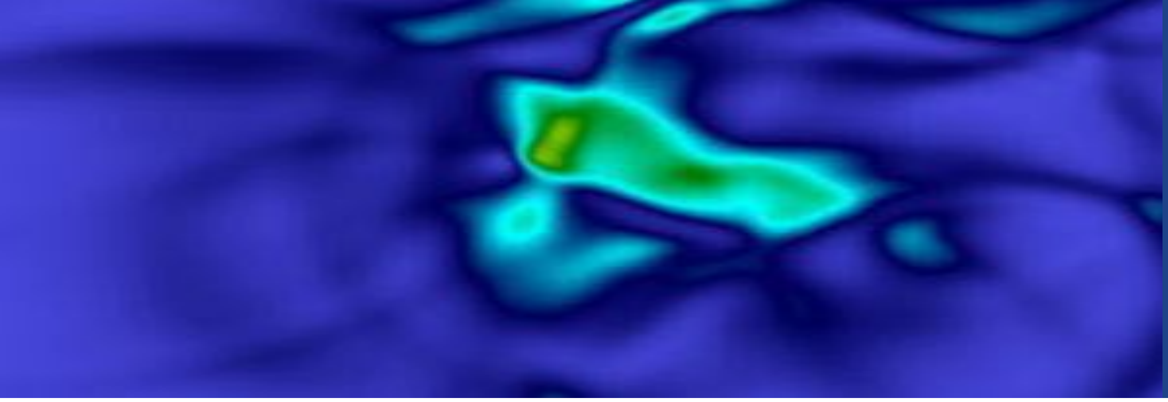

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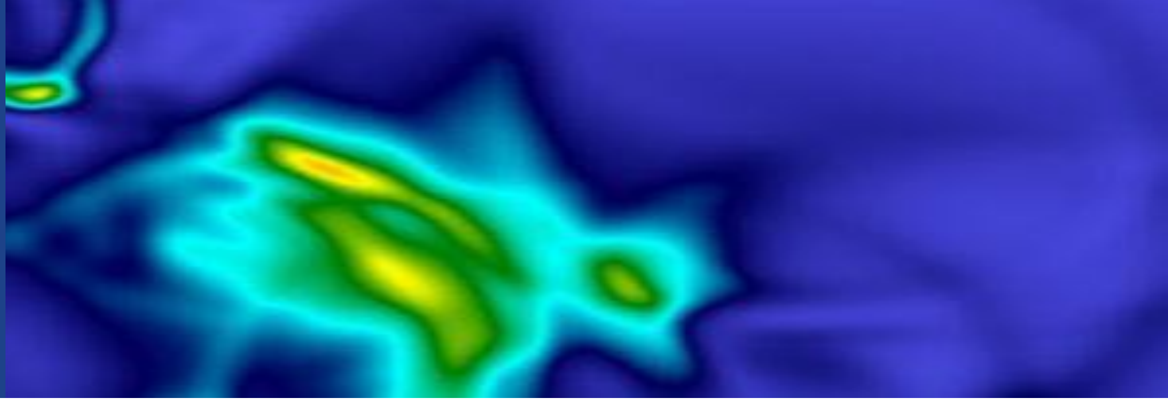


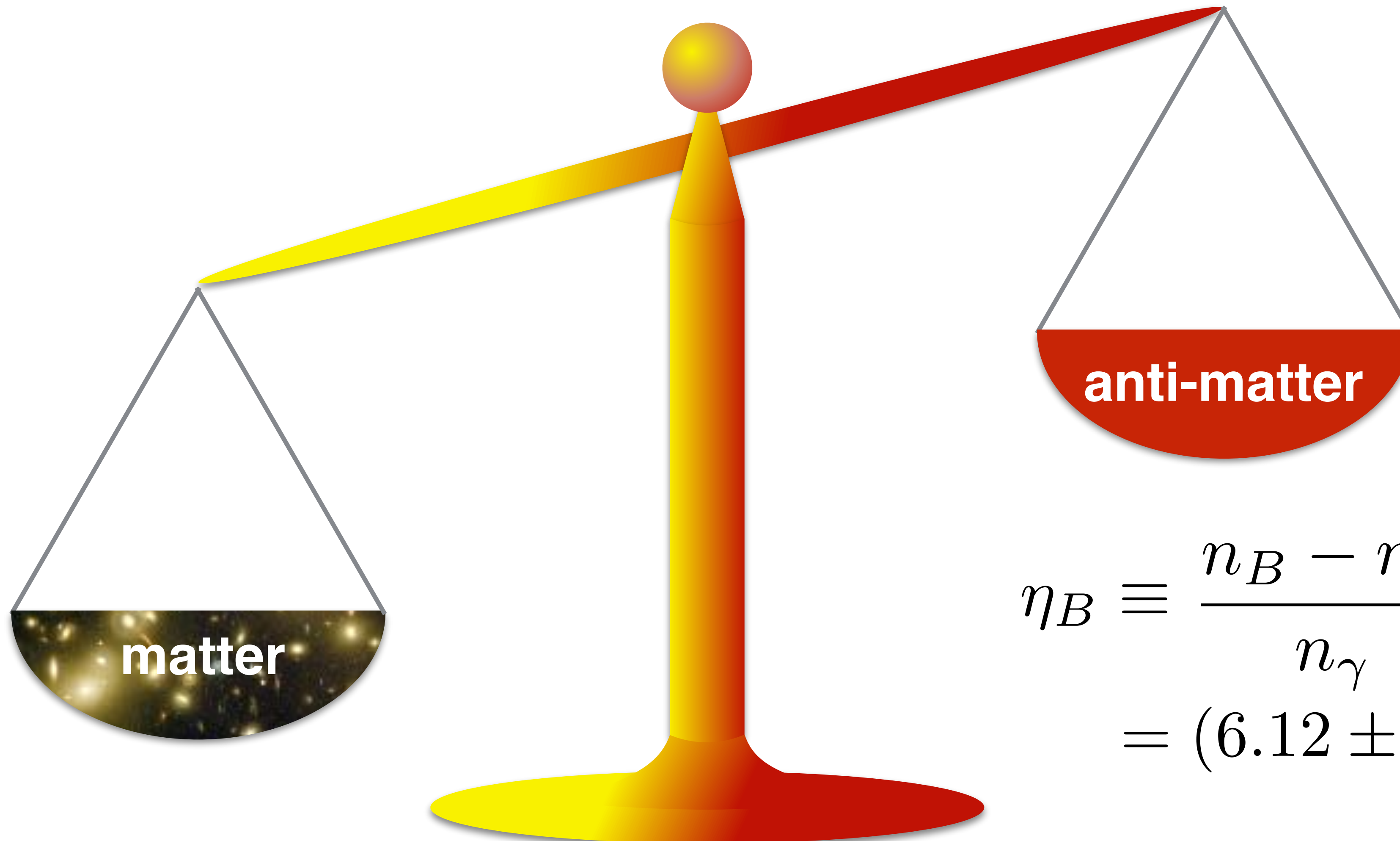
Baryogenesis via Leptonic Phase Transition

Ye-Ling Zhou, Southampton, 10 December 2018

SHEP Southampton High Energy Physics

Science & Technology Facilities Council

Baryon asymmetry



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

Planck 2018

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

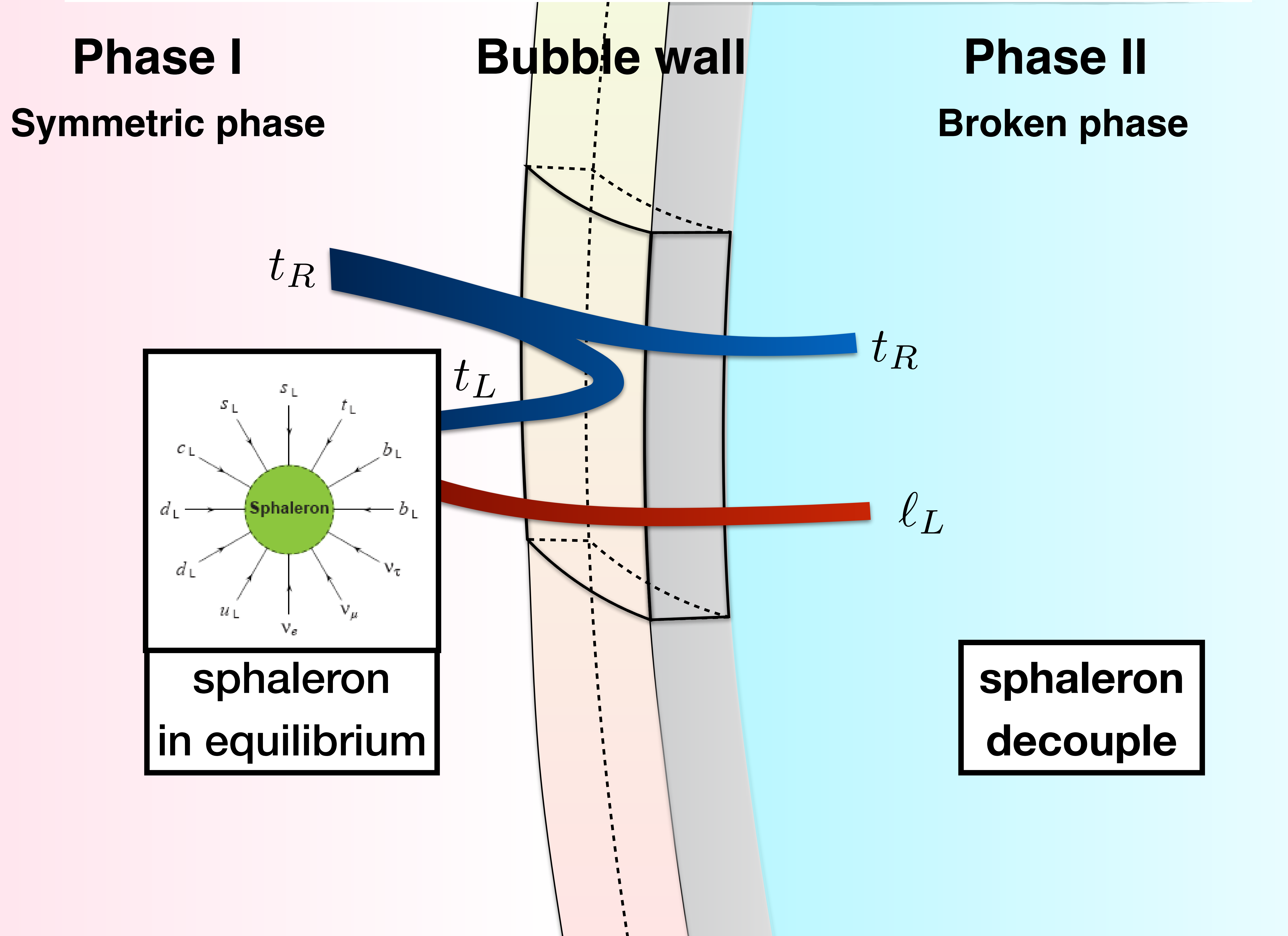
Sakharov conditions for baryogenesis

B violation

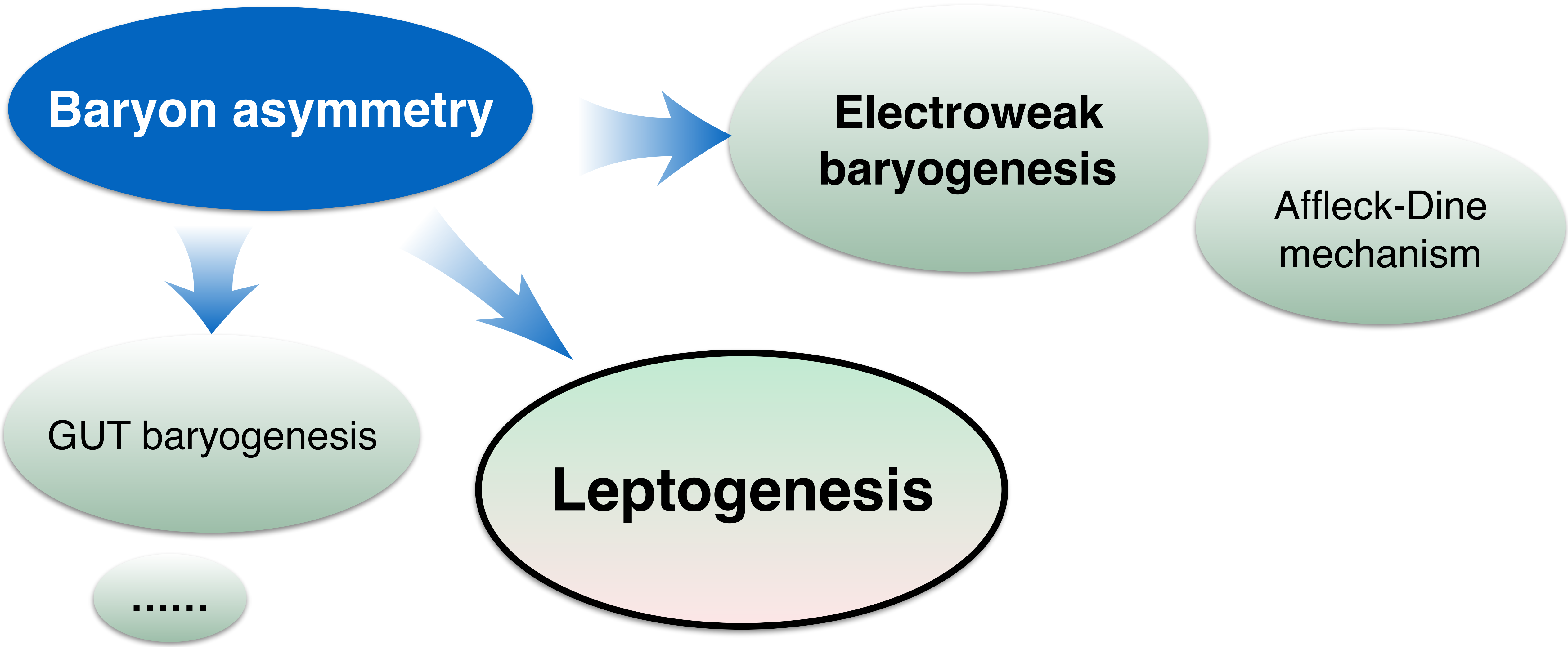
C/CP violation

Out of equilibrium dynamics

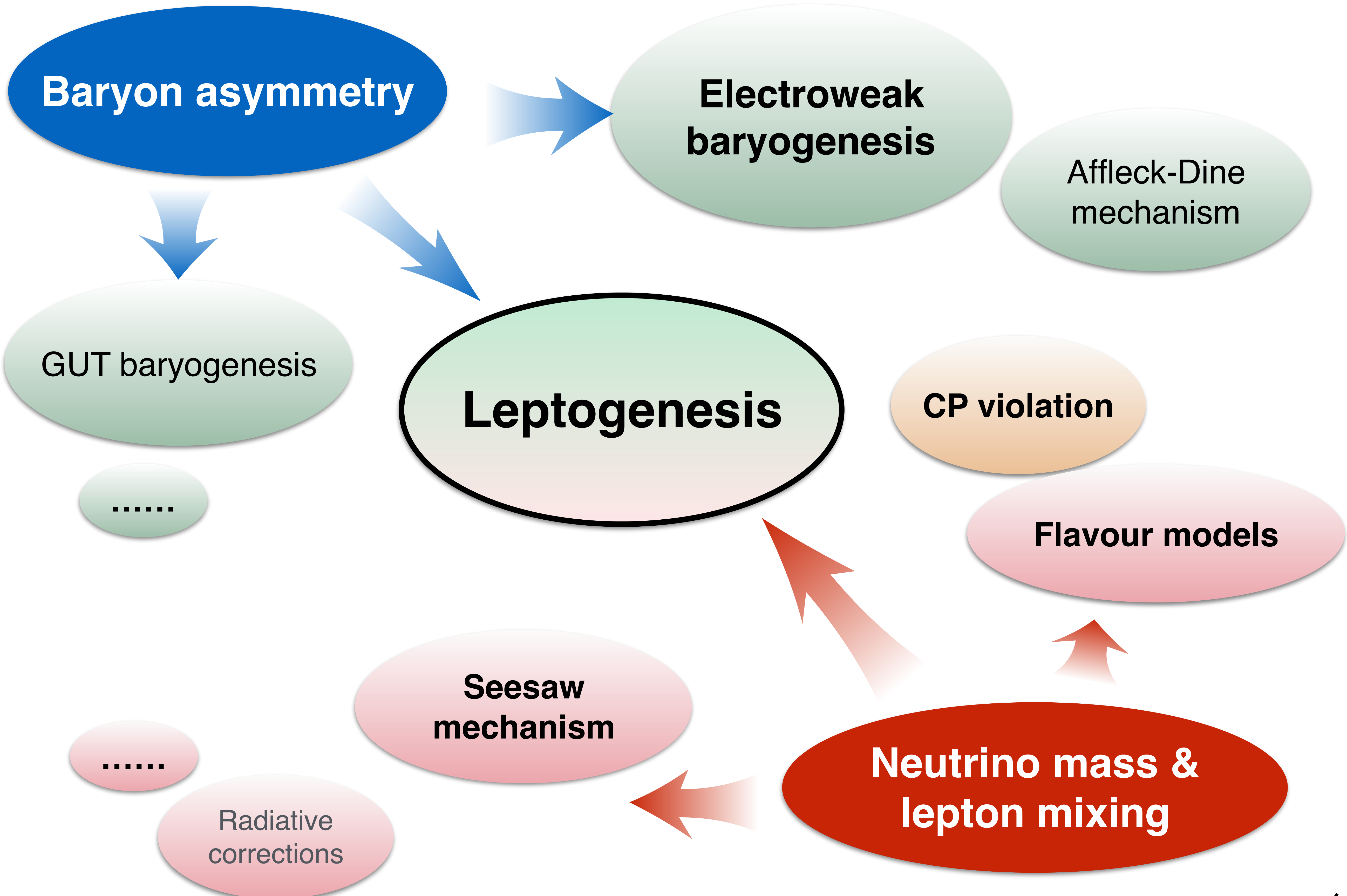
Baryogenesis via electroweak phase transition



Baryogenesis



Leptogenesis



Origin of neutrino masses

- Weinberg Operator

Lepton number violation

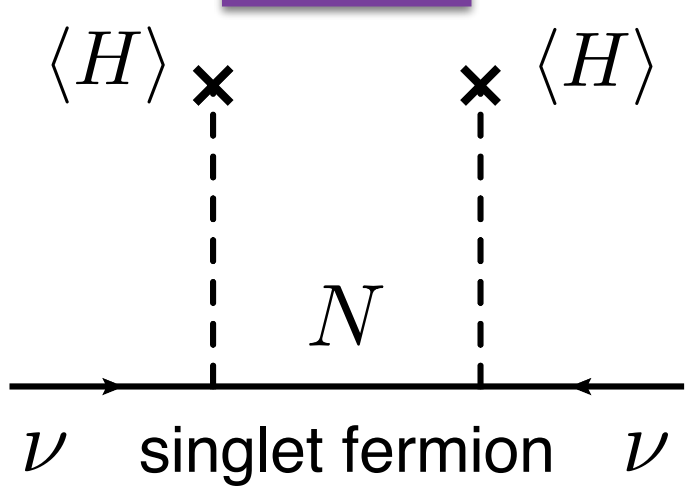
$$\mathcal{L}_W = \frac{\lambda_{\alpha\beta}}{\Lambda} \ell_{\alpha L} H C \ell_{\beta L} H + \text{h.c.}$$

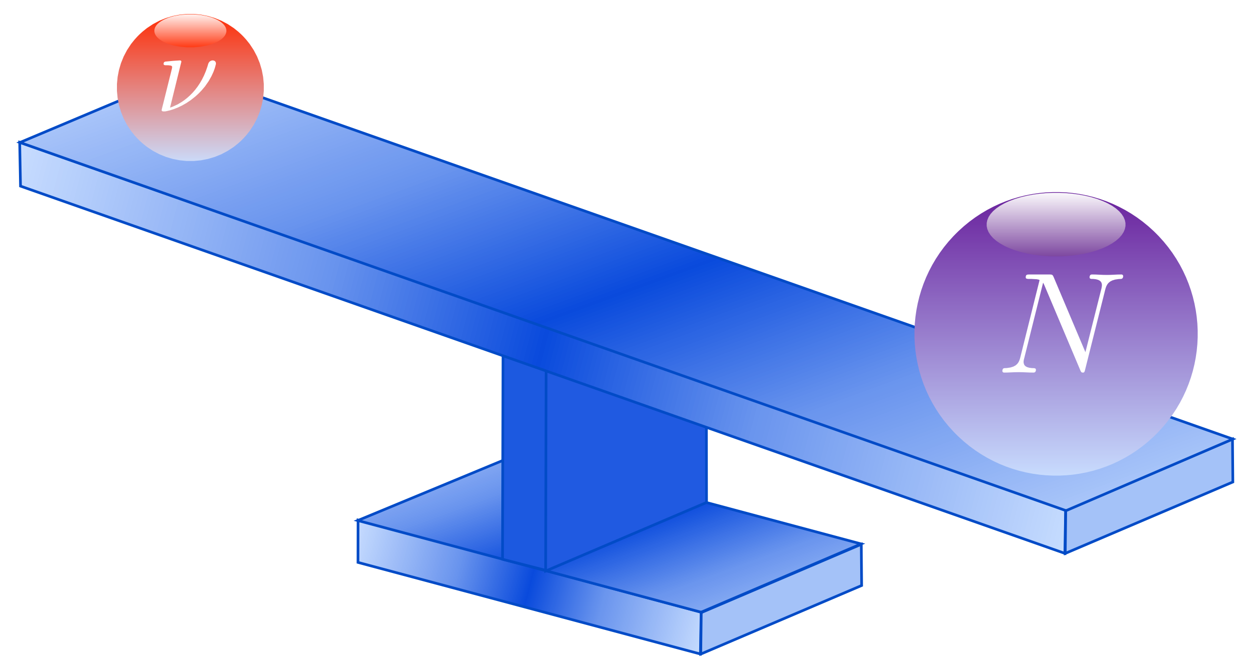
Majorana masses

$$m_\nu = \lambda \frac{v_H^2}{\Lambda} \qquad \frac{\Lambda}{\lambda} \sim 10^{15}\ \text{GeV}$$

- Seesaw mechanism

Type I



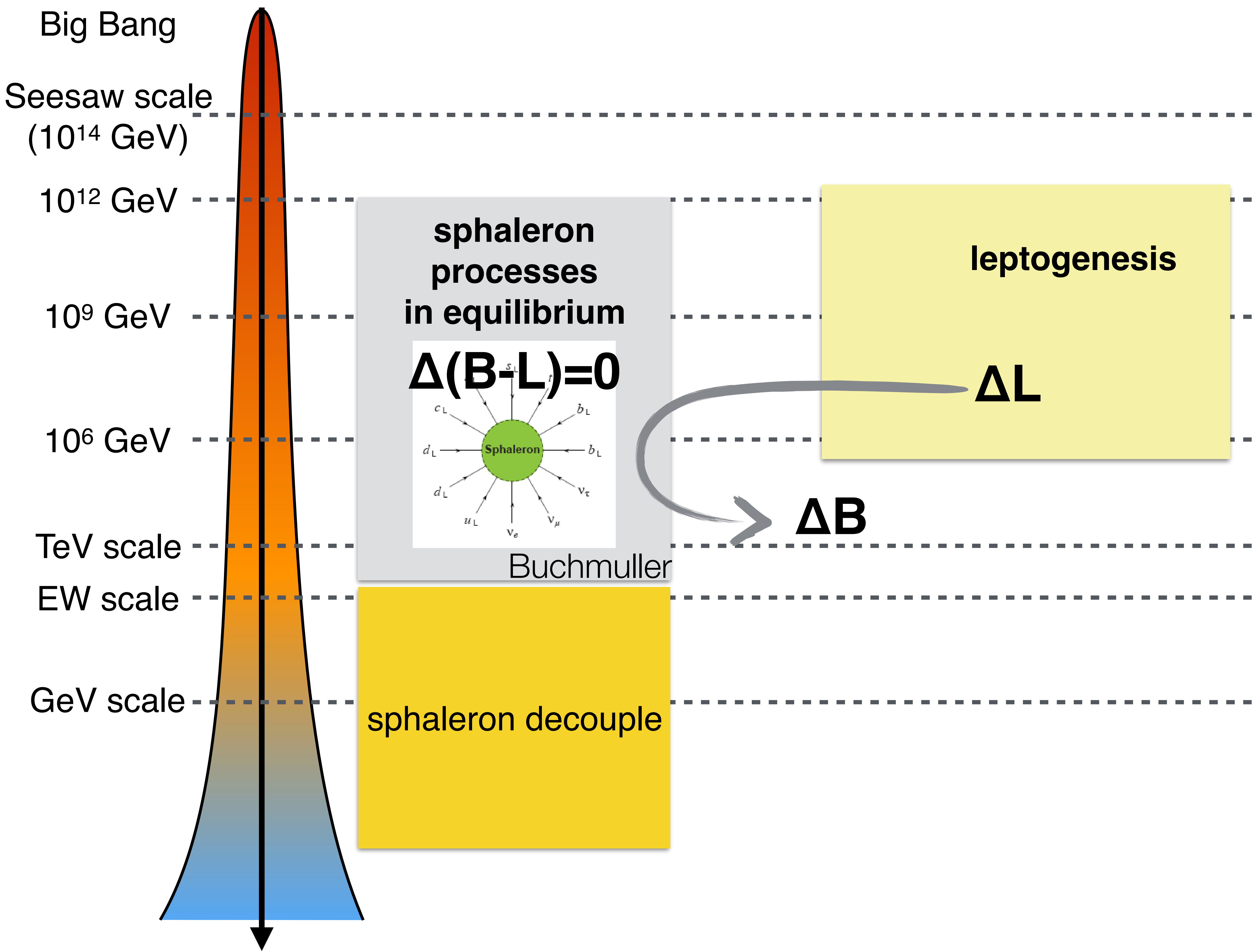


$$-\mathcal{L} = y \bar{\ell} H N + \frac{1}{2} m_N \overline{N^c} N + \text{h.c.}$$

$$\frac{\Lambda}{\lambda} \sim 10^{15}\ \text{GeV}$$

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

Baryogenesis via leptogenesis



Sakharov conditions for leptogenesis

SM L/B-L violation

C/CP violation

Out of equilibrium dynamics

Leptogenesis via ...

in the framework of seesaw

via RH neutrino decay

flavour effect

resonant decay

via RH neutrino oscillation

via Weinberg operator

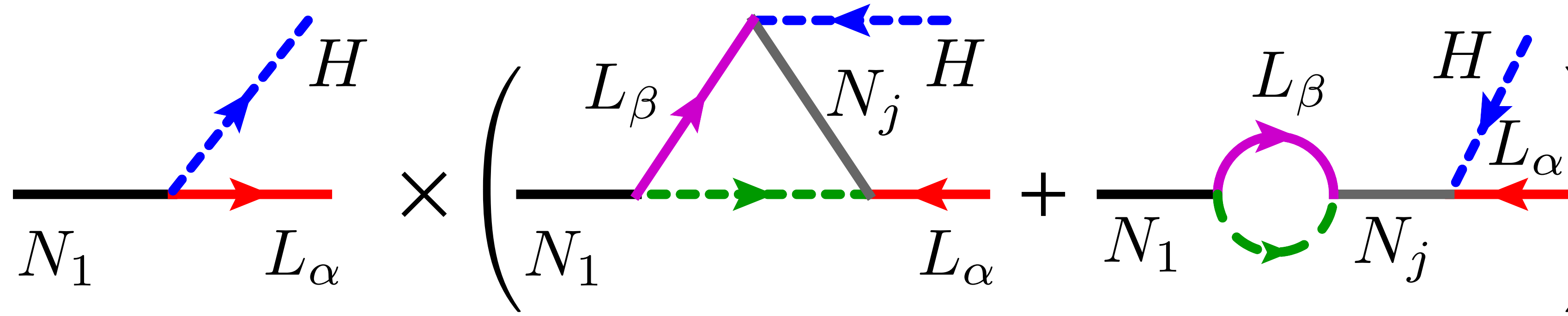
Leptogenesis via RH neutrinos

- Classical thermal leptogenesis (in type-I seesaw)

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

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

$$\Delta f_{\ell_\alpha} \propto \mathrm{Im} \left\{ \cdots \times \left(\cdots + \cdots \right) \right\}$$



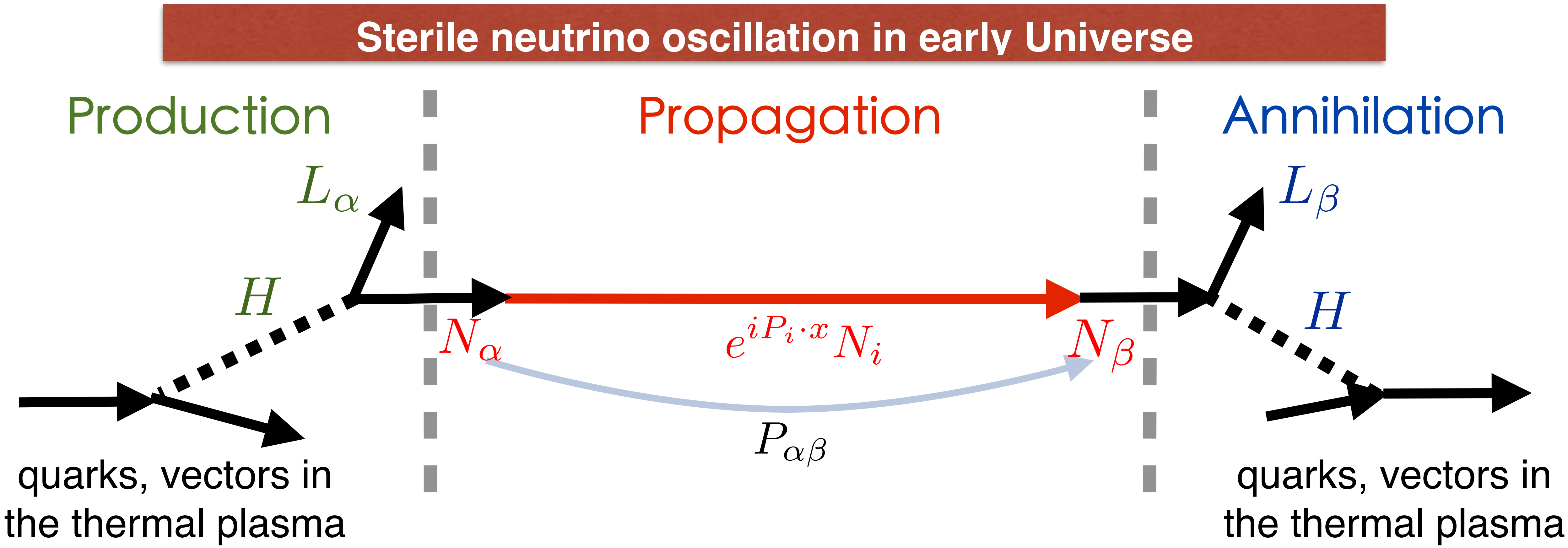
$$\propto \mathrm{Im}\{Y^*_{\nu\alpha 1}(Y^\dagger_\nu Y_\nu)_{1j} Y_{\nu\alpha j}\}$$

[Fukugita, Yanagida, 1986]

- Flavour effects, Resonant leptogenesis, N_2 decay leptogenesis, $\cdots$

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



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

$$P(N_\alpha \to N_\beta) - P(\overline{N}_\alpha \to \overline{N}_\beta) \propto \mathrm{Im}\{\exp(-i\int_0^t \frac{\Delta M_{ij}^2}{2E} a(t)dt)\}$$

CP violation $\alpha \neq \beta$ $\quad \times\, \mathrm{Im}\{Y_{\alpha i}Y^*_{\beta i}Y^*_{\alpha j}Y_{\beta j}\}$ $\quad i \neq j$

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

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

Leptogenesis via Weinberg operator

Weinberg operators satisfied two of three 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.

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

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

No washout if there are no other LNV sources.

- We assume a cosmological phase transition, which leads to a spacetime-varying Weinberg operator, to give rise to CP violation.

Motivation for leptonic phase transitions

A lot of symmetries have been proposed in the lepton sector.
Their breaking may lead to a time-varying Weinberg operator.

- **B-L symmetry breaking**

  To generate a CP violation, at least two scalars are needed.

- **Flavour & CP symmetry breaking**

Flavour symmetries	Continuous	Discrete
Abelian	Fraggatt-Nielson, L_{mu}-L_{tau} …	Z_n
Non-Abelian	SU(3), SO(3), …	A_4, S_4, A_5, $\Delta(48)$, …

Motivation for leptonic phase transitions

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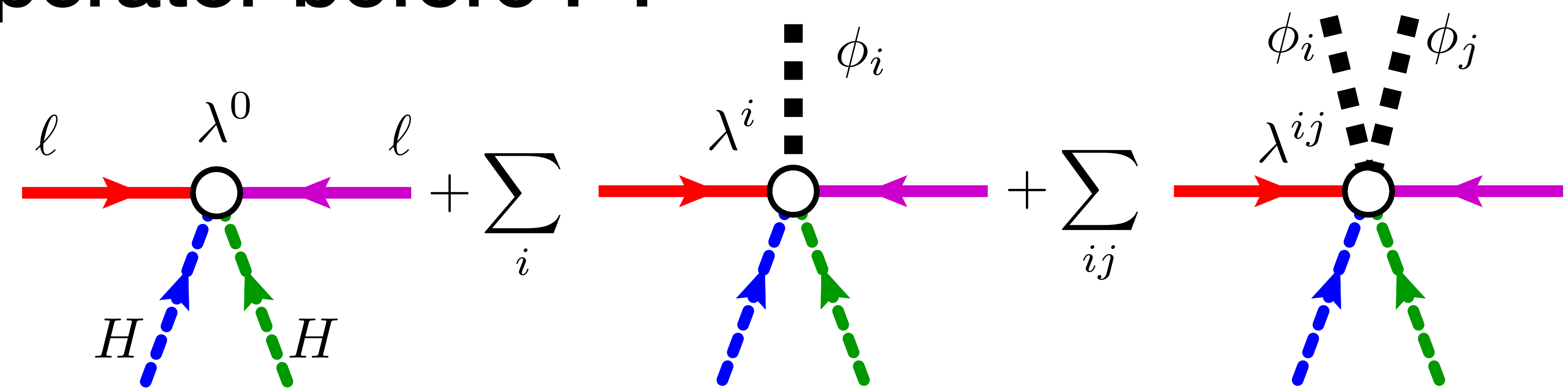
Phase Transition (PT)

PT-induced spacetime-varying Weinberg operator

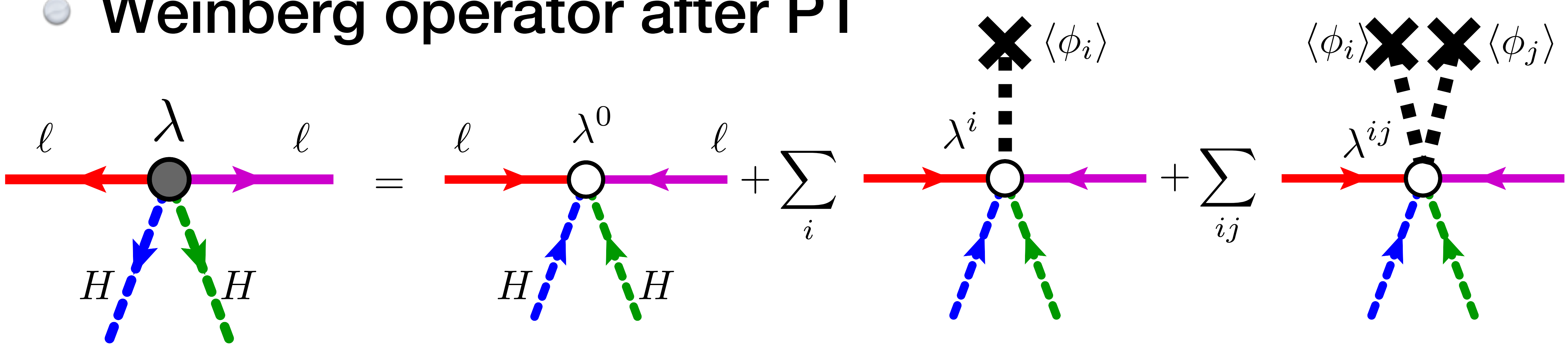
$$\mathcal{L}_{\rm W} = \frac{\lambda_{\alpha\beta}}{\Lambda}\ell_{\alpha L} H C \ell_{\beta L} H + \frac{\lambda^*_{\alpha\beta}}{\Lambda}\overline{\ell_{\alpha L}} H^* C \overline{\ell_{\beta L}} H^* ,$$

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

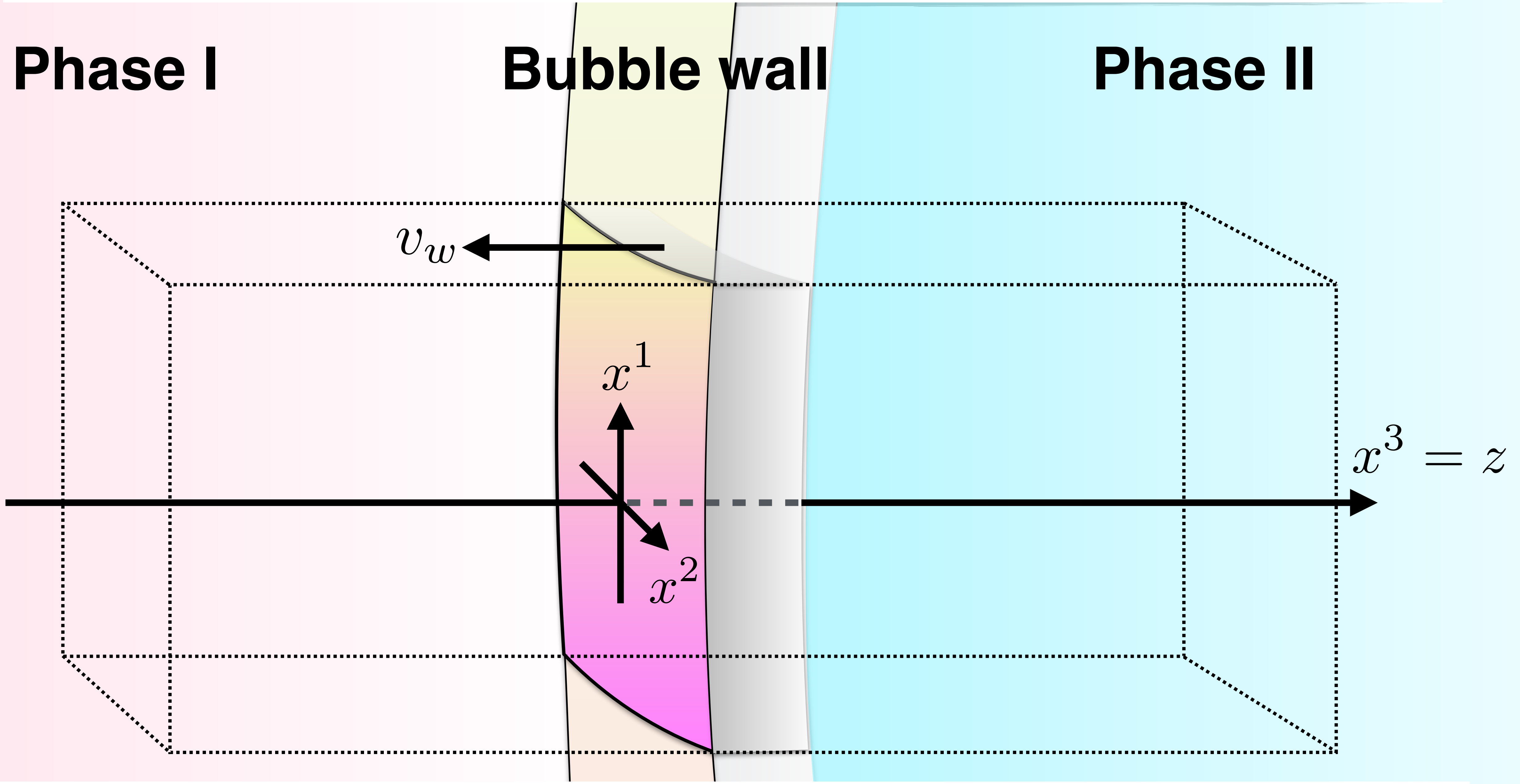
- Weinberg operator before PT

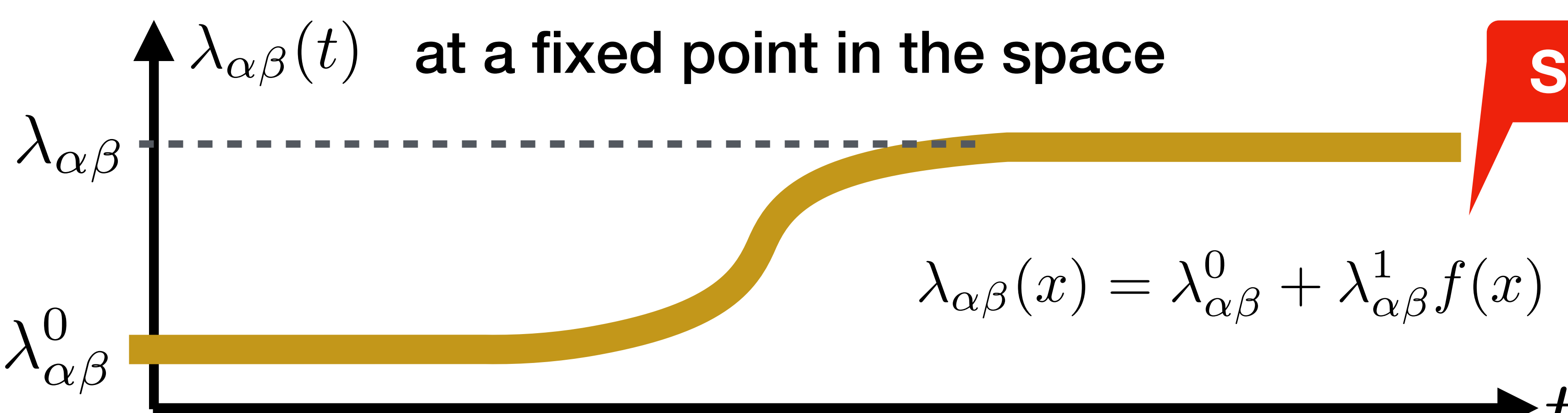


- Weinberg operator after PT



PT-induced spacetime-varying Weinberg operator





$$\lambda_{\alpha\beta}(x) = \lambda^0_{\alpha\beta} + \lambda^1_{\alpha\beta} f(x)$$

Single-scalar case

$$f(t \to -\infty) = 0$$

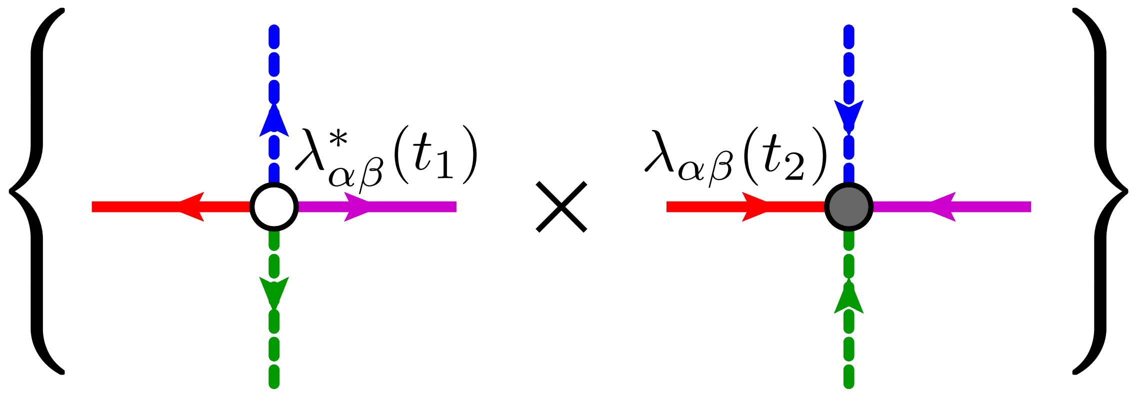
$$f(t \to +\infty) = 1$$

$$\lambda^0_{\alpha\beta} + \lambda^1_{\alpha\beta} \equiv \lambda_{\alpha\beta}$$

How to calculate lepton-antilepton asymmetry?

- In a semi-classical approximation   arXiv:1808.00475

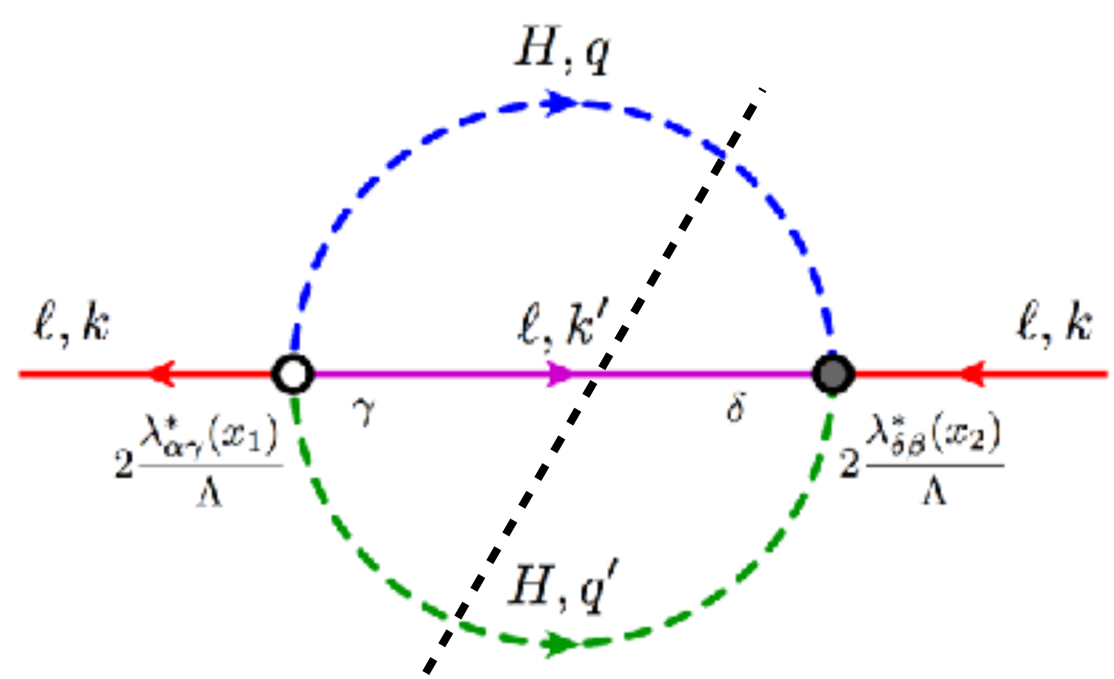
The lepton asymmetry is obtained by the interference of the interference of two Weinberg operators at different spacetimes.

$\Delta n_\ell \propto \mathrm{Im}$ 

- In the Closed Time Path (CTP) formalism.

The lepton asymmetry is determined to the self energy corrections including CPV source in CTP formalism

arXiv:1609.07969, 1808.00470



EOM of lepton and antilepton

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

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

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

- Decoherence effect is included by replacing the incoming and outgoing momentums $k_{\rm in} \to K_{\rm in} = k_{\rm in} + \frac{i}{2L}$, $k_{\rm out} \to K_{\rm out} = k_{\rm out} - \frac{i}{2L}$

L: decoherence length to avoid the the interference with infinite distance difference

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

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

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

Wave functions

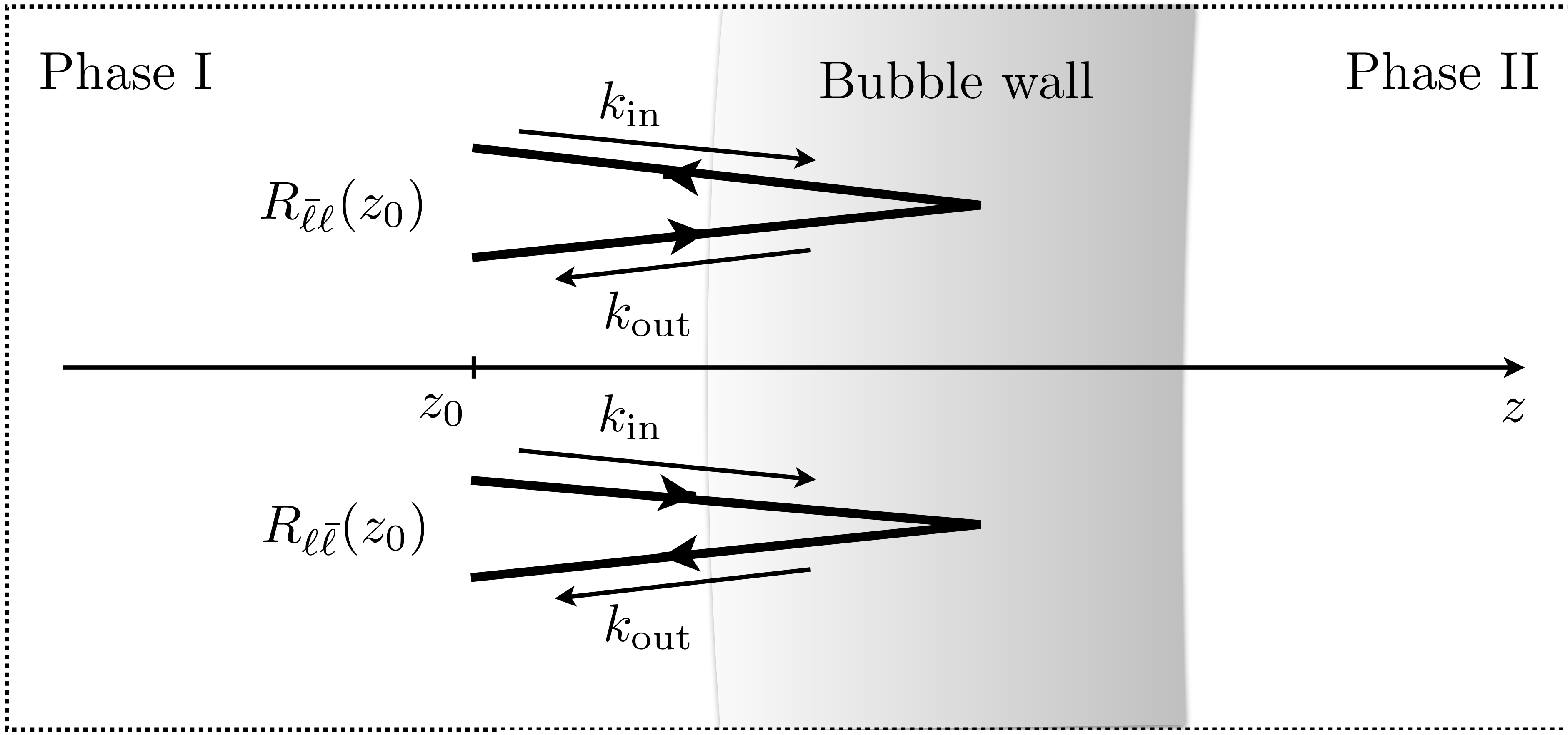
$$\chi_\ell(x) = \begin{pmatrix} \chi_\nu(x) \\ \chi_l(x) \end{pmatrix}, \quad \chi_{\bar{\ell}}(x) = \begin{pmatrix} -\chi_{\bar{\nu}}(x) \\ \chi_{\bar{l}}(x) \end{pmatrix},$$

Majorana-like mass matrix

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

Lepton-antilepton transition

In the rest wall frame



$z_1 = z - z_0$

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

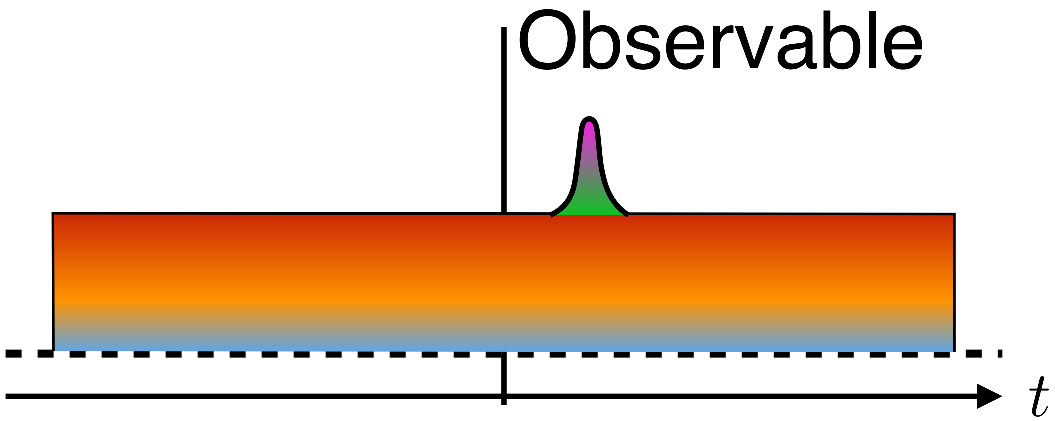
lepton to antilepton $$R_{\ell\bar{\ell}}(z_0) = i\int_0^{+\infty} dz_1 e^{-z_1/L} e^{ik_{\rm out}z_1} M_\ell(z_0+z_1) e^{-ik_{\rm in}z_1}$$

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

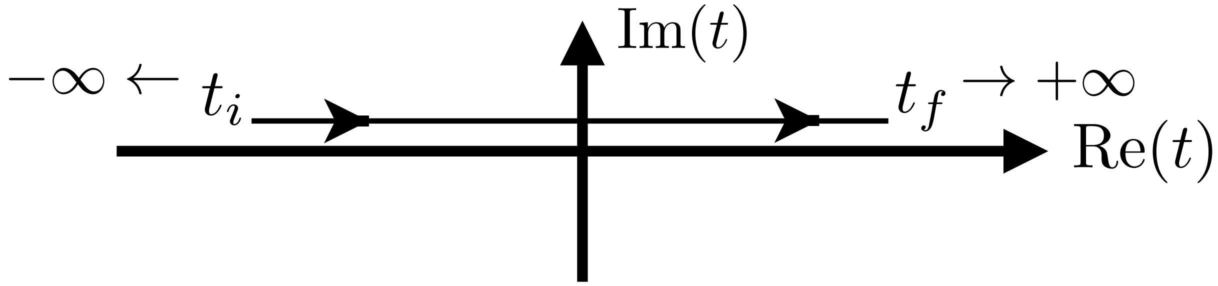
Asymmetry

Motivation for closed-time-path (CTP) approach

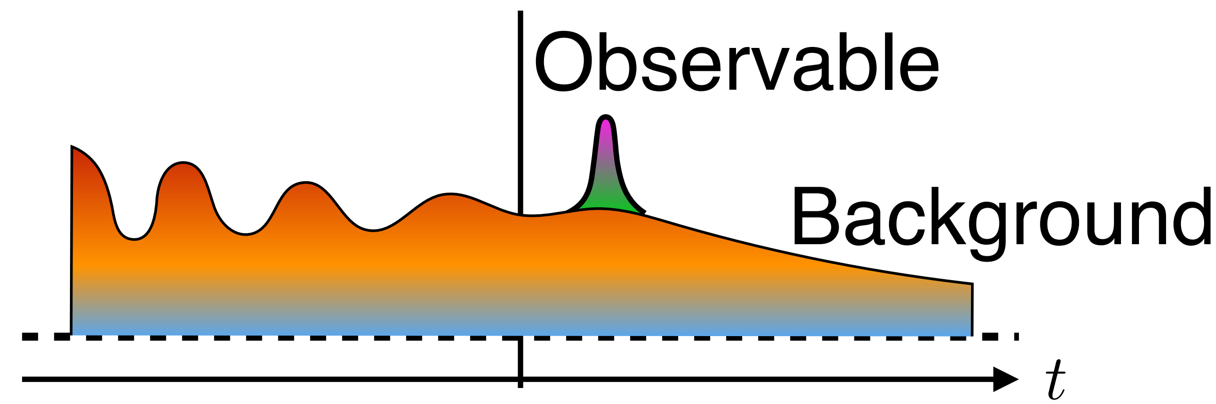
- QFT at zero temperature or in thermal equilibrium



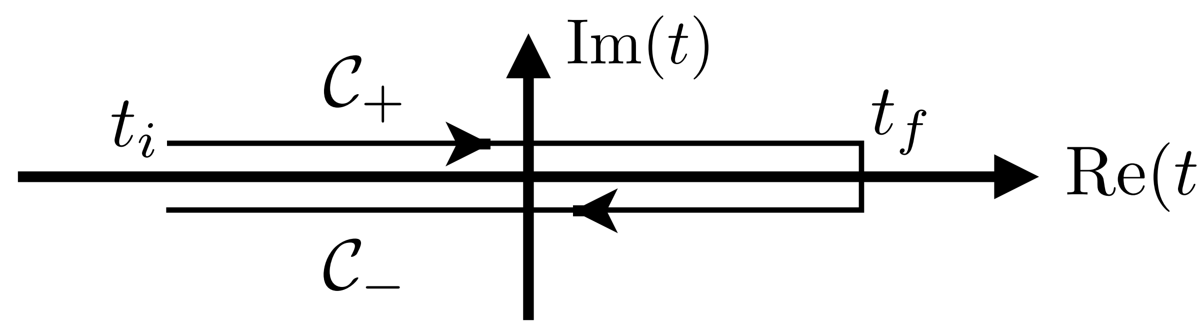
Vacuum/background is in thermal equilibrium, time-dependent



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

CTP approach

- Propagators

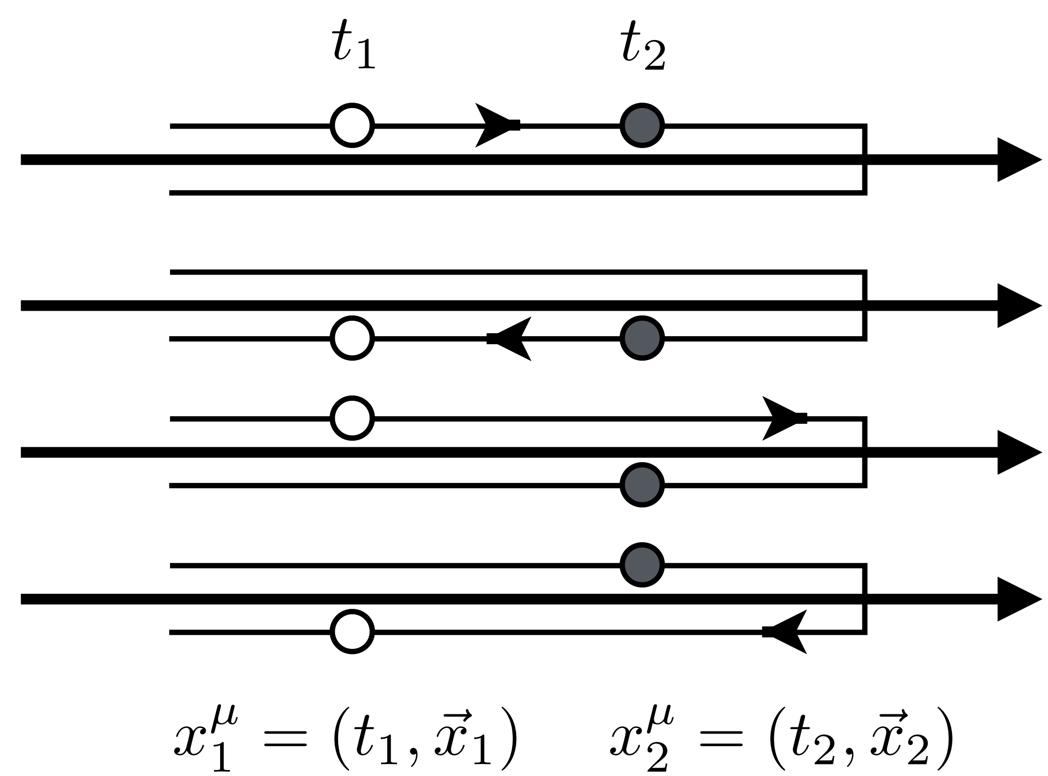
Feynman $S^{T}_{\alpha\beta}(x_1,x_2) = \langle T[\ell_\alpha(x_1)\bar{\ell}_\beta(x_2)]\rangle$

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

Wightman

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

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



- 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

Leptogenesis in CTP approach

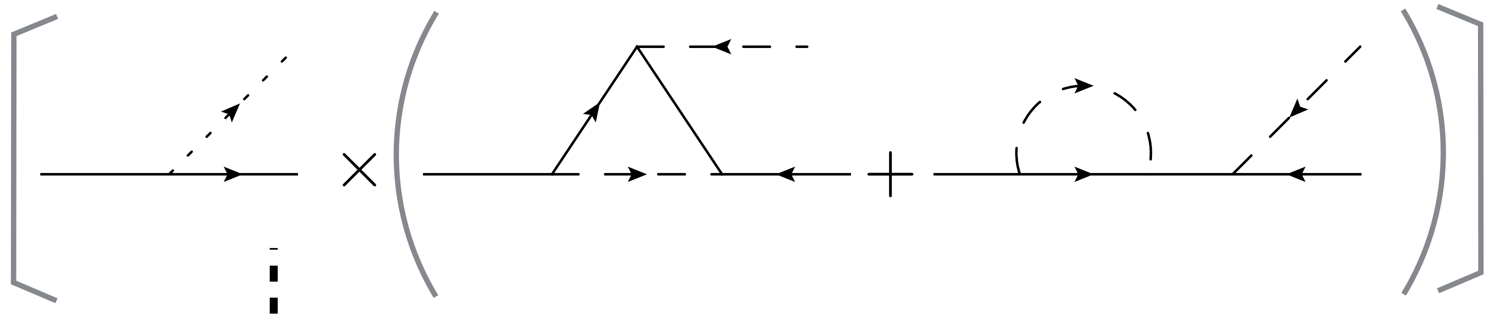
Incomplete list

Buchmuller, Fredenhagen, hep-ph/0004145; Prokopec, Schmidt, Weinstock, hep-ph/0312110; hep-ph/0406140; De Simone, Riotto, hep-ph/0703175; 0705.2183; Cirigliano, De Simone, Isidori, Masina, Riotto, 0711.0778; Anisimov, Buchmuller, Drewes, Mendizabal, 0812.1934; Garny, Hohenegger, Kartavtsev, Lindner, 0909.1559; Garny, Hohenegger, Kartavtsev, Lindner, 0911.4122; Cirigliano, Lee, Ramsey-Musolf, Tulin, 0912.3523; Anisimov, Buchmuller, Drewes, Mendizabal, 1001.3856; Garny, Hohenegger, A. Kartavtsev, 1002.0331; Beneke, Garbrecht, Herranen, Schwaller, 1002.1326; Beneke, Garbrecht, Fidler, Herranen, Schwaller, 1007.4783; Garbrecht, 1011.3122; Anisimov, Buchmuller, Drewes, Mendizabal, 1012.5821; Garbrecht, Herranen, 1112.5954; Garny, Kartavtsev, Hohenegger, 1112.6428; Drewes, B. Garbrecht, 1206.5537; Garbrecht, 1210.0553; Frossard, Garny, Hohenegger, Kartavtsev, Mitrouskas, 1211.2140; Drewes, 1303.6912; Garbrecht, Ramsey-Musolf, 1307.0524; Hohenegger, A. Kartavtsev, 1309.1385; Iso, Shimada, Yamanaka, 1312.7680; Iso, Shimada, 1404.4816; Hohenegger, Kartavtsev, 1404.5309; Garbrecht, Gautier and Klaric, 1406.4190; Bhupal Dev, Millington, Pilaftsis, Teresi, 1410.6434; Drewes, Kang, 1510.05646; Kartavtsev, Millington, Vogel, 1601.03086; Hambye, Teresi, 1606.00017; Drewes, Garbrecht, Gueter, Klaric, 1606.06690…………

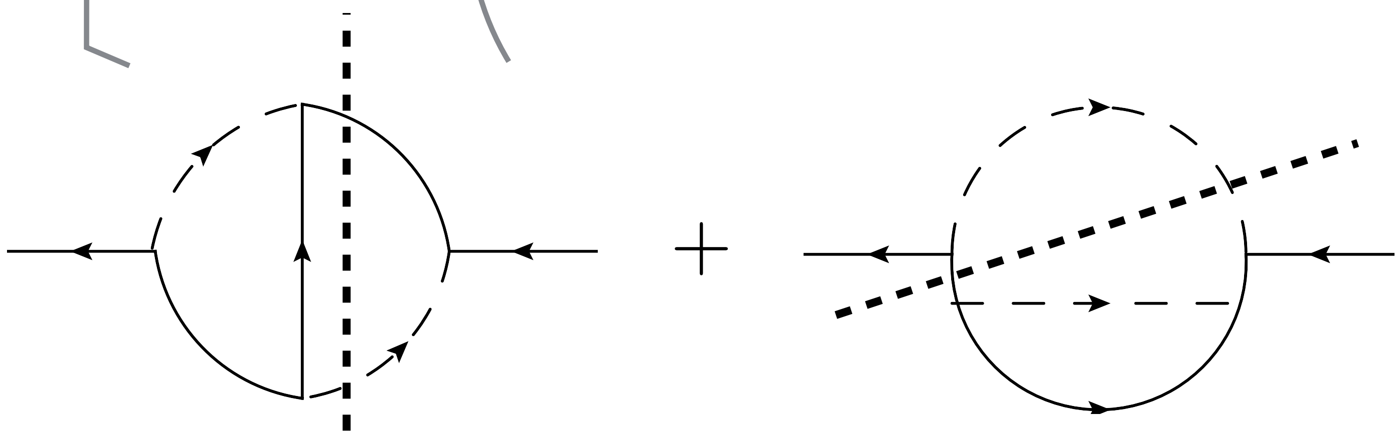
Classical formalism vs CTP formalism

- Leptogenesis via RH neutrino decay

Anisimov, Buchmuller, Drewes, Mendizabal, 1012.5821

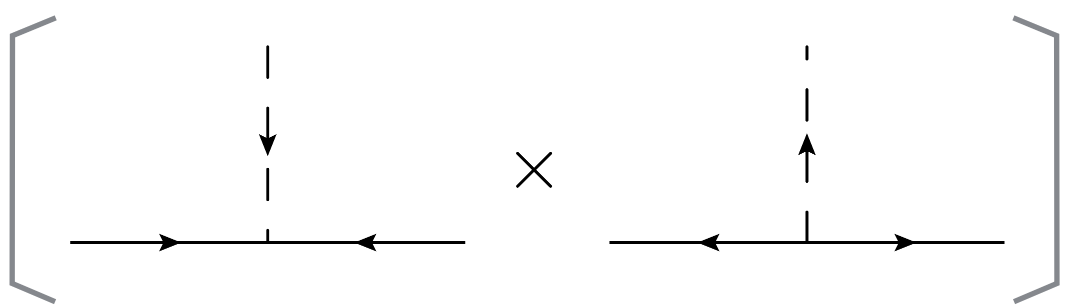
Im 

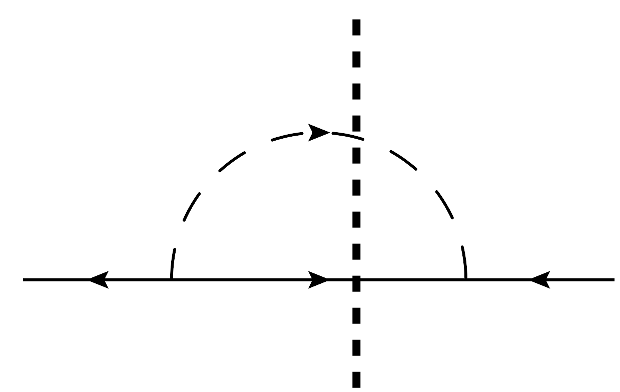
CPV source in classical formalism



Self energies including CPV source in CTP formalism

- Leptogenesis via RH neutrino oscillation

Im 

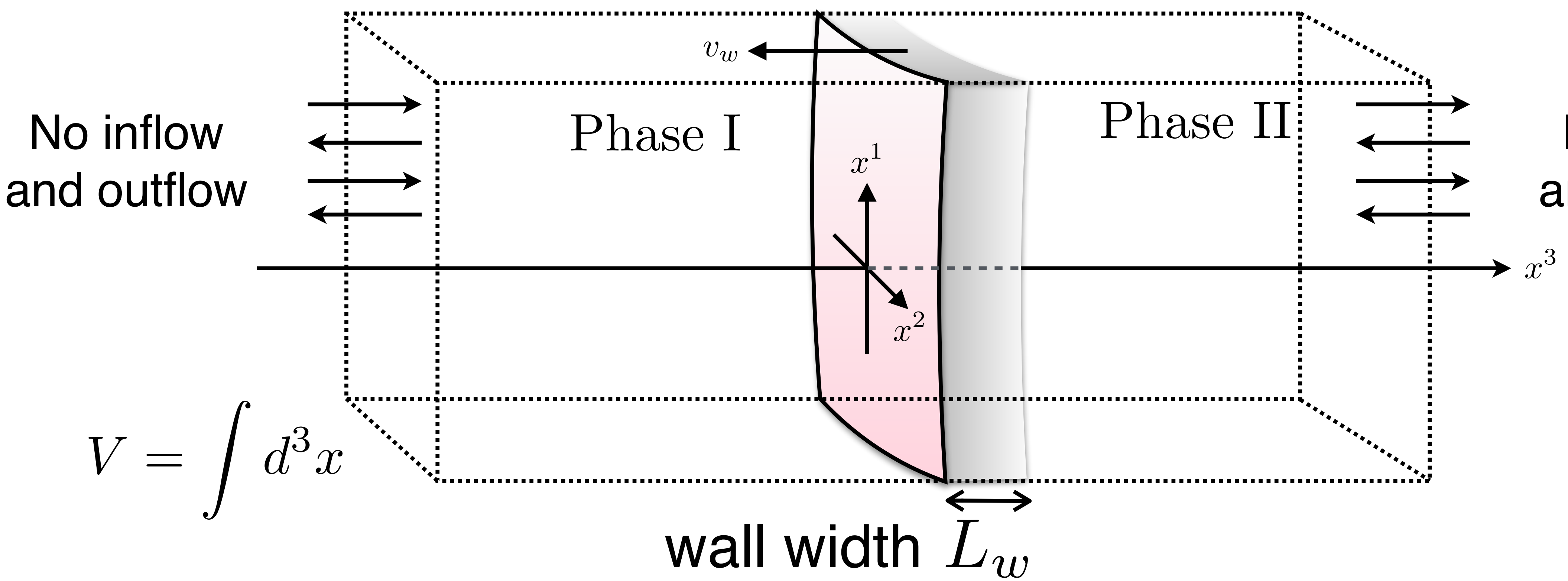


CPV source in classical formalism

Self energy including CPV source in CTP formalism

CTP approach

Bubble expansion in the rest plasma frame



$$V = \int d^3x$$

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

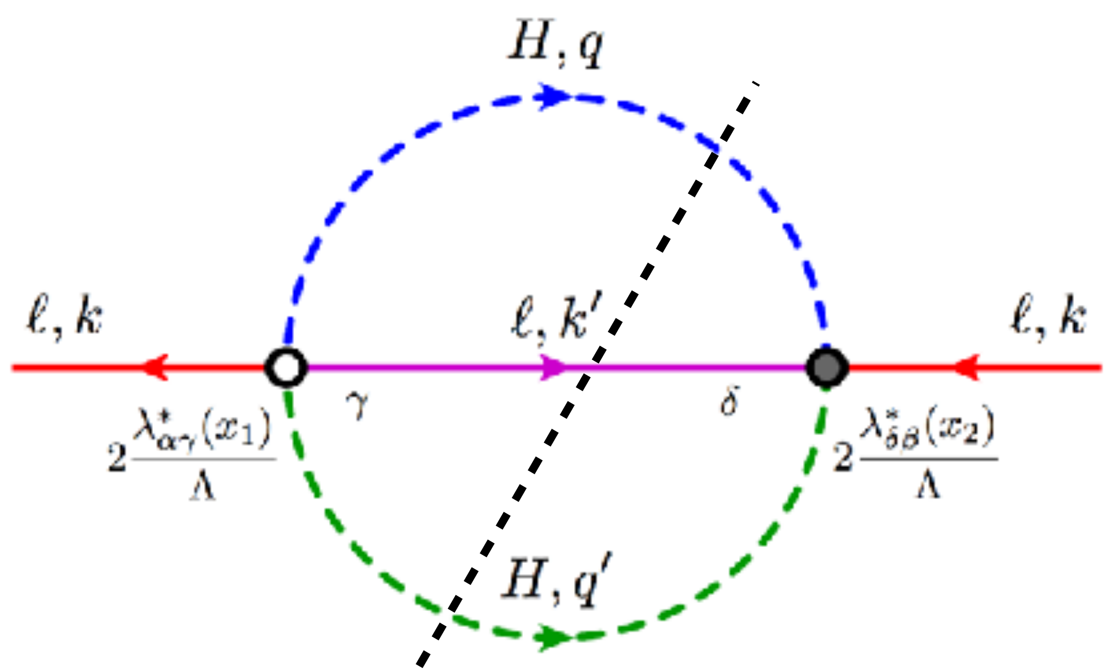
$$= -\int \underline{d^4x d^4r}\, \mathrm{tr}\Big[\Sigma^>(x_1, x_2) S^<(x_2, x_1) - \Sigma^<(x_1, x_2) S^>(x_2, x_1)\Big] .$$

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

Leptogenesis via Weinberg operator

- CPV 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

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

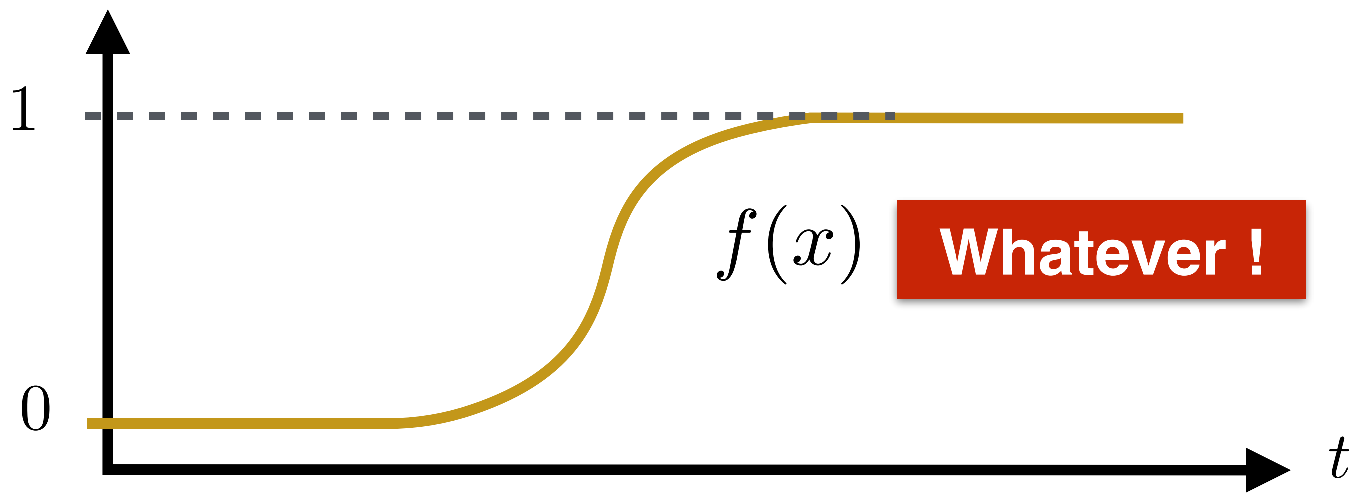
$$\mathcal{M} = i\int \frac{d^4k}{(2\pi)^4}\frac{d^4k'}{(2\pi)^4}\frac{d^4q}{(2\pi)^4}\frac{d^4q'}{(2\pi)^4}e^{iK\cdot(-r)}\left\{\Delta^<_q(x)\Delta^<_{q'}(x)\mathrm{tr}[S^<_k(x)S^<_{k'}(x)] - \Delta^>_q(x)\Delta^>_{q'}(x)\mathrm{tr}[S^>_k(x)S^>_{k'}(x)]\right\}$$

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.

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

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

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

time-dependent integration

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

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

thermal mass

$$m_{\mathrm{th},H}^2 = \mathrm{Re}\Pi \qquad m_{\mathrm{th},\ell} = \mathrm{Re}\Sigma$$

thermal width

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

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

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

$$r \to r^P = (r^0, -\mathbf{r}), \quad k_n \to k_n^P = (k_n^0, -\mathbf{k}_n)$$

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

Influence of thermal effects

- Performing the time-dependent integration

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

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

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

$$y = r^0$$

$$y^- = y - i\beta/2$$

Integrating out the time

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

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

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

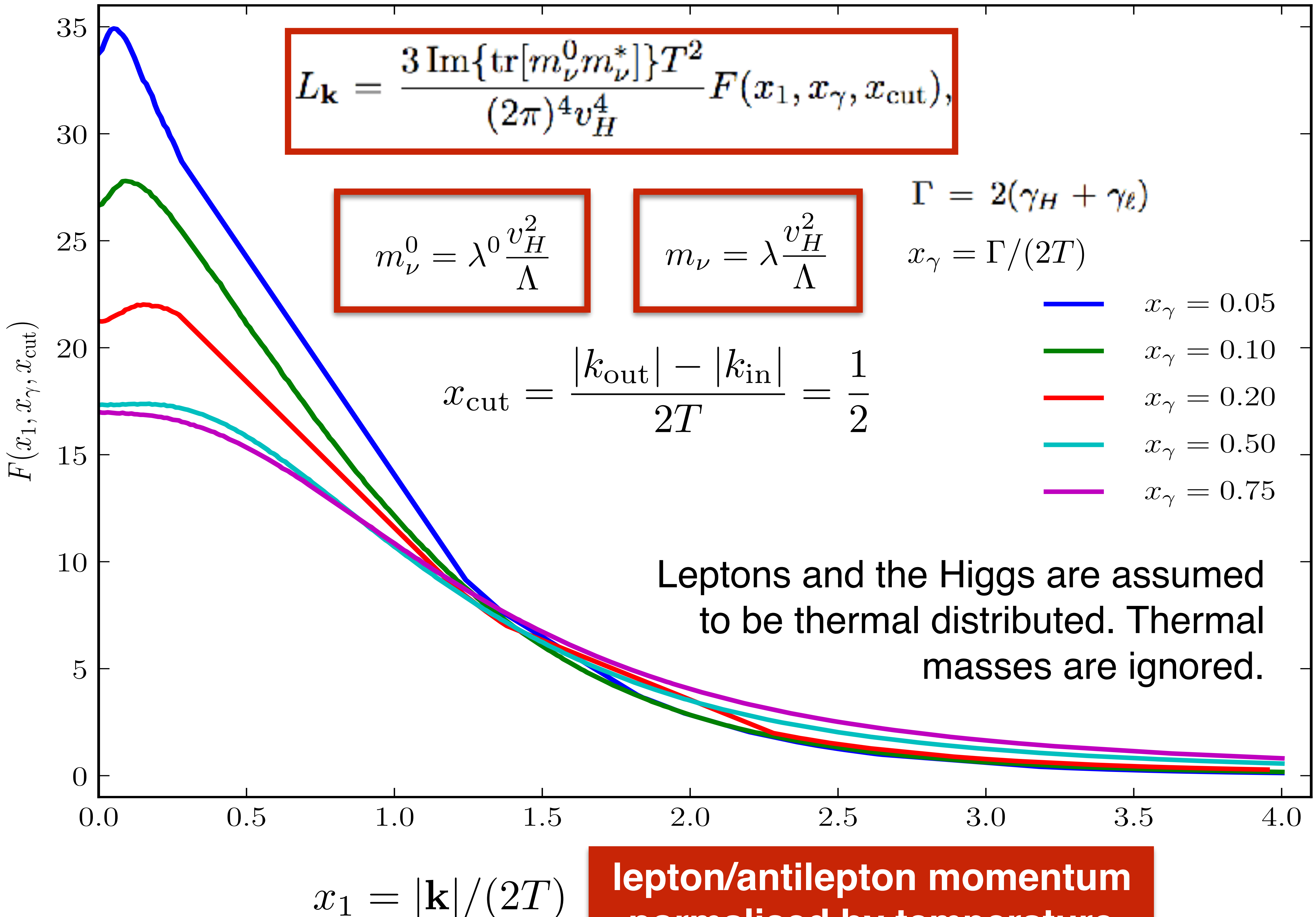
$$\int_{-\infty}^{+\infty} dy y M = 2\int_0^{+\infty} dy y M$$

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

$$= -\sum_{\eta_2,\eta_3,\eta_4=\pm1} \frac{\Omega_{\eta_2\eta_3\eta_4}\Gamma \sinh(\beta\Omega_{\eta_2\eta_3\eta_4}/2)[1-\eta_2\hat{\mathbf{k}}\cdot\hat{\mathbf{k}}']}{32\omega_{\mathbf{q}}\omega_{\mathbf{q}'}(\Omega_{\eta_2\eta_3\eta_4}^2+\Gamma^2)^2 \sinh(\omega_{\mathbf{q}}\beta/2)\sinh(\omega_{\mathbf{q}'}\beta/2)\cosh(\omega_{\mathbf{k}}\beta/2)\cosh(\omega_{\mathbf{k}'}\beta/2)}$$

Influence of thermal effects

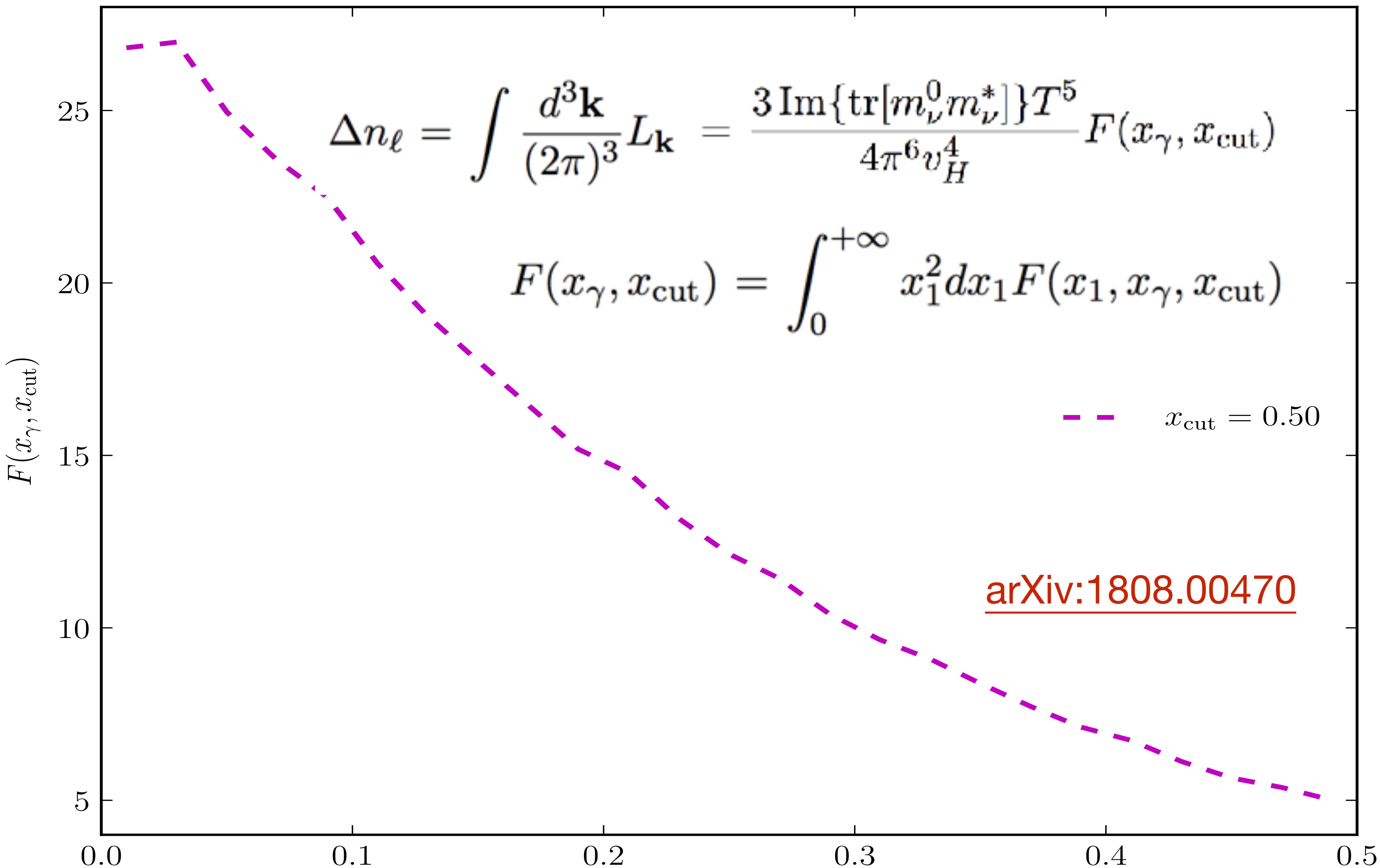
Asymmetry between lepton and antilepton momentum distribution



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

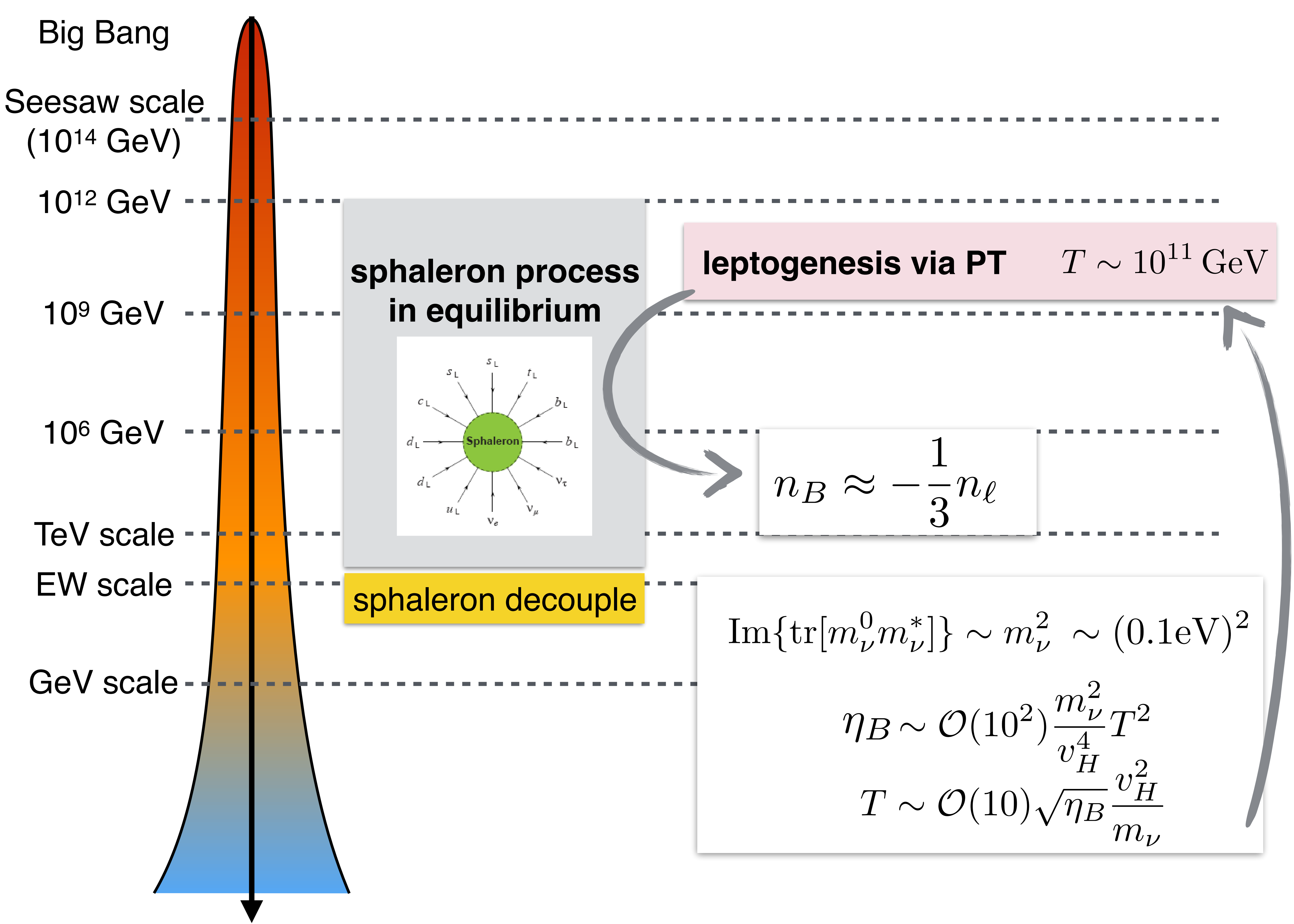
- In the single-scalar case

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

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

Effective nu mass before PT	**Effective nu mass after PT**
Depend on lepton model	**Measured by nu experiment**
A_4, S_4, U(1), SO(3)?	nu oscillation exp： DUNE, T2HK, …
determined by order of flavons getting vevs	0v2β exp: Gerda, EXO-200, KamLAND-Zen

Temperature for phase transition



Case study: CSD(n) models (preliminary)

- CSD(n) models with 2 RH neutrinos

King, 0506297

$$\frac{y_a}{v_a}(\ell \cdot \Phi_a)N_a H + \frac{y_b}{v_b}(\ell \cdot \Phi_b)N_b H + M_a \overline{N_a^c} N_a + M_b \overline{N_b^c} N_b + \text{h.c.}$$

ℓ and $\Phi_{a,b}$ are triplets, and $N_{a,b}$ and H are singlets in the flavour space.

After RH neutrinos decouple and scalars get VEVs,

$$\lambda(x) = \frac{|y_a|^2}{v_a^2}\Phi_a(x)\Phi_a^T(x) + \frac{|y_b|^2}{v_b^2} e^{i\eta}\Phi_b(x)\Phi_b^T(x)$$

- Neutrino mass matrix in CSD(n) models

$$\Phi_a(t \to +\infty) = \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} v_a \qquad \Phi_b(t \to +\infty) = \begin{pmatrix} 1 \\ n \\ n-2 \end{pmatrix} v_a \qquad n \in \mathbf{Z}$$

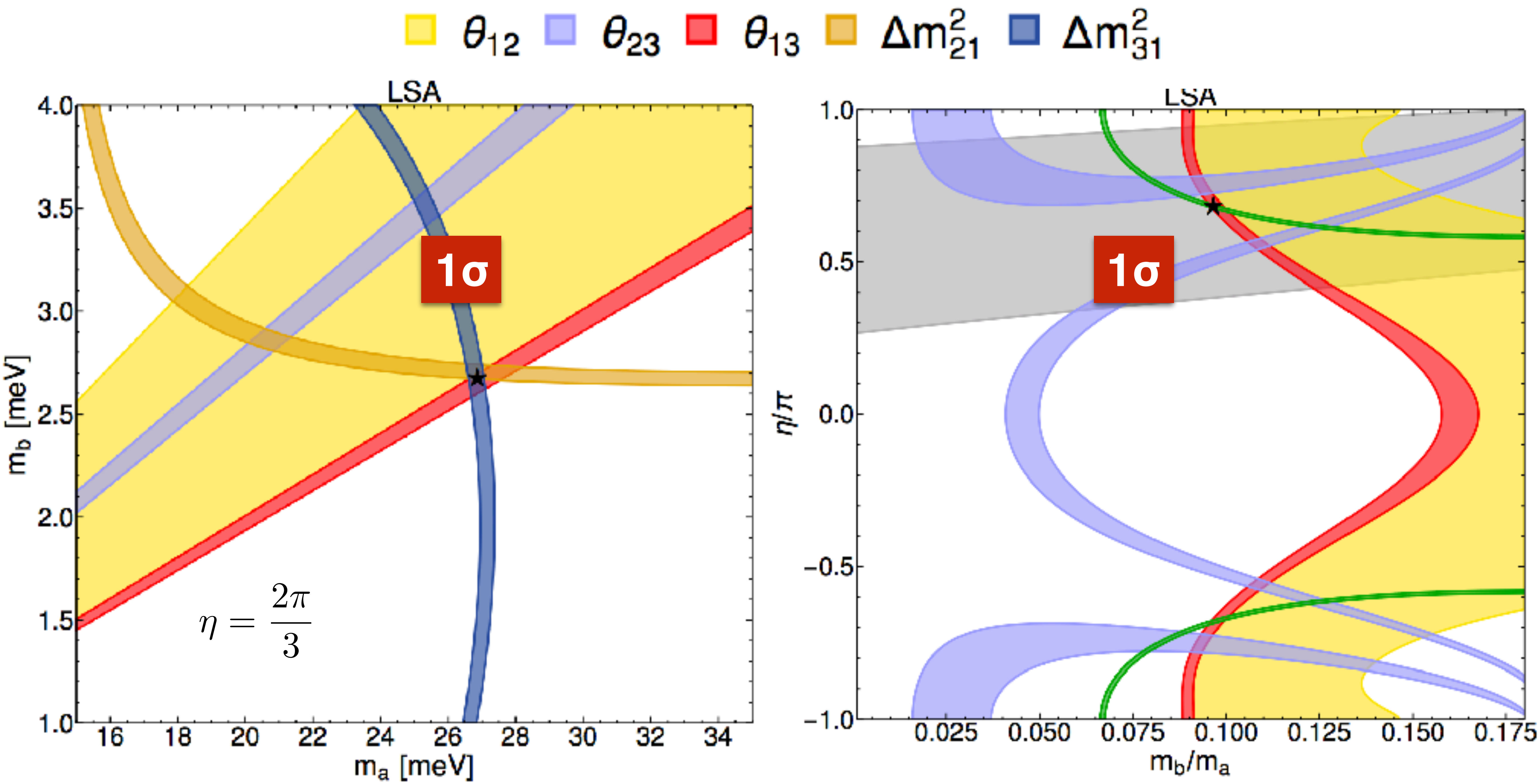
$$m_a = |y_a|^2 \frac{v_H^2}{\Lambda} \qquad m_b = |y_b|^2 \frac{v_H^2}{\Lambda}$$

$$M_\nu \equiv M_\nu(t \to +\infty) = m_a \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} + m_b e^{i\eta} \begin{pmatrix} 1 & n & (n-2) \\ n & n^2 & n(n-2) \\ (n-2) & n(n-2) & (n-2)^2 \end{pmatrix}$$

Case study: CSD(n) models (preliminary)

- CSD(n=3)

parameter space constrained by NuFit 3.0



P. Ballett, S. King, S. Pascoli, N. Prouse, T.C. Wang, 1612.01999

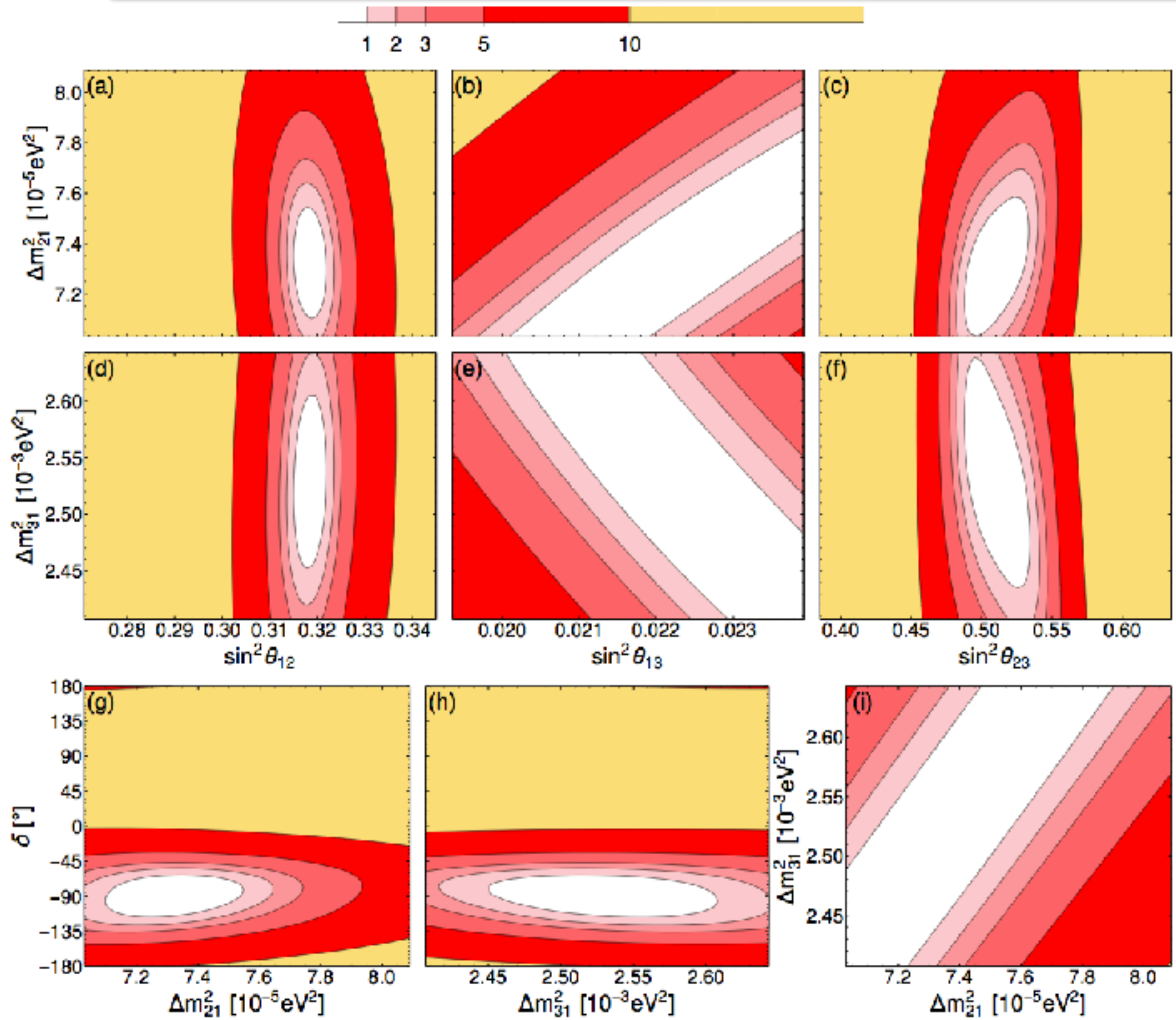
Case study: CSD(n) models (preliminary)

- CSD(n=3)

$$\eta = \frac{2\pi}{3}$$

P. Ballett,
S. King,
S. Pascoli,
N. Prouse,
T.C. Wang,
1612.01999

Predicted sensitivity of JUNO&DUNE&T2HK to exclude CSD(3) in Nσ



Case study: CSD(n) models (preliminary)

- CSD(n) for leptogenesis

Assuming Φ_a gets a VEV before Φ_b , we consider leptogenesis from the phase transition of Φ_b

$$M_\nu^0 = m_a \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$$

$$M_\nu = m_a \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} + m_b e^{i\eta} \begin{pmatrix} 1 & n & (n-2) \\ n & n^2 & n(n-2) \\ (n-2) & n(n-2) & (n-2)^2 \end{pmatrix}$$

$$\mathrm{Im}\{\mathrm{tr}[M_\nu^0 M_\nu^*]\} = -m_a m_b \sin\eta \times 4(n-1)^2$$

- CSD(n=3) for leptogenesis

$$\mathrm{Im}\{\mathrm{tr}[M_\nu^0 M_\nu^*]\} = -16 m_a m_b \sin\eta \sim -0.1\ \mathrm{eV}^2$$

Summary

- I give a brief review of leptogenesis.
- I introduce a novel mechanism of leptogenesis via phase transition.
- No explicit new particles are required, but just a spacetime-varying Weinberg operator.
- The spacetime-varying coefficient of the Weinberg operator is triggered by a phase transition.
- In order to generate enough baryon-antibaryon asymmetry, the temperature for phase transition should be around 10^{11} GeV.

Thank you very much!