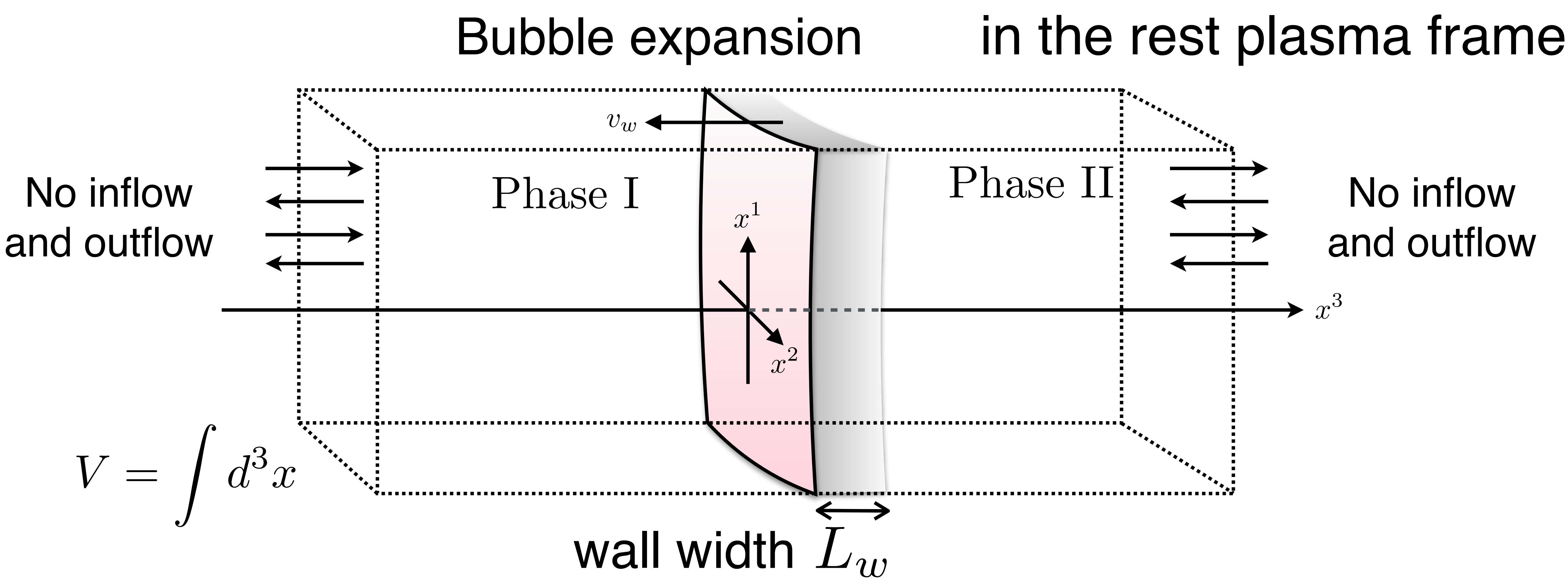




CPV source in classical formalism

Self energy including CPV source in CTP formalism

Lepton asymmetry in CTP approach



$$\Delta N_\ell = N_\ell - N_{\overline{\ell}} = -\int \frac{d^4x_1 d^4k}{(2\pi)^4} \mathrm{tr}[\gamma^\mu i \frac{\partial}{\partial x_1^\mu}(S_k^<(x_1) + S_k^>(x_1))]$$

$$= -\int \underline{d^4x d^4r}\, \mathrm{tr}\Big[\Sigma^>(x_1, x_2) S^<(x_2, x_1) - \Sigma^<(x_1, x_2) S^>(x_2, x_1)\Big] .$$

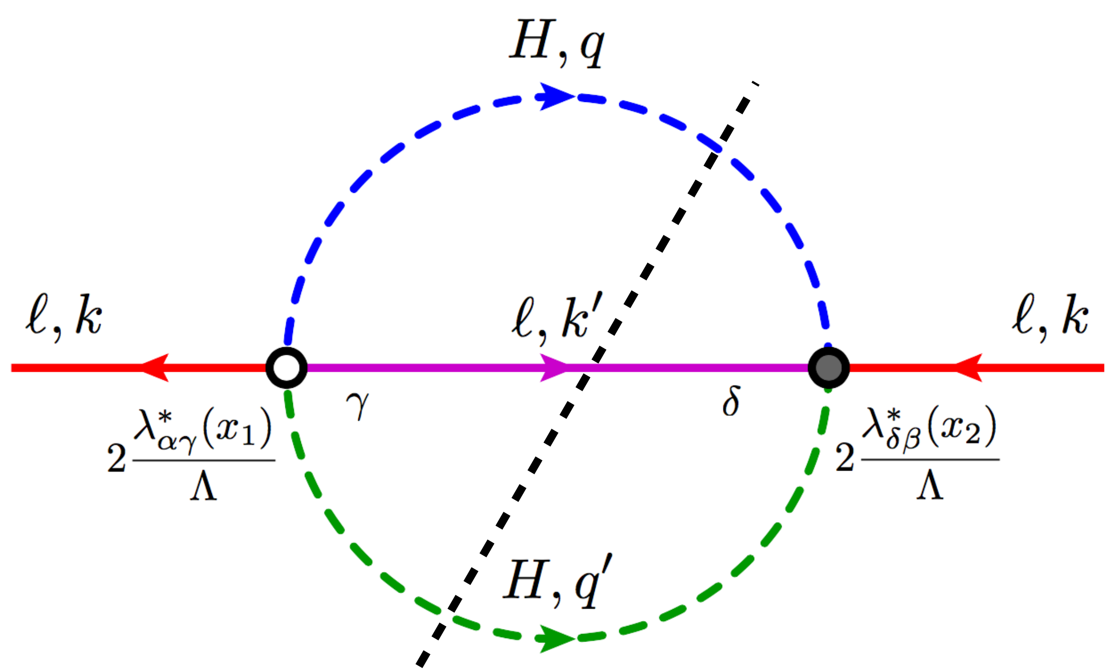
$$x = \frac{1}{2}(x_1 + x_2) \qquad r = x_1 - x_2$$

Lepton asymmetry in CTP approach

- **CP-violating self energy**

$$\Sigma^{<,>}_{\alpha\beta}(x_1,x_2) = 3 \times \frac{4}{\Lambda^2}\sum_{\gamma\delta}\lambda^*_{\alpha\gamma}(x_1)\lambda_{\delta\beta}(x_2)$$

$$\times \Delta^{>,<}(x_2,x_1)\Delta^{>,<}(x_2,x_1)S^{>,<}_{\gamma\delta}(x_2,x_1)\,,$$



- **Lepton asymmetry**

$$\Delta N_\ell = -\frac{12}{\Lambda^2}\int \underline{d^4x d^4r\,(-i)\mathrm{tr}[\lambda^*(x_1)\lambda(x_2)]}\underline{\mathcal{M}}\,.$$

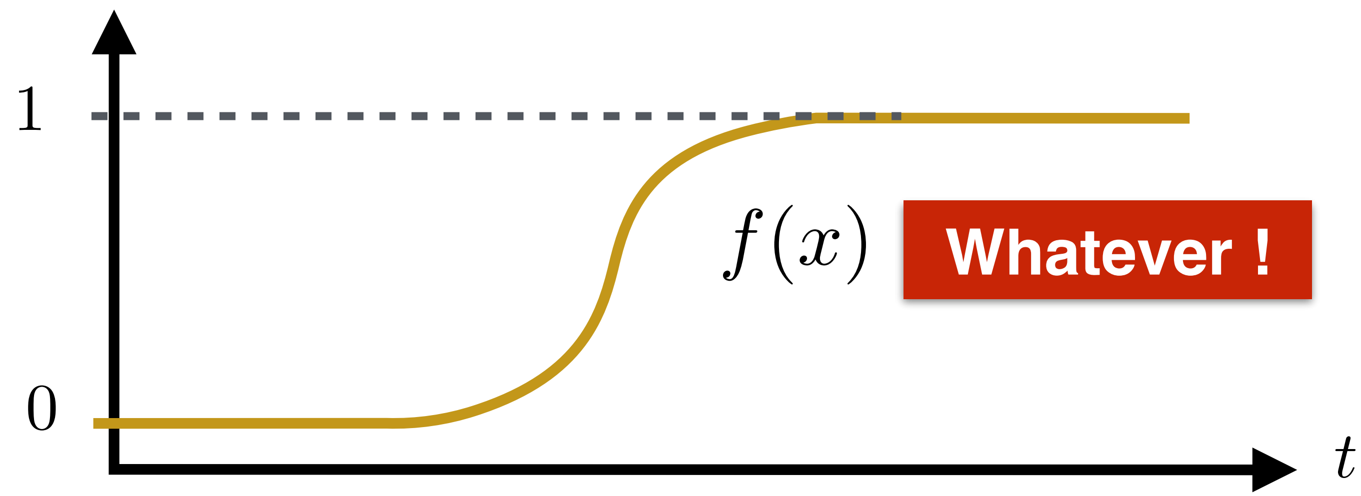
$$\mathcal{M} = i\int \frac{d^4k}{(2\pi)^4}\frac{d^4k'}{(2\pi)^4}\frac{d^4q}{(2\pi)^4}\frac{d^4q'}{(2\pi)^4}e^{iK\cdot(-r)}\left\{\Delta^<_q(x)\Delta^<_{q'}(x)\mathrm{tr}[S^<_k(x)S^<_{k'}(x)] - \Delta^>_q(x)\Delta^>_{q'}(x)\mathrm{tr}[S^>_k(x)S^>_{k'}(x)]\right\}$$

The final lepton asymmetry is determined by **the behaviour of Weinberg operator during the phase transition** and **thermal properties of leptons and the Higgs**.

Influence of phase transition

- **Single-scalar phase transition**

$$\lambda(x) = \lambda^0 + \lambda^1 f(x) \qquad f(x) \equiv \frac{\langle \phi(x) \rangle}{v_\phi}$$



$$m_\nu^0 = \lambda^0 \frac{v_H^2}{\Lambda}$$

$$m_\nu = \lambda \frac{v_H^2}{\Lambda}$$

$$\int d^4x \mathrm{Im}\{\mathrm{tr}[\lambda^*(x_1)\lambda(x_2)]\} = \mathrm{Im}\{\mathrm{tr}[\lambda^0\lambda^*]\}\left(r^0 - \frac{r^3}{v_w}\right)V$$

$$\Delta n_\ell^{\mathrm{I}} = -\frac{12}{\Lambda^2}\mathrm{Im}\{\mathrm{tr}[\lambda^0\lambda^*]\}\boxed{\int d^4r\, r^0\, \mathcal{M}}$$ **time-dependent integration**

$$\Delta n_\ell^{\mathrm{II}} = \frac{12}{v_w\Lambda^2}\mathrm{Im}\{\mathrm{tr}[\lambda^0\lambda^*]\}\boxed{\int d^4r\, r^3\, \mathcal{M}}$$ **space-dependent integration**

$$\Delta n_\ell = \Delta n_\ell^{\mathrm{I}} + \Delta n_\ell^{\mathrm{II}}$$

Influence of phase transition

- **Multi-scalar phase transition (in the thick-wall limit)**

e.g., $\lambda(x) = \lambda^0 + \lambda^1 f_1(x) + \lambda^2 f_2(x)$

$$\mathrm{Im}\{\mathrm{tr}[\lambda^*(x_1)\lambda(x_2)]\} = \mathrm{Im}\{\mathrm{tr}[\lambda^0\lambda^{1*}]\}[f_1(x_1) - f_1(x_2)] + \mathrm{Im}\{\mathrm{tr}[\lambda^0\lambda^{2*}]\}[f_2(x_1) - f_2(x_2)]$$
$$+\mathrm{Im}\{\mathrm{tr}[\lambda^{1*}\lambda^2]\}[f_1(x_1)f_2(x_2) - f_1(x_2)f_2(x_1)]$$

Interferences of different scalar VEVs cannot be neglected.

$$\int d^4r \mathrm{Im}\{\mathrm{tr}[\lambda^*(x_1)\lambda(x_2)]\}\mathcal{M} = \int d^4r \mathrm{Im}\{\mathrm{tr}[\lambda^*(x+r/2)\lambda(x-r/2)]\}\mathcal{M}$$
$$\approx \mathrm{Im}\{\mathrm{tr}[\lambda^*(x)\partial_\mu\lambda(x)]\}\int d^4r r^\mu \mathcal{M}\,.$$

$$\Delta n_\ell^{\mathrm{I}} \propto \mathrm{Im}\{\mathrm{tr}[\lambda^*(x)\partial_t\lambda(x)]\}\int d^4r\, r^0\, \mathcal{M}$$

time-dependent integration

$$\Delta n_\ell^{\mathrm{II}} \propto \mathrm{Im}\{\mathrm{tr}[\lambda^*(x)\partial_z\lambda(x)]\}\int d^4r\, r^3\, \mathcal{M}$$

space-dependent integration

Time derivative/spatial gradient

Influence of thermal effects

Thermal effects influence the time- and space-dependent integration.

$$\int d^4r\, r^0\, \mathcal{M} \qquad \int d^4r\, r^3\, \mathcal{M}$$

$$\mathcal{M} = i\int \frac{d^4k}{(2\pi)^4}\frac{d^4k'}{(2\pi)^4}\frac{d^4q}{(2\pi)^4}\frac{d^4q'}{(2\pi)^4} e^{iK\cdot(-r)} \left\{\Delta_q^<(x)\Delta_{q'}^<(x)\mathrm{tr}[S_k^<(x)S_{k'}^<(x)] - \Delta_q^>(x)\Delta_{q'}^>(x)\mathrm{tr}[S_k^>(x)S_{k'}^>(x)]\right\}$$

- **Resummed propagators of the Higgs and leptons**

$$\Delta_q^{<,>} = \frac{-2\varepsilon(q^0)\mathrm{Im}\Pi_q^R}{[q^2+\mathrm{Re}\Pi_q^R]^2+[\mathrm{Im}\Pi_q^R]^2}\left\{\vartheta(\mp q^0)+f_{B,|q^0|}(x)\right\},$$

$$S_k^{<,>} = \frac{-2\varepsilon(k^0)\mathrm{Im}\Sigma_k^{R\,2}}{[k^2+\mathrm{Re}\Sigma_q^{R\,2}]^2+[\mathrm{Im}\Sigma_q^{R\,2}]^2}\left\{\vartheta(\mp k^0)-f_{F,|q^0|}(x)\right\}P_L \not{k} P_R\,,$$

thermal equilibrium $\quad f_{B,|q^0|} \equiv \frac{1}{e^{\beta|q^0|}-1}, \qquad f_{F,|k^0|} \equiv \frac{1}{e^{\beta|k^0|}+1},$

thermal mass $\quad m^2_{\mathrm{th},H} = \mathrm{Re}\Pi \qquad m_{\mathrm{th},\ell} = \mathrm{Re}\Sigma$

thermal width $\quad \gamma_H = \frac{\mathrm{Im}\Pi}{2m_{\mathrm{th},H}} \qquad \gamma_\ell = \frac{\mathrm{Im}\Sigma^2}{2m_{\mathrm{th},\ell}} \qquad \gamma = 6/L$

By assuming thermal equilibrium in the rest frame of plasma, the space-dependent integration is zero.

$\mathcal{M}$ **is invariant under parity transformation**

$$r \to r^P = (r^0, -\mathbf{r})\,, \quad k_n \to k_n^P = (k_n^0, -\mathbf{k}_n) \quad \Longrightarrow \quad \int d^4r\, r^3\, \mathcal{M} = 0$$

Influence of thermal effects

- **Performing the time-dependent integration**

From 4D momentum space to 3D momentum space + 1D time

$$\Delta_{\mathbf{q}}^{<,>}(t_1,t_2) = \int \frac{dq^0}{2\pi} e^{-iq^0 y} \Delta_q^{<,>} = \frac{\cos(\omega_{\mathbf{q}} y^{\mp})}{2\omega_{\mathbf{q}} \sinh(\omega_{\mathbf{q}}\beta/2)} e^{-\gamma_{H,\mathbf{q}}|y|}, \qquad y = r^0$$

$$S_{\mathbf{k}}^{<,>}(t_1,t_2) = \int \frac{dk^0}{2\pi} e^{-ik^0 y} S_k^{<,>} = -P_L \frac{\gamma^0 \cos(\omega_{\mathbf{k}} y^{\mp}) + i\vec{\gamma}\cdot\hat{\mathbf{k}} \sin(\omega_{\mathbf{k}} y^{\mp})}{2\cosh(\omega_{\mathbf{k}}\beta/2)} e^{-\gamma_{\ell,\mathbf{k}}|y|}, \qquad y^- = y - i\beta/2$$

Integrating out the time

$$\omega_{\mathbf{q}} = \sqrt{m_{H,\mathrm{th}}^2 + \mathbf{q}^2},\ \omega_{\mathbf{k}} = \sqrt{m_{\ell,\mathrm{th}}^2 + \mathbf{k}^2} \text{ and } \hat{\mathbf{k}} \equiv \mathbf{k}/\omega_{\mathbf{k}}$$

$$\int d^4r\, y\mathcal{M} = 2\int \frac{d^3\mathbf{k}}{(2\pi)^3}\frac{d^3\mathbf{q}}{(2\pi)^3}\frac{d^3\mathbf{q}'}{(2\pi)^3}\int dy\, yM\,,$$

$$\Gamma = 2(\gamma_H + \gamma_\ell)$$

$$\int_{-\infty}^{+\infty} dy y M = 2\int_0^{+\infty} dy y M$$

$$= 2\int_0^{+\infty} dy y \frac{\mathrm{Im}\{\cos(\omega_{\mathbf{q}} y^-)\cos(\omega_{\mathbf{q}'} y^-)[\cos(\omega_{\mathbf{k}} y^-)\cos(\omega_{\mathbf{k}'} y^-) + \hat{\mathbf{k}}\cdot\hat{\mathbf{k}}' \sin(\omega_{\mathbf{k}} y^-)\sin(\omega_{\mathbf{k}'} y^-)]\}}{8\omega_{\mathbf{q}}\omega_{\mathbf{q}'}\sinh(\omega_{\mathbf{q}}\beta/2)\sinh(\omega_{\mathbf{q}'}\beta/2)\cosh(\omega_{\mathbf{k}}\beta/2)\cosh(\omega_{\mathbf{k}'}\beta/2)} e^{-\Gamma y}$$

$$= -\sum_{\eta_2,\eta_3,\eta_4=\pm 1} \frac{\Omega_{\eta_2\eta_3\eta_4}\Gamma \sinh(\beta\Omega_{\eta_2\eta_3\eta_4}/2)[1-\eta_2\hat{\mathbf{k}}\cdot\hat{\mathbf{k}}']}{32\omega_{\mathbf{q}}\omega_{\mathbf{q}'}(\Omega_{\eta_2\eta_3\eta_4}^2 + \Gamma^2)^2 \sinh(\omega_{\mathbf{q}}\beta/2)\sinh(\omega_{\mathbf{q}'}\beta/2)\cosh(\omega_{\mathbf{k}}\beta/2)\cosh(\omega_{\mathbf{k}'}\beta/2)}$$

Influence of thermal effects

Asymmetry between lepton and antilepton momentum distribution

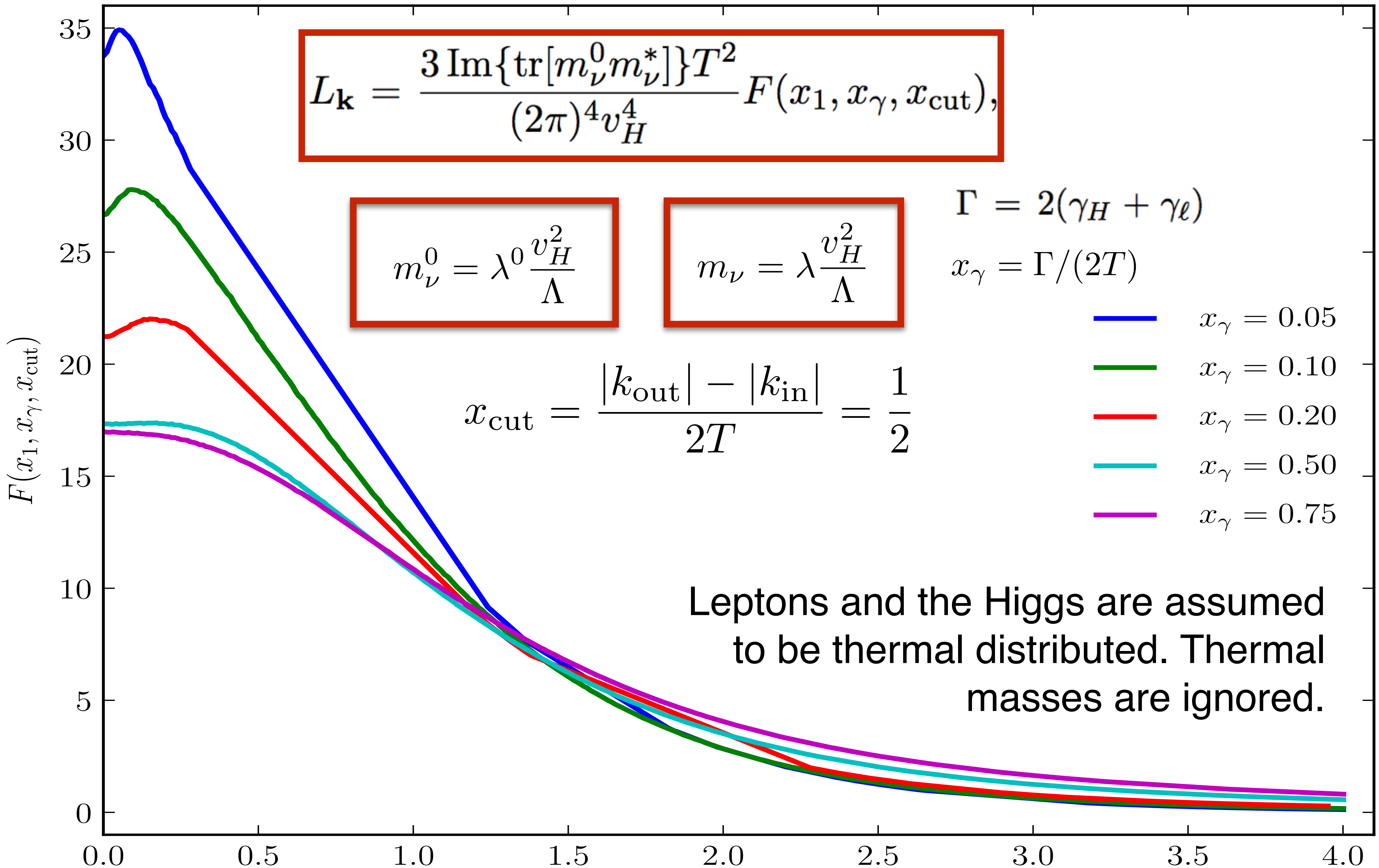
$$L_{\mathbf{k}} = \frac{3\,\mathrm{Im}\{\mathrm{tr}[m_\nu^0 m_\nu^*]\}T^2}{(2\pi)^4 v_H^4} F(x_1, x_\gamma, x_{\mathrm{cut}}),$$

$$m_\nu^0 = \lambda^0 \frac{v_H^2}{\Lambda} \qquad m_\nu = \lambda \frac{v_H^2}{\Lambda}$$

$$\Gamma = 2(\gamma_H + \gamma_\ell)$$

$$x_\gamma = \Gamma/(2T)$$

$$x_{\mathrm{cut}} = \frac{|k_{\mathrm{out}}| - |k_{\mathrm{in}}|}{2T} = \frac{1}{2}$$



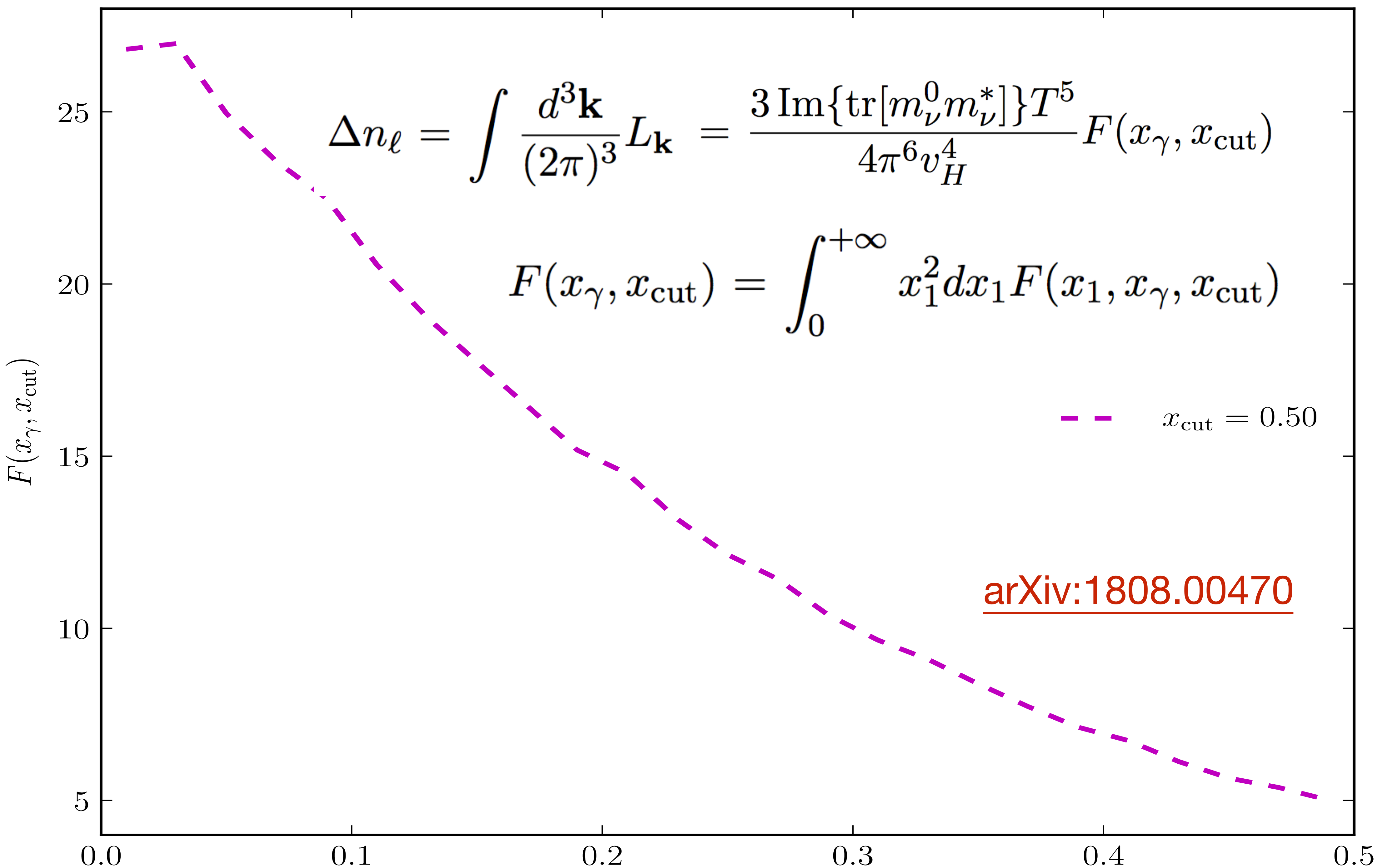
Leptons and the Higgs are assumed to be thermal distributed. Thermal masses are ignored.

$$x_1 = |\mathbf{k}|/(2T)$$

lepton/antilepton momentum normalised by temperature

Leptogenesis via Weinberg operator (in CTP approach)

Asymmetry between lepton and antilepton number density



$x_\gamma = \Gamma/(2T)$

Damping rate normalised by temperature

Lepton models vs neutrino experiments

- **In the single-scalar case**

$$\Delta n_\ell = \frac{3\,\mathrm{Im}\{\mathrm{tr}[m_\nu^0 m_\nu^*]\}T^5}{4\pi^6 v_H^4} F(x_\gamma, x_{\mathrm{cut}})$$

$$M_\nu^0 = \frac{\lambda^0}{\Lambda} v_H^2 \qquad\qquad M_\nu = \frac{\lambda}{\Lambda} v_H^2$$

Effective nu mass before PT	Effective nu mass after PT
Depend on lepton model	Measured by nu experiment

determined by symmetries
(Discrete, U(1), SO(3), SO(10)…)
and order of scalars getting vevs

nu oscillation exp： DUNE, T2HK, …

0v2β exp: Gerda, EXO-200, KamLAND-Zen

Temperature for phase transition

Big Bang

Seesaw scale (10^{14} GeV)

10^{12} GeV

10^{9} GeV

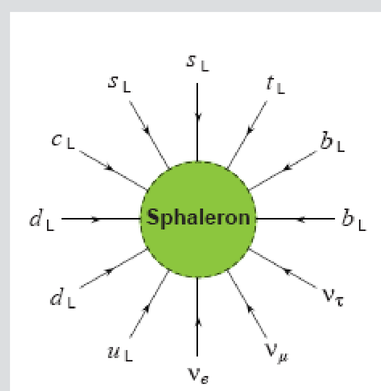
10^{6} GeV

TeV scale

EW scale

GeV scale

sphaleron process in equilibrium



sphaleron decouple

leptogenesis via PT $T \sim 10^{11}\,\mathrm{GeV}$

$$n_B \approx -\frac{1}{3} n_\ell$$

$$\mathrm{Im}\{\mathrm{tr}[m_\nu^0 m_\nu^*]\} \sim m_\nu^2 \;\sim (0.1\mathrm{eV})^2$$

$$\eta_B \sim \mathcal{O}(10^2)\frac{m_\nu^2}{v_H^4}T^2$$

$$T \sim \mathcal{O}(10)\sqrt{\eta_B}\frac{v_H^2}{m_\nu}$$

Summary

- I give a brief review of neutrino mass and mixing. Models related to these issues usually introduces new symmetries, which may result in a spacetime-varying Weinberg operator.
- I introduce a novel mechanism of leptogenesis via phase transition. No explicit new particles are required, but just a spacetime-varying Weinberg operator.
- In order to generate enough baryon-antibaryon asymmetry, the temperature for phase transition is roughly around 10^{11} GeV.

Thank you very much!