Neutrino Spectral Property at Electroweak Scale Temperature

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References

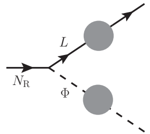
K. Miura, Y. Hidaka, D. Satow and T. Kunihiro, Phys. Rev. D **88**, 065024 (2013).

Baryon Number Asymmetry in Universe (BAU)

BAU: $\eta_{\rm B} = (n_{\rm B} - \bar{n}_{\rm B})/s \simeq (8.7 \pm 0.3) \times 10^{-11}$.

Sakharov Cond.	Standard Model	Leptogenesis
$\not{B}$	$SU_W(2)$ Sphaleron	$\not{L}$ (N_R decay) $\xrightarrow{\text{Sphaleron}}$ $\not{B}$
$\not{C}$ & $\not{CP}$	CKM (not enough)	Loop Eff. in N_R decay
Non-Equilibrium	No	$T < M_R$

Leptogenesis, Particularly in Low Energy Scale



$N_R =$ Right-Handed Neutrino

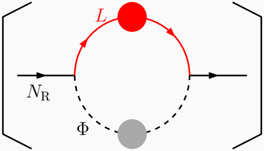
$L^T = (\nu, l)$

$\Phi =$ Higgs Doublet

If the mass difference between two N_Rs is in the order of their CP-violating decay width, the CP asymmetry is dynamically enhanced (Pilaftsis ('97)), and the leptogenesis in the EW scale can be relevant (Pilaftsis et.al. ('05)).

Spectral Density of Leptons in Leptogenesis

$\mathrm{Im}\ \Sigma_{\mathrm{N_R}} = \mathrm{Im}$



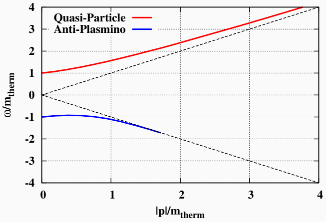
$N_R =$ Right-Handed Neutrino
$L^T = (\nu, l)$
$\Phi =$ Higgs Doublet

$$\tilde{G}_{\mathrm{Lepton}}(\mathbf{k}, i\omega_n; T) = \int_{-\infty}^{\infty} d\omega \ \frac{\rho^{(\nu,l)}_{\mathrm{Left}}(\mathbf{k}, \omega; T)}{\omega - i\omega_n} \ . \qquad (1)$$

If the standard-model leptons have non-trivial spectral properties in EW scale plasma, the lepton number creation via the N_R decay may be significantly modified (c.f. Kiessig et.al., PRD. 2010).

Spectral Property of Finite T Gauge Theory

- There is a growing interest in the collective nature of the fermions in the scenario of thermal leptogenesis (Drewes, arXiv:1303.6912).



- In QED and QCD at extremely high T, the Hard Thermal-Loop (HTL) approx. indicates that a probe fermion interacting with thermally excited gauge bosons and anti-fermions admits a collective excitation mode (See, The text book by LeBellac).
- In the neutrino dispersion relation in the electroweak scale plasma, the existence of a novel branch in the ultrasoft-energy region has been indicated by using the HTL and the unitary gauge (Boyanovsky, PRD. 2005).

From QGP to Particle Cosmology

Goal: We investigate Neutrino Spectral Density at $T \gtrsim M_{\rm W,Z}$

1. Without restricting ourselves to the dispersion,
2. In R_ξ Gauge (Fujikawa et.al. PRD. 1972),
3. and Discuss $N_{\rm R}$ Decay Rate.

Hints in QGP Physics

- The Spectral Density of massless fermion coupled with the massive mesonic mode in plasma (an effective discription of QGP) has been investigated and shown to have a Three-Peak Structure with a Ultrasoft Mode. (Kitazawa et.al. ('05-'06), Harada et.al. ('08), w.o. HTL).
- In particular, when the fermion is coupled with the massive *vectorial* meson, the Gauge Independent Nature of the three-peak structure has been confirmed (Satow et.al. ('10)) by using the Stueckelberg formalism.

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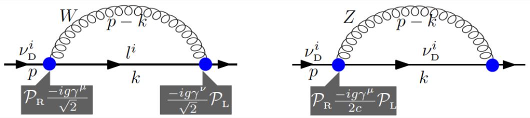
Spectral Density of Massless LH-Neutrino



$$\rho^{(\nu)}(\mathbf{p},\omega;T) = \sum_{s=\pm} \left[\mathcal{P}_R \Lambda_{s,\mathbf{p}} \gamma^0 \mathcal{P}_L\right] \rho_s^{(\nu)}(|\mathbf{p}|,\omega;T)$$

$$\mathcal{P}_{L/R} = \frac{1 \mp \gamma_5}{2}\ , \quad \Lambda_{\pm,\mathbf{p}} = \frac{1 \pm \gamma^0 \boldsymbol{\gamma}\cdot\mathbf{p}/|\mathbf{p}|}{2} \tag{2}$$

$$\rho_\pm^{(\nu)}(|\mathbf{p}|,\omega;T) = \frac{-\mathrm{Im}\ \Sigma_\pm^{(\nu)}(|\mathbf{p}|,\omega;T)/\pi}{\{\omega - |\mathbf{p}| \mp \mathrm{Re}\Sigma_\pm^{(\nu)}(|\mathbf{p}|,\omega;T)\}^2 + \{\mathrm{Im}\Sigma_\pm^{(\nu)}(|\mathbf{p}|,\omega;T)\}^2}\ .$$

Higgs Effective Potential (R_ξ Gauge)

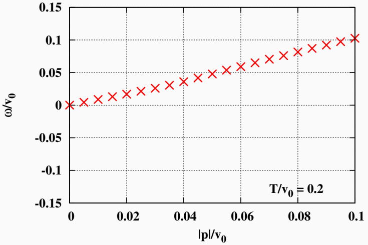
$$V_{\rm eff} = -\frac{\mu_0^2}{2}\left[1 - \frac{T^2(2\lambda + 3g^2/4 + g'^{\,2}/4)}{4\mu_0^2}\right] v^2(T) + \frac{\lambda}{4} v^4(T) \,, \qquad (3)$$

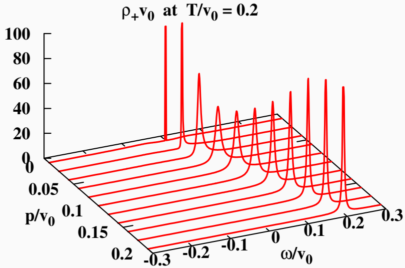
$$M_{\rm W}(T) = \frac{gv(T)}{2} + \mathcal{O}(gT) \,, \quad M_{\rm Z}(T) = \frac{\sqrt{g^2 + g'^2}\; v(T)}{2} + \mathcal{O}(gT) \qquad (4)$$

- The ξ dependences cancel out among the Nambu-Goldstone modes, longitudinal modes of weak bosons, and the ghost (Text Book by Kapusta).
- The effective potential leads to the second-order phase transition. Note that in reality the possibility of the strong first-order transition has been ruled out within the standard model (Kajantie et.al.('96), Y.Aoki et.al.('99), Csikor et.al.('99, '00)).
- The temperature region satisfying $M_{\rm W,Z}(T) \lesssim T \ll v(T)$ should exist, and a non-trivial spectral property is anticipated there.

Low Temperature Region

$$T/v_0 = 0.2\ , \quad T/M_W(T) \simeq 0.63\ , \tag{5}$$

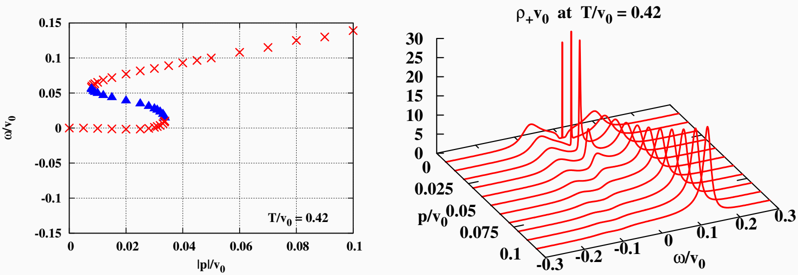




$$\omega - |\mathbf{p}| - \mathrm{Re}\ \Sigma_+(\omega, |\mathbf{p}|, T) = 0$$

Intermediate Temperature Region I

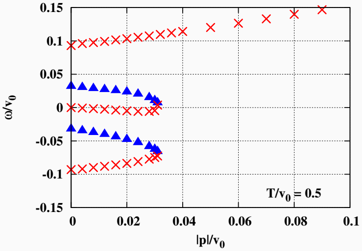
$$T/v_0 = 0.42\ , \quad T/M_W(T) \simeq 1.45\ , \tag{6}$$

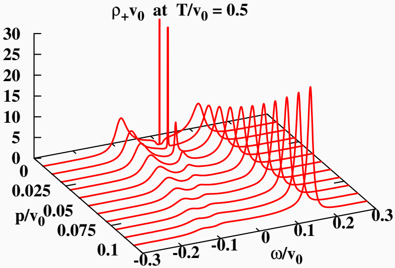


$$\omega - |\mathbf{p}| - \mathrm{Re}\ \Sigma_+(\omega, |\mathbf{p}|, T) = 0$$

Intermediate Temperature Region II

$$T/v_0 = 0.5\ , \quad T/M_W(T) \simeq 1.83\ , \tag{7}$$

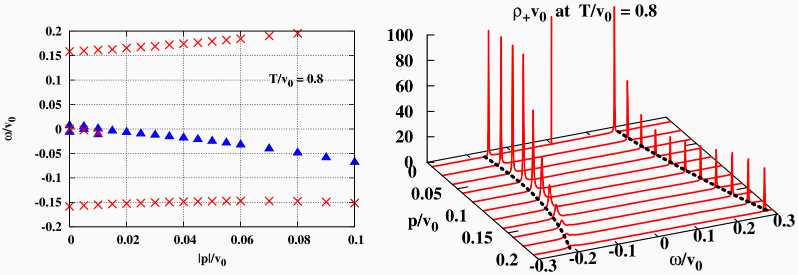




$$\omega - |\mathbf{p}| - \mathrm{Re}\ \Sigma_+(\omega, |\mathbf{p}|, T) = 0$$

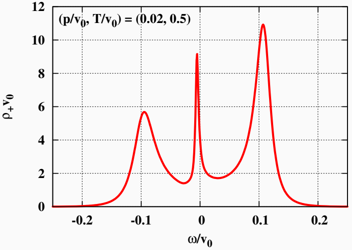
High Temperature Region

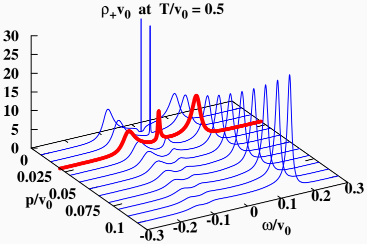
$$T/v_0 = 0.8\ , \quad T/M_W(T) \simeq 4.9\ .$$



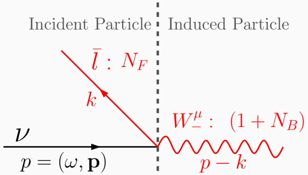
- The spectral property becomes closer to the HTL result.
- $T/v(T) \simeq 1.59 > 1$: The additional thermal-loop corrections may modify the spectral property (Hidaka-Satow-Kunihiro, Ncul.Phys.A, 2012).

Spectral Density at $(|\mathbf{p}|/v_0, T/v_0) = (0.02, 0.5)$





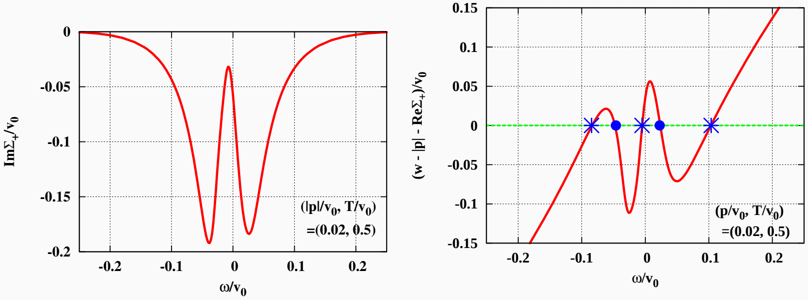
Landau Damping



$$
\begin{aligned}
\mathrm{Im}\Sigma_{+}^{(\nu)} \quad &\ni \quad \int_k \delta\left[\omega + |\mathbf{k}| - \sqrt{|\mathbf{p}-\mathbf{k}|^2 + M_{\mathrm{W,Z}}^2}\right] \\
&\quad \times \left[N_{\mathrm{F}}(1+N_{\mathrm{B}}) + N_{\mathrm{B}}(1-N_{\mathrm{F}})\right] \cdot \left[\cdots\right] \\
&\ni \quad \int_{x_0}^{\infty} dx\ x N_{\mathrm{B}}(x) = \sum_{n=1}^{\infty} \frac{e^{-nx_0}}{n^2}\left[1 + nx_0\right] \\
&\to \quad \zeta(2) \quad (T \gg M_{\mathrm{W,Z}}, \omega, |\mathbf{p}|)\ , x_0 = \frac{\omega^2 - |\mathbf{p}|^2 - M_{\mathrm{W,Z}}^2}{2T(\omega - |\mathbf{p}|)} > 0\ .
\end{aligned}
$$

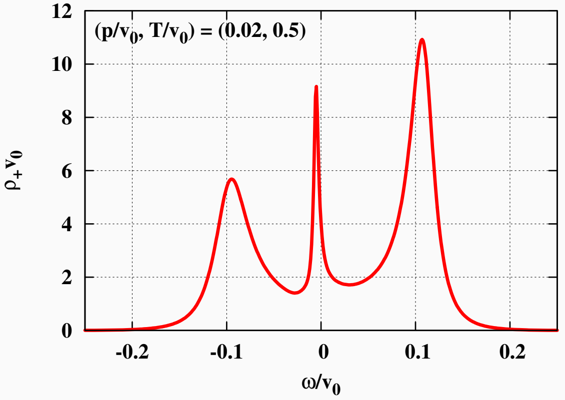
Self-Energy in Three-Peak Region

$$\frac{T}{v_0} = 0.5 \ , \quad \frac{|\mathbf{p}|}{v_0} = 0.02 \ . \tag{8}$$

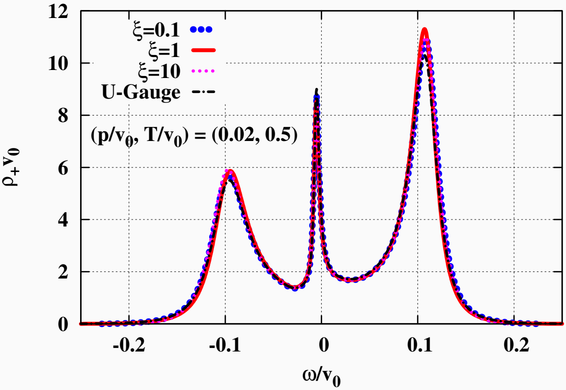


(c.f. Kitazawa-Kunihiro-Nemoto, PTP 2007).

Spectral Density at $(|\mathbf{p}|/v_0, T/v_0) = (0.02, 0.5)$



ξ Depenence of Three-Peak Spectral Density



Sphaleron Freeze-out Temperature

The net baryon number $N_{\rm b}$ is produced in the sphaleron process when the changing rate of $N_{\rm b}$ is larger than the expanding rate of the universe,

$$\left| \frac{1}{N_{\rm b}} \frac{dN_{\rm b}}{dt} \right| \geq H(T) \ , \qquad (9)$$

where,

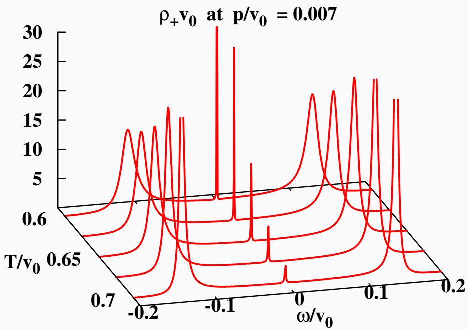
$$H(T) = 1.66 \sqrt{N_{\rm dof}} \frac{T^2}{M_{\rm PL}} \simeq T^2 \times 1.41 \times 10^{-18} \ ({\rm GeV}) \ , \qquad (10)$$

$$\frac{1}{N_{\rm b}} \frac{dN_{\rm b}}{dt} = -1023 \cdot g^7 v(T) \exp\left[-1.89 \frac{4\pi v(T)}{gT} \right] \ , \qquad (11)$$

and we obtain

$$T \geq T_* \simeq 160 \ {\rm GeV} \ , \quad T_*/v_0 \simeq 0.65 \ . \qquad (12)$$

Neutrino Spectral Density around $T = T_*$



$$\frac{T_*}{v_0} \simeq 0.65 \; , \qquad \frac{T_*}{v(T)} \sim 1 \; . \tag{13}$$

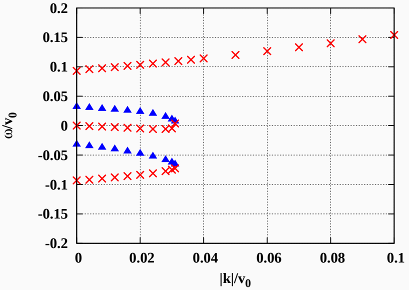
$N_{\rm R}$ Decay Rate

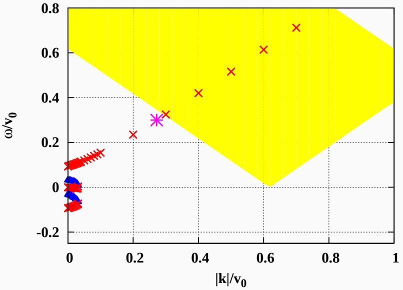
$$N_{\rm R} \longrightarrow \mathcal{P}_{\rm L} \begin{bmatrix} \nu_{\rm D} \\ l \end{bmatrix} \mathcal{P}_{\rm R} + \begin{bmatrix} \phi_2 + i\phi_1 \\ h - i\phi_3 \end{bmatrix} , \qquad (14)$$

$$\Gamma_{N_{\rm R}\to\nu+\phi_{1,2}}(p) = \frac{-(Y^\dagger Y)_{11}}{4p_0|\mathbf{p}|} \int_\omega \int_{k_-(\omega)}^{k_+(\omega)} d|\mathbf{k}| \; \rho_\pm^{(\nu)}(\omega, |\mathbf{k}|)$$
$$\times \left[\frac{1}{e^{\omega/T}+1} + \frac{1}{e^{(\omega-p^0)/T}-1} \right] F_{\rm quad}(\omega, |\mathbf{k}|, |\mathbf{p}|, M_{\rm R}) \, . \qquad (15)$$

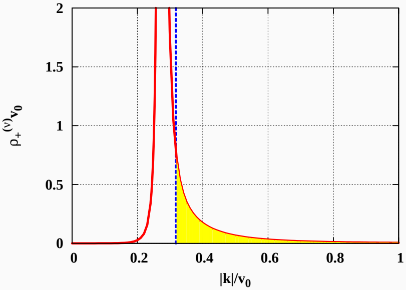
N_{R} Decay Rate: Support vs 3-Peak Region

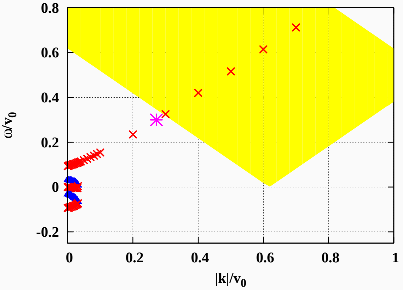
Preliminary Result for $(M_{\mathrm{R}}/v_0, |\mathbf{p}|/v_0, T/v_0) = (1.0, 0.5, 0.5)$





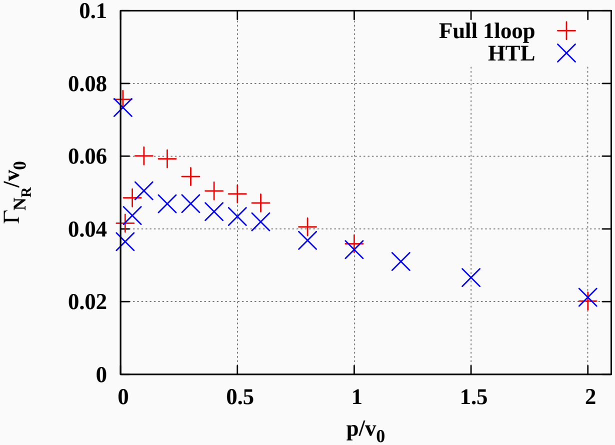
N_R Decay Rate: Support vs Width





N_{R} Decay Rate: Full 1loop vs HTL

Preliminary Result for $(M_{\mathrm{R}}/v_0, T/v_0) = (1.0, 0.5)$



Summary

- We have investigated the spectral properties of standard-model left-handed neutrinos at finite T around the electroweak scale in R_ξ gauge.
- The spectral density of SM neutrino has the three-peak structure with the ultrasoft mode with a physical significance when $T/M_{\mathrm{W,Z}} \gtrsim 1$.
- The three-peak appears at temperature comparable to T_* within the one-loop approximation. However, it may not have a significant contribution to N_{R} the decay rate...
- The decay rate including the full one-loop spectral density of ν gets larger than the HTL result. This would be because of the width effect.
- Future Work: Fermion mass effect, Resummation scheme at high temperature, Spectral property of N_{R}, and many others!

Thanks for Your Attention!