DESY THEORY WORKSHOP
26 - 29 September 2017

Fundamental physics in the cosmos:
The early, the large and the dark Universe

DESY Hamburg, Germany

HELMHOLTZ ASSOCIATION

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Leptogenesis via Weinberg operator

Ye-Ling Zhou, IPPP Durham, 27 September 2017

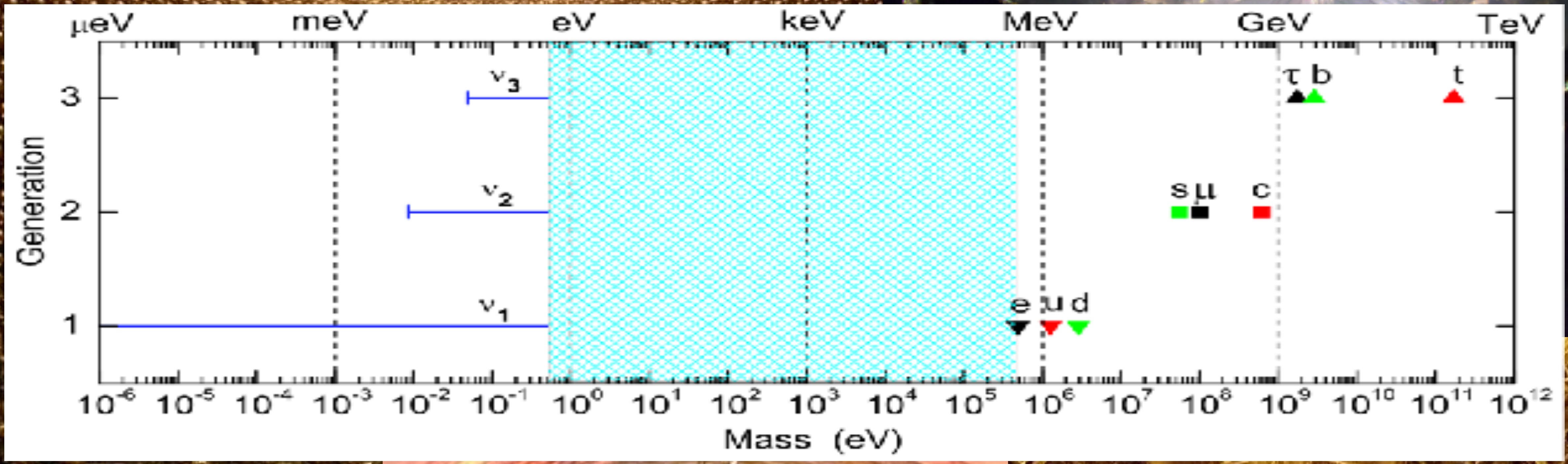
IP3

νmass

erc
European Research Council

elusives
neutrinos, dark matter & dark energy physics

Origin of neutrino masses



Why neutrinos have masses and these masses are so tiny?

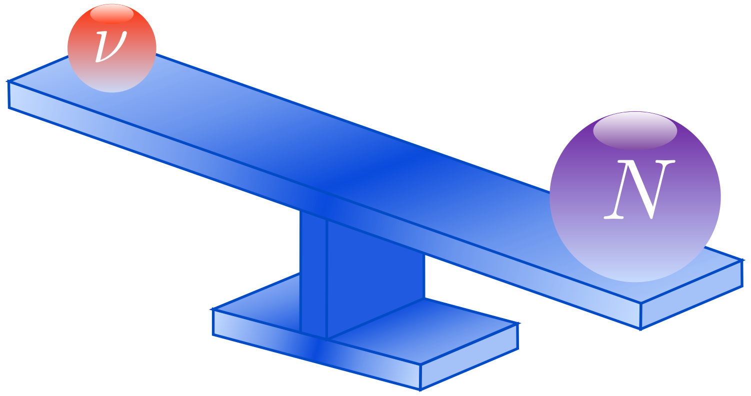
In the SM without extending particle content, the only way to generate a neutrino mass is using higher dimensional operators.

Weinberg operator **ΔL=2**

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

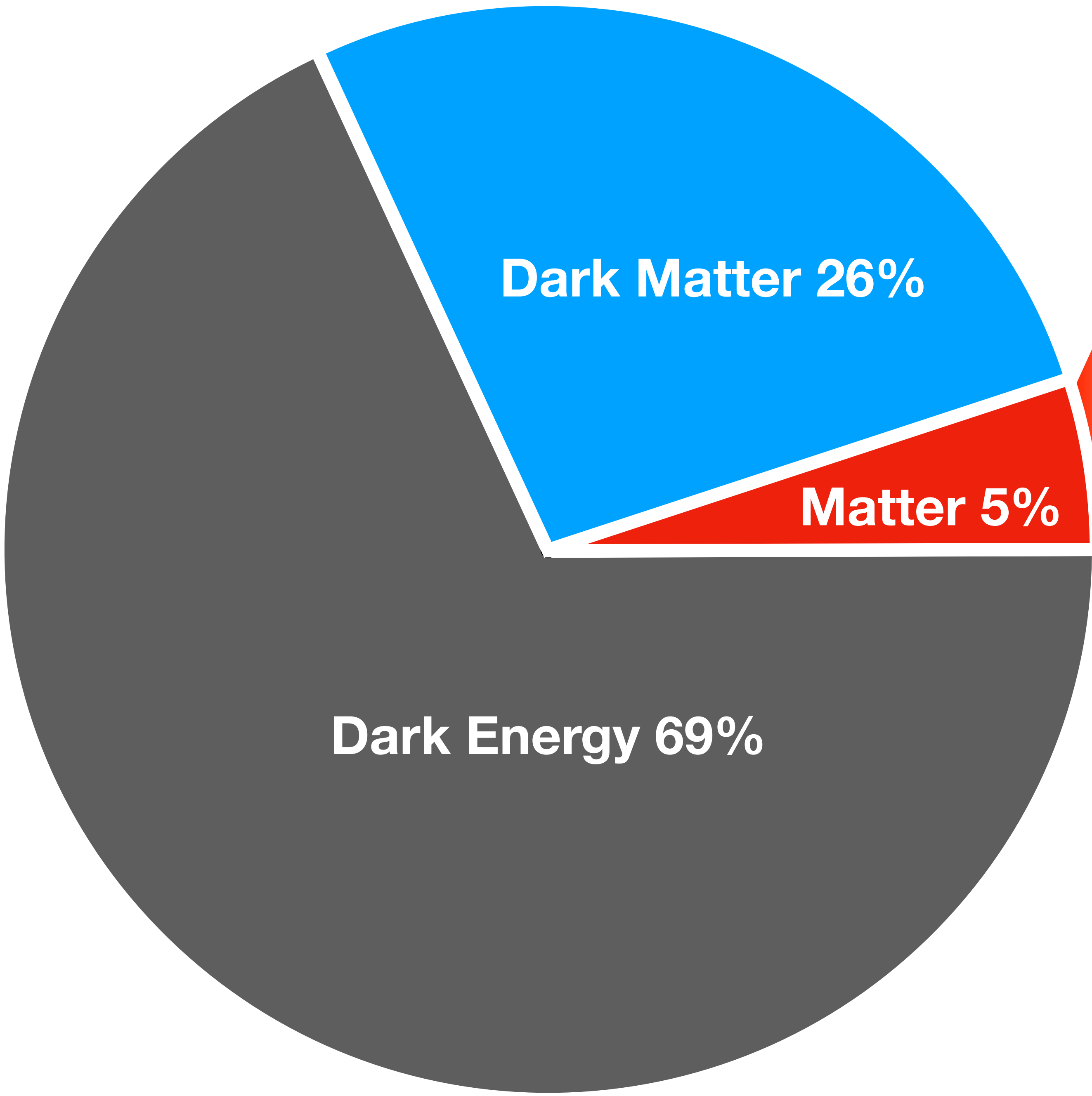
$$m_\nu = \lambda \frac{v_H^2}{\Lambda} \qquad \frac{\Lambda}{\lambda} \sim 10^{15}\ \text{GeV}$$

UV Completion of the Weinberg operator



type-I,II,III seesaw, inverse seesaw, loop corrections, R-parity violation,…

Baryon-antibaryon asymmetry



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

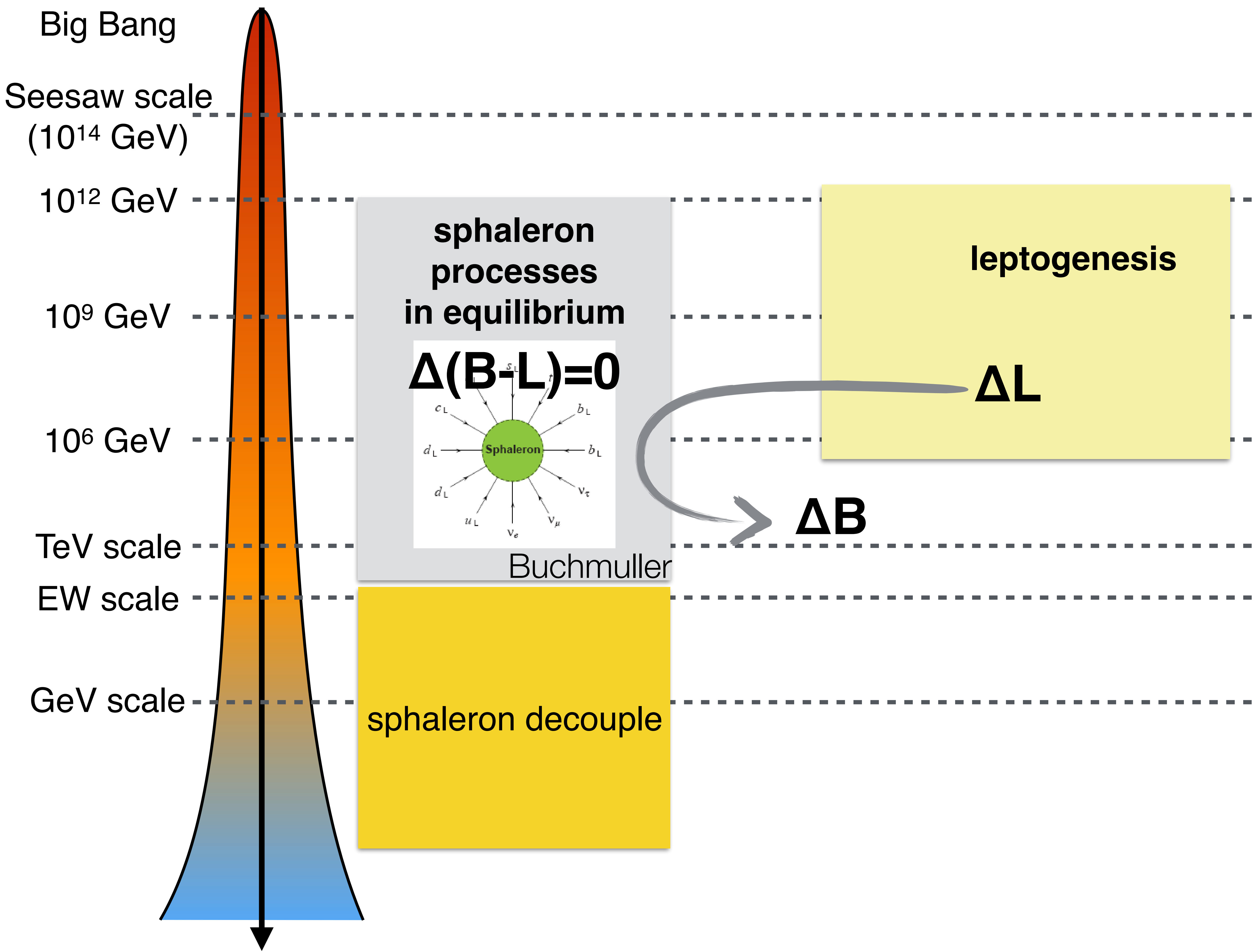
$$\eta_B \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma}$$
$$= 6.105^{+0.086}_{-0.081} \times 10^{-10}$$

Planck 2015

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

[1] Parameter	[2] 2013N(DS)	[3] 2013F(DS)	[4] 2013F(CY)	[5] 2015F(CHM)	[6] 2015F(CHM) (Plik)
$100\theta_{MC}$	1.04131 ± 0.00063	1.04126 ± 0.00047	1.04121 ± 0.00048	1.04094 ± 0.00048	1.04086 ± 0.00048
$\Omega_b h^2$	0.02205 ± 0.00028	0.02234 ± 0.00023	0.02230 ± 0.00023	0.02225 ± 0.00023	0.02222 ± 0.00023
$\Omega_c h^2$	0.1199 ± 0.0027	0.1189 ± 0.0022	0.1188 ± 0.0022	0.1194 ± 0.0022	0.1199 ± 0.0022
H_0	67.3 ± 1.2	67.8 ± 1.0	67.8 ± 1.0	67.48 ± 0.98	67.26 ± 0.98

Baryogenesis via leptogenesis



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

[Fukugita, Yanagida, 1986]

RH neutrino decay

flavour effect

resonant decay

RH neutrino oscillation

Akhmedov, Rubakov, Smirnov, 9803255

Weinberg operator

Silvia Pascoli, Jessica Turner, **YLZ**, arXiv:1609.07969

Leptogenesis via Weinberg operator

Three Sakharov conditions are satisfied as follows:

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

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

and their CP-conjugate processes

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

$$\Gamma_{\rm W} \sim \langle \sigma n \rangle \sim \frac{1}{4\pi}\frac{\lambda^2}{\Lambda^2}T^3 \sim \frac{1}{4\pi}\frac{m_\nu^2}{v_H^4}T^3 \quad < \quad H_u \sim 10\frac{T^2}{m_{\rm pl}}$$

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

No washout if there are no other LNV sources.

- **We assume that a time-varying Weinberg operator, to give rise to CP violation.**

Motivation for varying Weinberg operator

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.

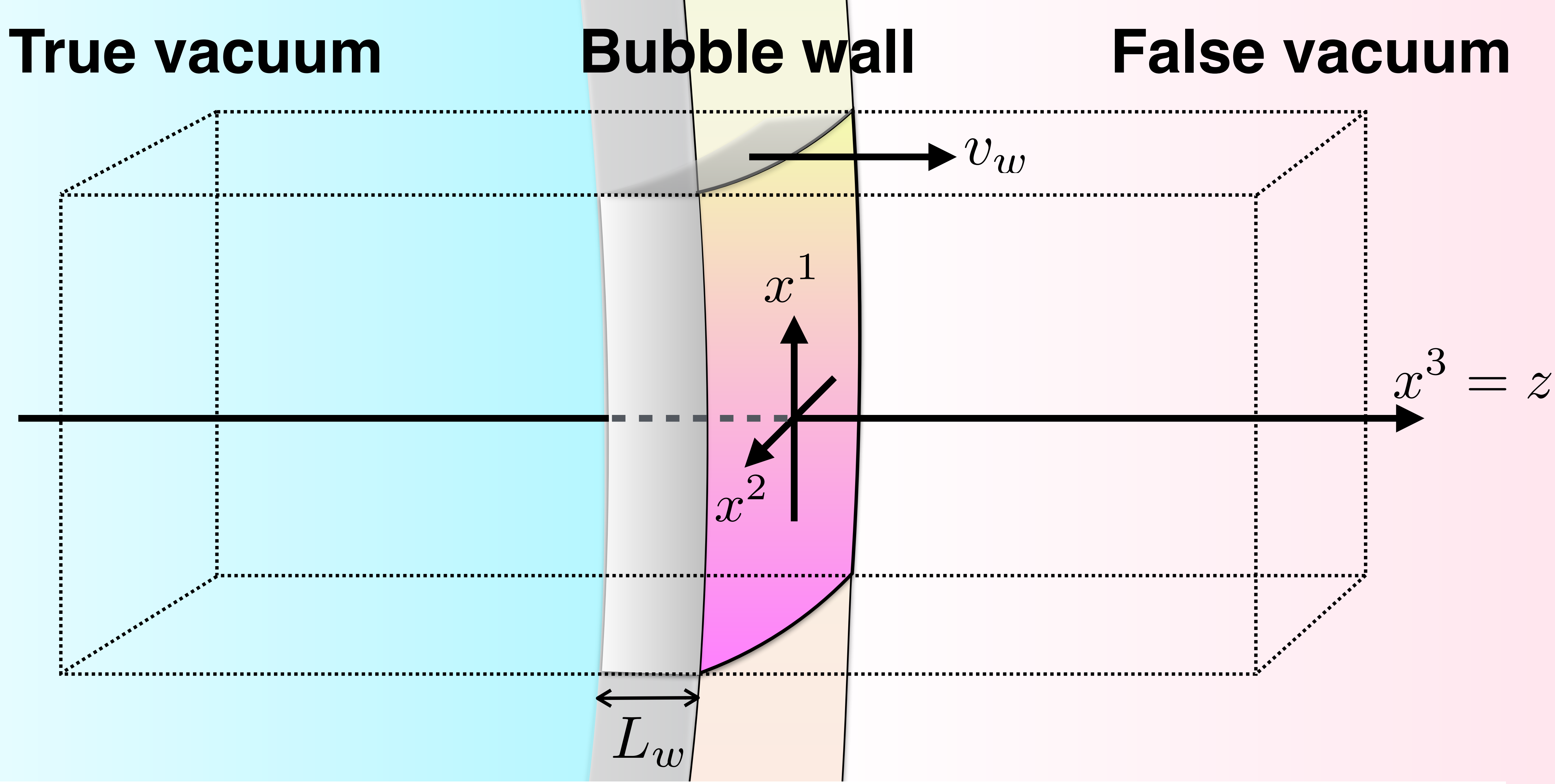
- **Flavour & CP symmetry breaking**

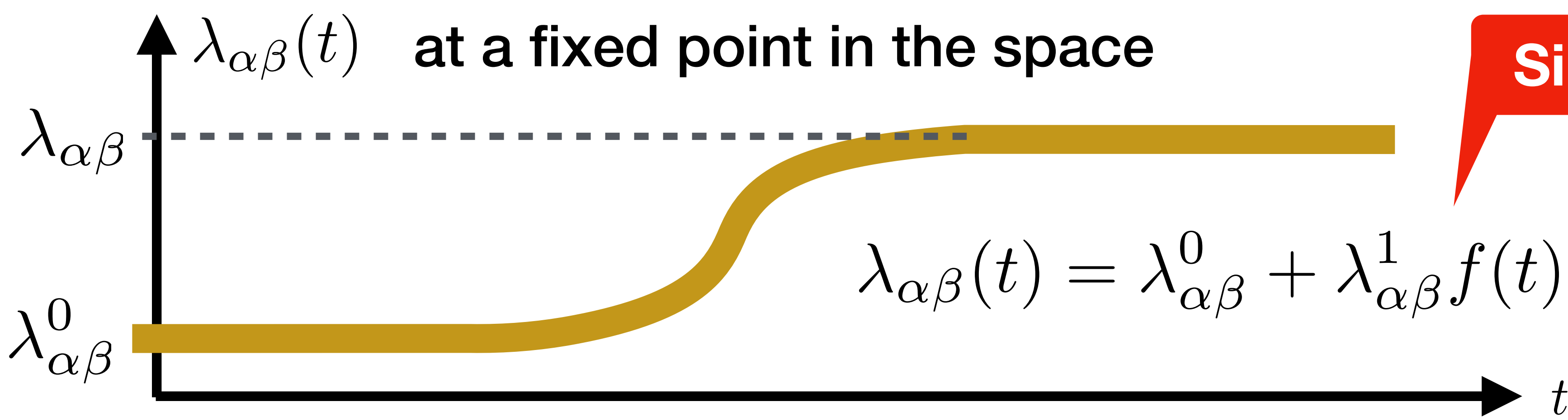
Flavour symmetries	Continuous	Discrete
Abelian	Fraggatt-Nielson, L_{mu}-L_{tau} …	Z_n
Non-Abelian	SU(3), SO(3), …	A_4, S_4, A_5, Δ(48), …

- **Other possible origins**

  Inflation or condensation in strongly coupled theories?

Assuming first-order phase transition





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

Single-scalar case

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

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

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

CP violation from varying Weinberg operator

- Example:

$$H^*_{\mathbf{q}} H^*_{\mathbf{q}'} \to \ell_{\mathbf{k}} \ell_{\mathbf{k}'}$$

- Canonical quantisation

$$S = \mathbf{1} + (-i) \int_{-\infty}^{+\infty} dt H_I(t) + \cdots ,$$

$$H_I(t) = \int d^3\mathbf{x} \mathcal{L}_W = \frac{1}{\Lambda} \int d^3\mathbf{x}\, \lambda_{\alpha\beta}(t) \ell_{\alpha L} H C \ell_{\beta L} H + \text{h.c.}$$

- Time-integrated magnitude

$$M(H^*_{\mathbf{q}} H^*_{\mathbf{q}'} \to \ell_{\mathbf{k}} \ell_{\mathbf{k}'}) \propto \frac{2}{\Lambda} \int_{-\infty}^{+\infty} dt\, \lambda^*_{\alpha\beta}(t) e^{i\Delta\omega t} e^{-i\Delta\mathbf{k}\cdot\mathbf{x}} ,$$

$$M(H_{\mathbf{q}} H_{\mathbf{q}'} \to \overline{\ell}_{\mathbf{k}} \overline{\ell}_{\mathbf{k}'}) \propto \frac{2}{\Lambda} \int_{-\infty}^{+\infty} dt\, \lambda_{\alpha\beta}(t) e^{i\Delta\omega t} e^{-i\Delta\mathbf{k}\cdot\mathbf{x}} .$$

$$\Delta\mathbf{k} = \mathbf{k} + \mathbf{k}' - \mathbf{q} - \mathbf{q}' .$$

$$\Delta\omega = \omega_{\mathbf{k}} + \omega_{\mathbf{k}'} - \omega_{\mathbf{q}} - \omega_{\mathbf{q}'}$$

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

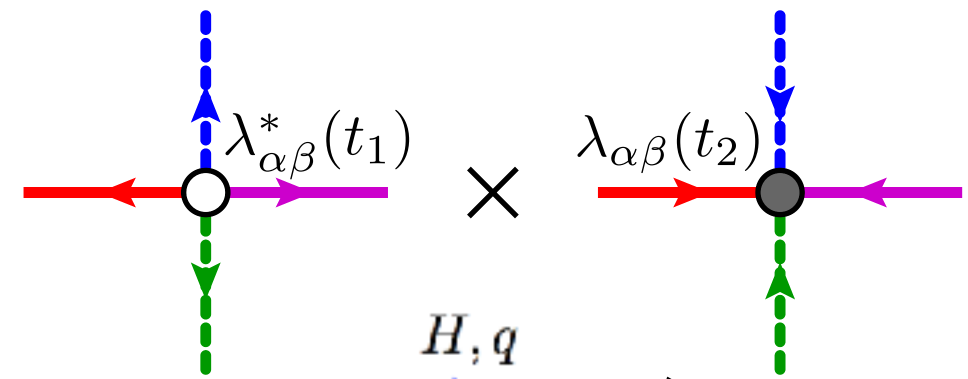
$$\Delta_{CP}(H^*_{\mathbf{q}} H^*_{\mathbf{q}'} \to \ell_{\mathbf{k}} \ell_{\mathbf{k}'}) \equiv \frac{|M(H^*_{\mathbf{q}} H^*_{\mathbf{q}'} \to \ell_{\mathbf{k}} \ell_{\mathbf{k}'})|^2 - |M(H_{\mathbf{q}} H_{\mathbf{q}'} \to \overline{\ell}_{\mathbf{k}} \overline{\ell}_{\mathbf{k}'})|^2}{|M(H^*_{\mathbf{q}} H^*_{\mathbf{q}'} \to \ell_{\mathbf{k}} \ell_{\mathbf{k}'})|^2 + |M(H_{\mathbf{q}} H_{\mathbf{q}'} \to \overline{\ell}_{\mathbf{k}} \overline{\ell}_{\mathbf{k}'})|^2}$$

Silvia Pascoli, Jessica Turner, **YLZ**, in process

Lepton asymmetry in closed-time-path approach

CPV source in classical formalism

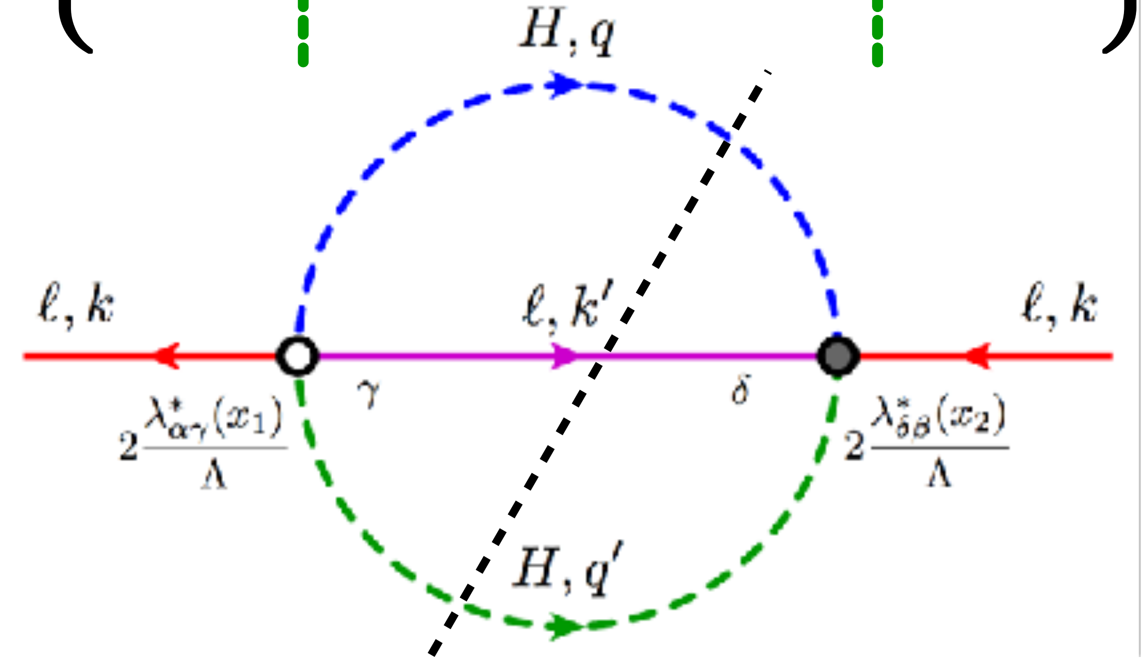
$$\Delta f_{\ell_\alpha} \propto \mathrm{Im}\left\{ \quad \times \quad \right\}$$



Self energies including CPV source in CTP formalism

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

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



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

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

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

Leptogenesis via Weinberg operator (in CTP approach)

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

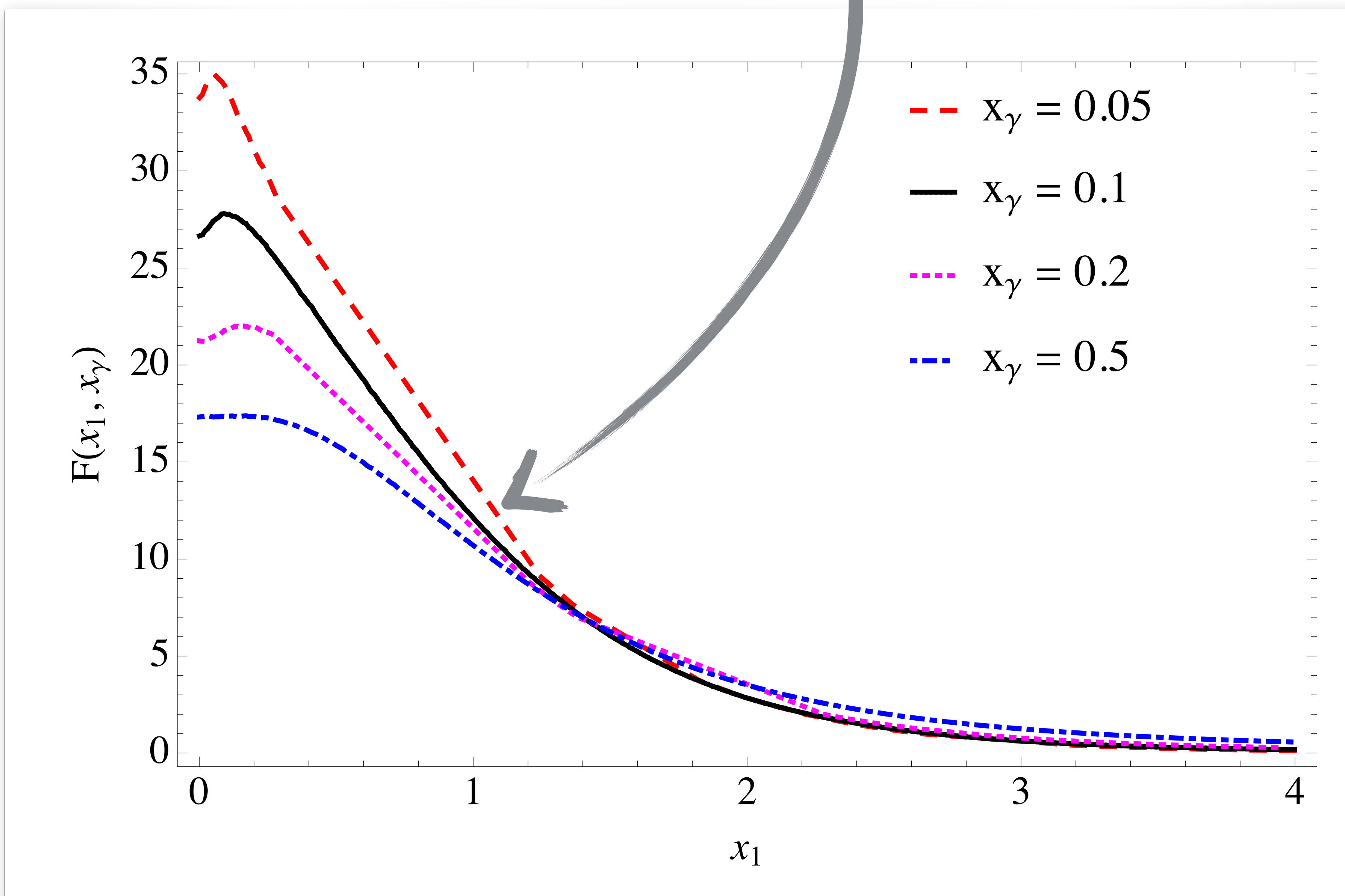
$$m_\nu^0 = \lambda^0 \frac{v_H^2}{\Lambda}$$

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

$$x_\gamma = (\gamma_H + \gamma_l)/T$$

Higgs thermal width

lepton thermal width

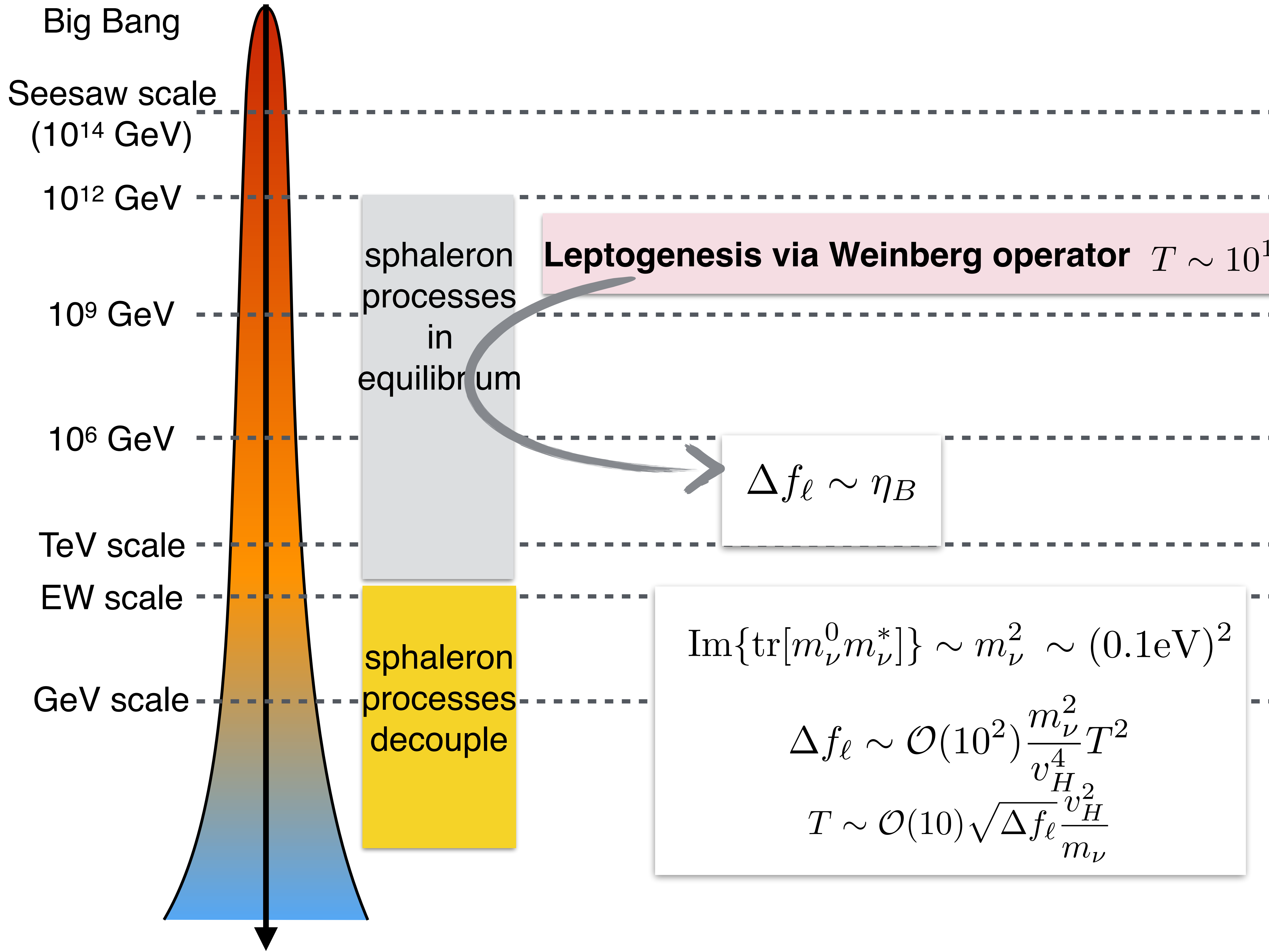


The thermal width corresponds to decoherence at large time duration.

Leptons and the Higgs are assumed to be thermal distributed.

Thermal masses are neglected.

Leptogenesis via RH neutrino decays



Leptogenesis via Weinberg operator $T \sim 10^{11}\,\mathrm{GeV}$

$$\Delta f_\ell \sim \eta_B$$

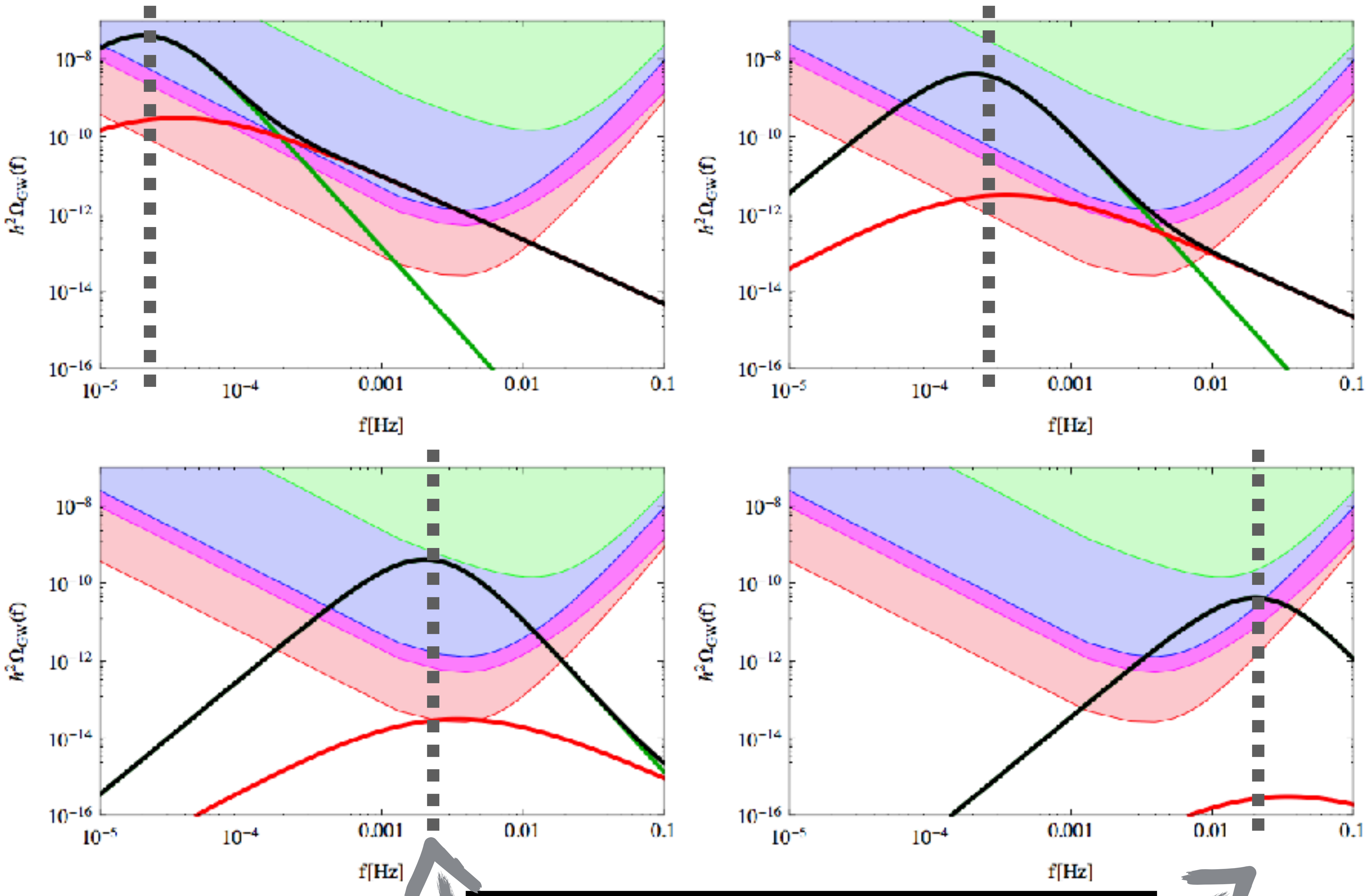
$$\mathrm{Im}\{\mathrm{tr}[m_\nu^0 m_\nu^*]\} \sim m_\nu^2 \sim (0.1\mathrm{eV})^2$$

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

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

Testability

Assuming 1st-order Phase transition



eLISA test strong EWPT

Caprini, et al, 1512.06239

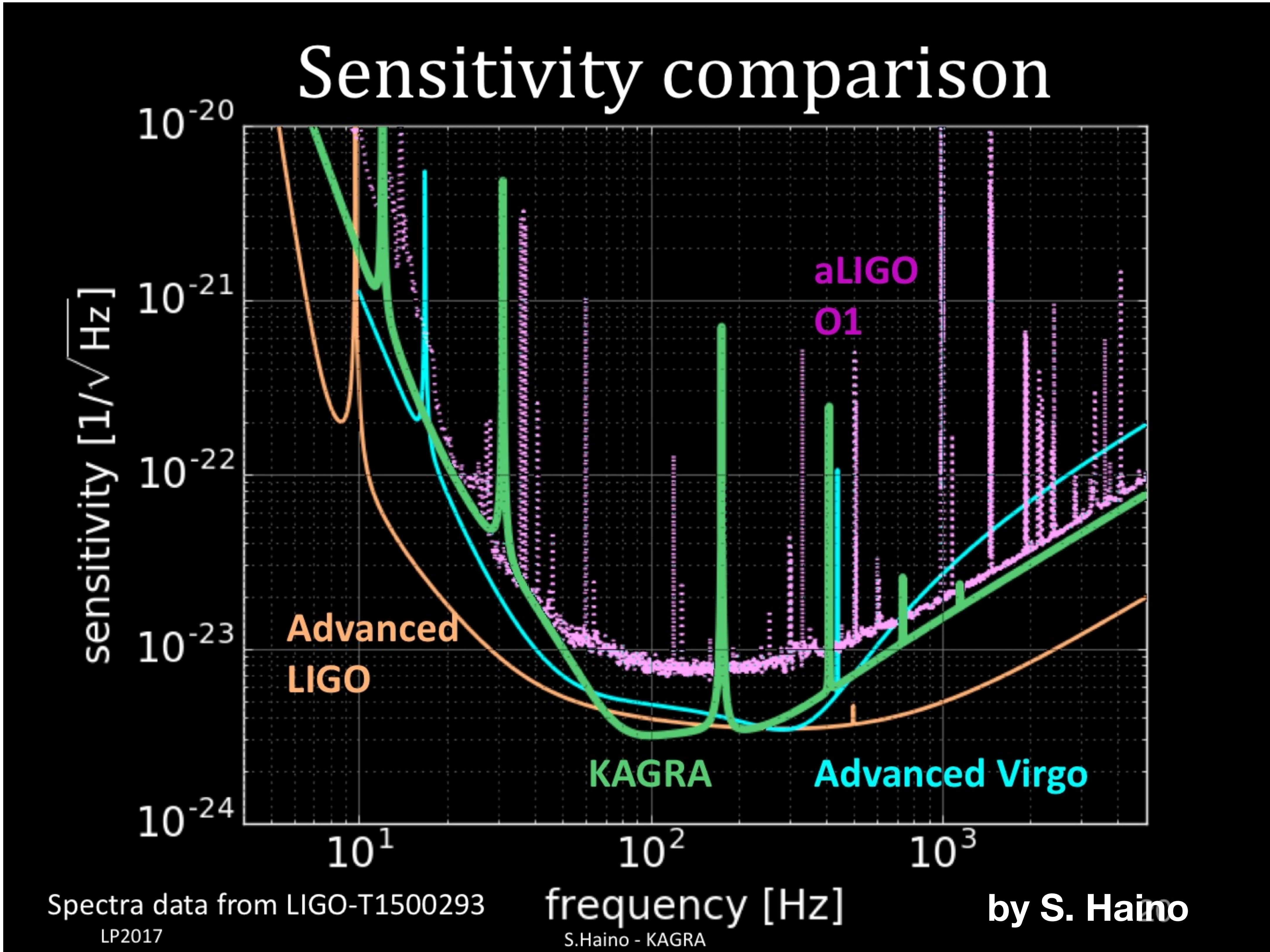
$$f_{\rm peak} \sim \mathcal{O}(10^{-7}) \times {\rm Hz} \times \frac{T}{\rm GeV}$$

Testability

Assuming 1st-order Phase transition

Using underground gravitational wave telescopes

aLIGO,
KAGRA,
Virgo
test
$10^{8\sim11}$ GeV
scale PT.



by S. Haino

Summary

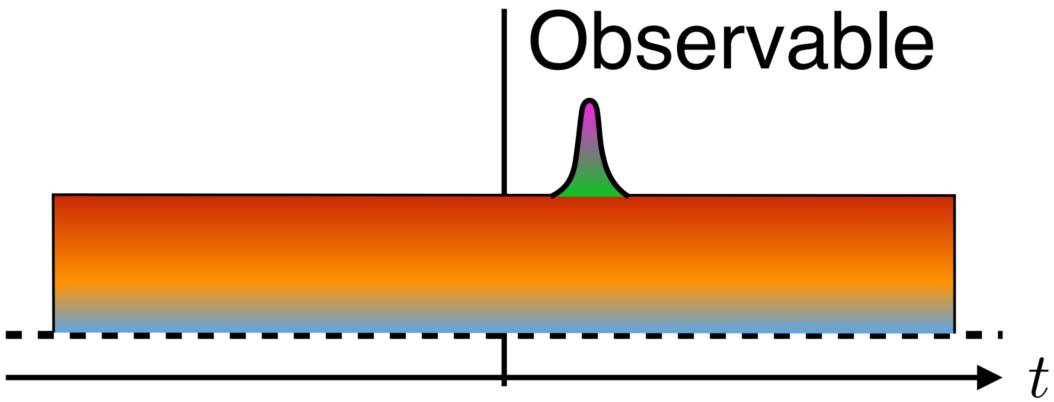
- I introduce a novel mechanism of leptogenesis via Weinberg operator.
- No explicit new particles are required, but just a time-varying Weinberg operator.
- Phase transition can be the origin of the time-varying Weinberg operator.
- Phase transition temperature is around 10^{11} GeV.
- The phase transition can be tested in the future underground GW interferometers.

Thank you very much!

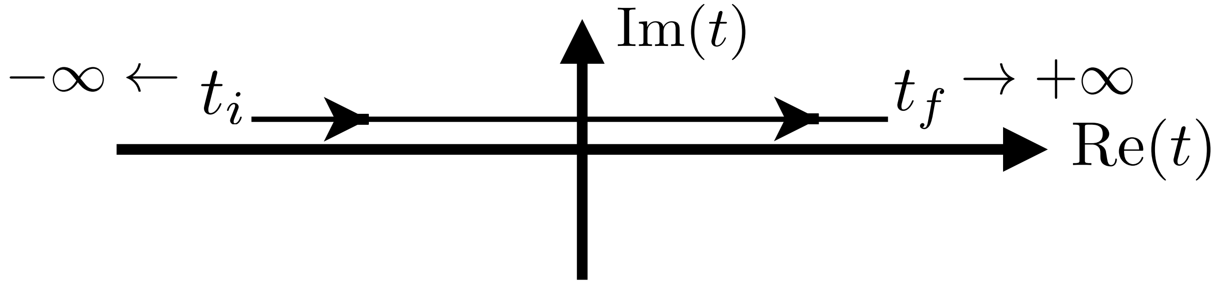
Back up

Motivation for closed-time-path (CTP) approach

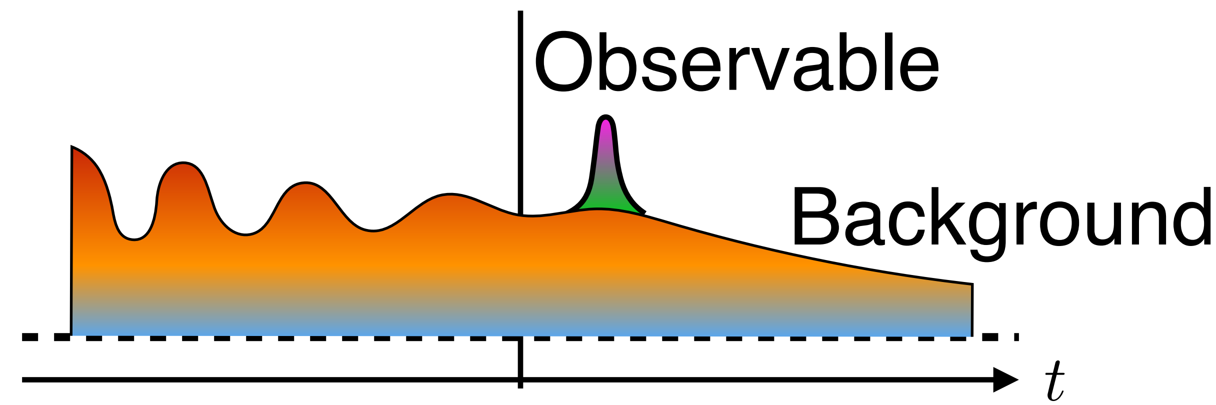
- **QFT at zero temperature or in thermal equilibrium**



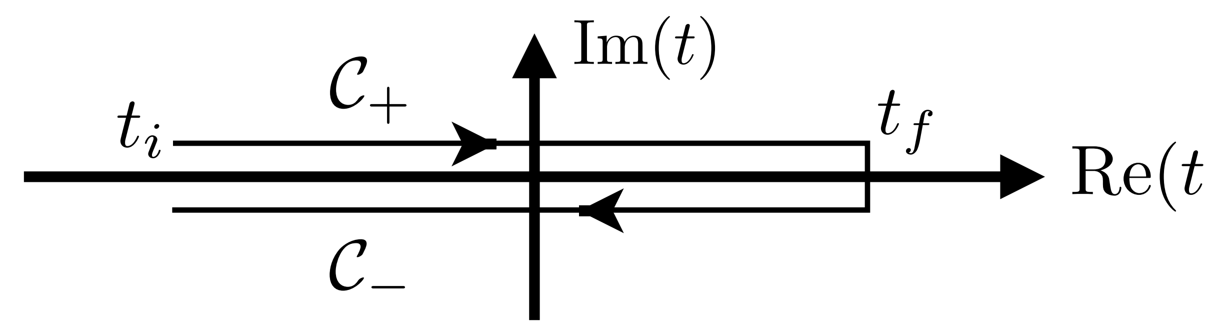
Vacuum/background is in thermal equilibrium, time-dependent



- **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**

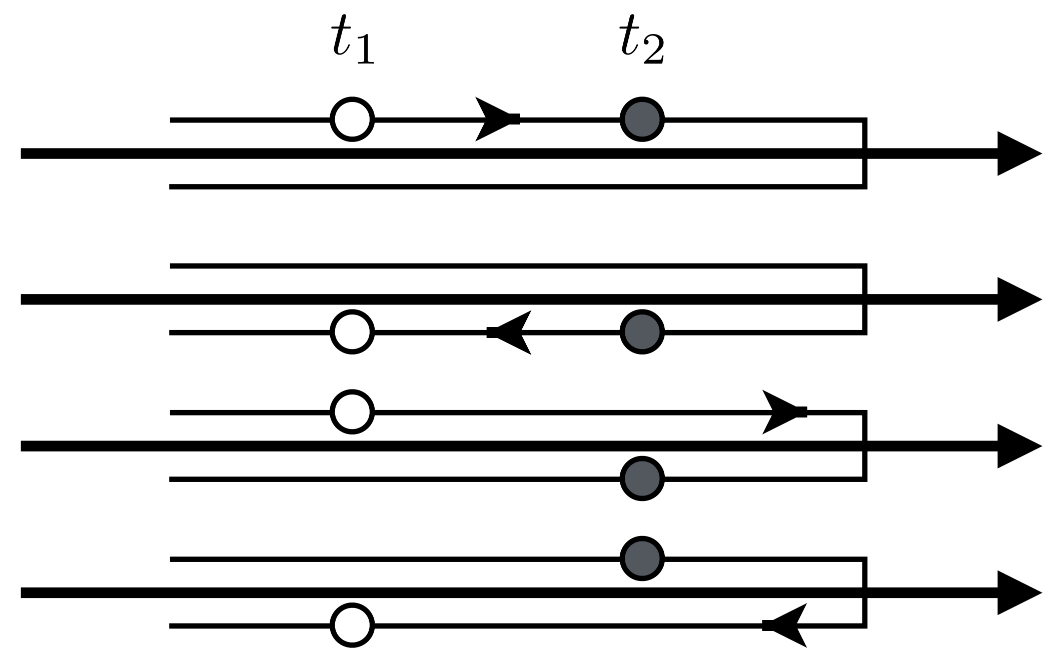
Feynman $S^{T}_{\alpha\beta}(x_1, x_2) = \langle T[\ell_\alpha(x_1)\bar{\ell}_\beta(x_2)]\rangle$

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

Wightman

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

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



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

- **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**

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

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

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

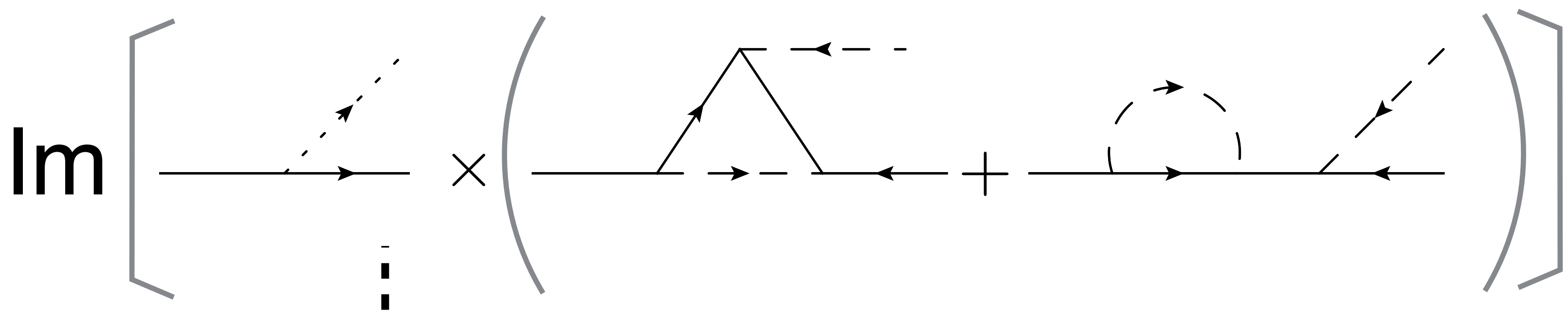
$$\Sigma^H = \Sigma^T - \frac{1}{2}(\Sigma^> + \Sigma^<)$$

CPV source

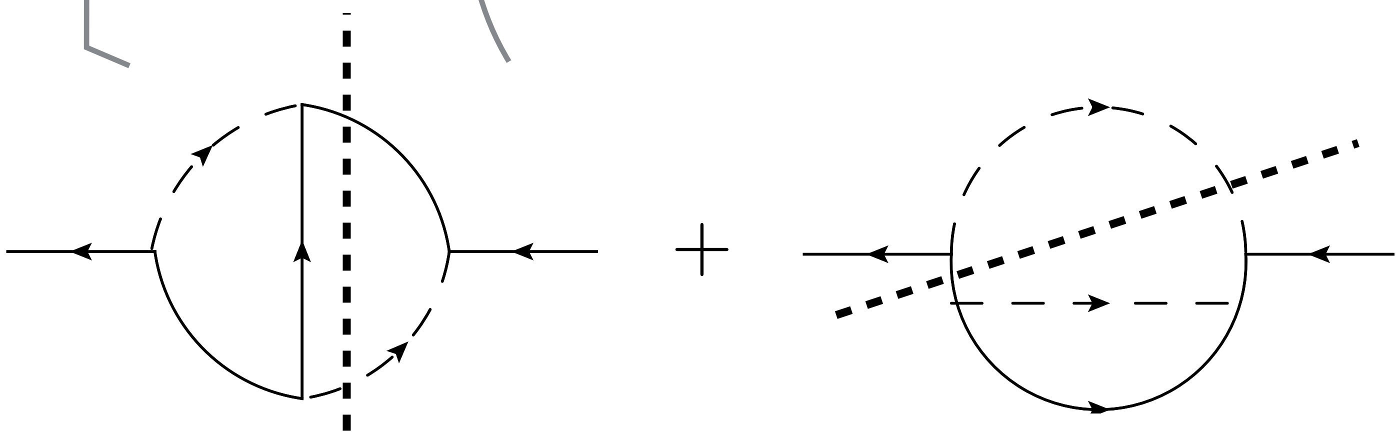
Classical formalism vs CTP formalism

- **Leptogenesis via RH neutrino decay**

Anisimov, Buchmuller, Drewes, Mendizabal, 1012.5821

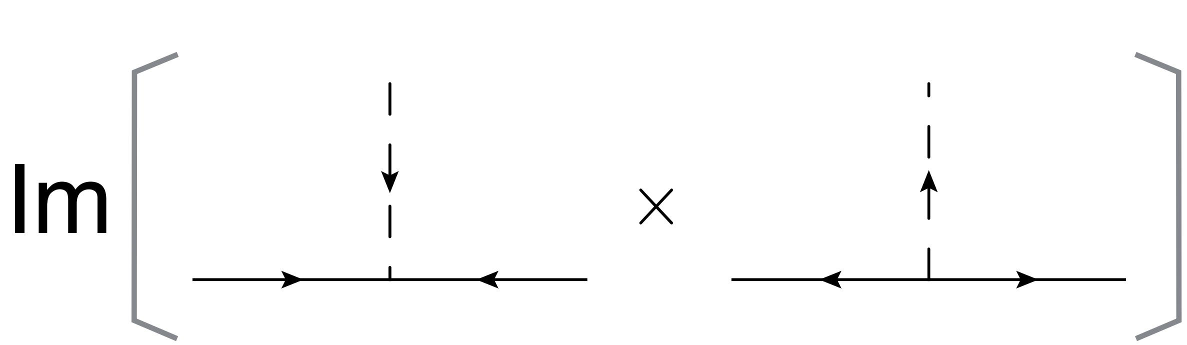


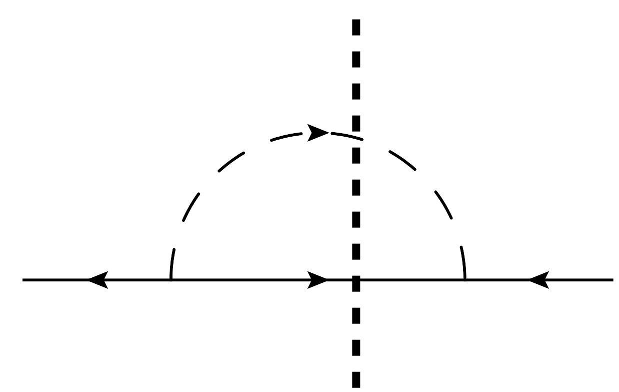
CPV source in classical formalism



Self energies including CPV source in CTP formalism

- **Leptogenesis via RH neutrino oscillation**





CPV source in classical formalism

Self energy including CPV source in CTP formalism

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

Silvia Pascoli, Jessica Turner, **YLZ**, in progress

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

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

$$S_k^{<,>} = \frac{-2\varepsilon(k^0)\mathrm{Im}\Sigma_k^{R2}}{[k^2+\mathrm{Re}\Sigma_q^{R2}]^2+[\mathrm{Im}\Sigma_q^{R2}]^2}\left\{\vartheta(\mp k^0)-f_{F,|q^0|}(x)\right\}P_L\not{k}P_R,$$

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

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

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

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

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

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