Neutrino Spectral Density at Electroweak Scale Temperature

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KMI[A], LNF-INFN[A], RIKEN[B], Kyoto Univ.[C]

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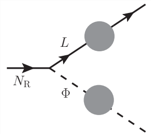
References

K. Miura, Y. Hidaka, D. Satow, and T. Kunihiro, arXiv:1306.1701 [hep-ph].

Leptogenesis, Particularly in Low Energy Scale



$N_R =$ Right-Handed Neutrino

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

$\Phi =$ Higgs Doublet

- The standard model (SM) seems to fail to explain the observed baryon asymmetry of the universe (BAU): $\eta_{\mathrm{B}} = (n_{\mathrm{B}} - \bar{n}_{\mathrm{B}})/n_\gamma \simeq 6.1 \times 10^{-10}$.
- An extension of the SM by adding right-handed Majorana neutrinos (N_{R}) may have a chance to account for the BAU (Fukugita et.al. ('86)): A decay of N_{R} (e.g. Fig.) generates a net lepton number, which are partially converted into the baryon number via sphaleron process in the electroweak (EW) phase trans. (Kuzmin et.al. ('85), Klinkhamer et.al.('84), Arnold et.al. ('87)).
- If the mass difference between two N_{R}s 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)).

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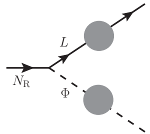

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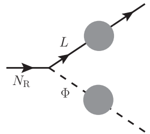

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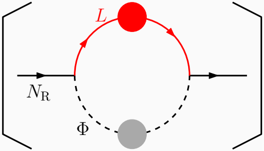
Spectral Density of Leptons in Leptogenesis

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



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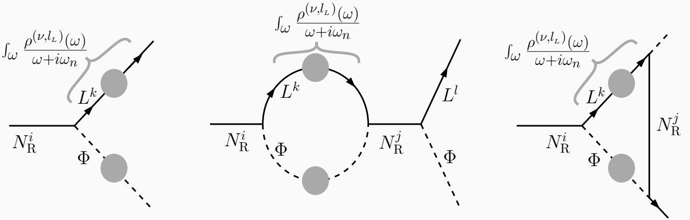
$$\tilde{G}_{\mathrm{Lepton}}(\mathbf{k}, i\omega_n; T) = \int_{-\infty}^{\infty} d\omega \ \frac{\rho^{(\nu,l)}_{\mathrm{Left}}(\mathbf{k}, \omega; T)}{\omega + i\omega_n} \ . \quad (1)$$

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).

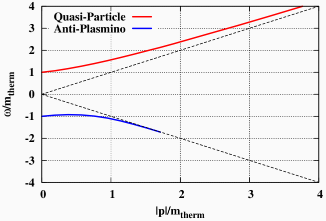
Spectral Density of Leptons in Leptogenesis



If the standard-model leptons have non-trivial spectral properties in EW scale plasma, the CP asymmetry would be modified.

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).

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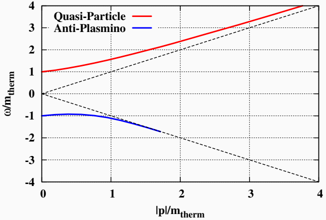

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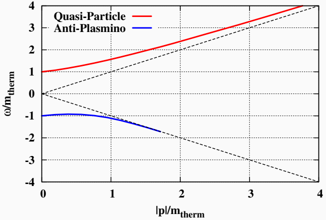

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From QGP to Particle Cosmology

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

1. Without restricting ourselves to the dispersion,
2. In R_ξ Gauge (Fujikawa et.al. PRD. 1972),
3. And discuss a possible implication to the leptogenesis.

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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Setups

- Massless Lepton Sector:

$$\mathcal{L}_{\rm L} = \sum_{i=e,\mu,\tau} \left[(\bar{\nu}^i, \bar{l}^i_{\rm L}) i \partial\!\!\!/ \begin{pmatrix} \nu^i \\ l^i_{\rm L} \end{pmatrix} + \bar{l}^i_{\rm R} i \partial\!\!\!/ \, l^i_{\rm R} \right] + \left[W^\dagger_\mu J^\mu_{\rm W} + J^{\mu\dagger}_{\rm W} W_\mu + Z_\mu J^\mu_{\rm Z} + A^{\rm EM}_\mu J^\mu_{\rm EM} \right] , \quad (2)$$

- Weak Bosons in R_ξ Gauge:

$$G_{\mu\nu}(q, T) = -\frac{(g_{\mu\nu} - q_\mu q_\nu / M^2_{\rm W,Z}(T))}{q^2 - M^2_{\rm W,Z}(T)} + \frac{q_\mu q_\nu / M^2_{\rm W,Z}(T)}{q^2 - \xi M^2_{\rm W,Z}(T)} . \quad (3)$$

- Weak Boson Masses $T \ll v(T)$ (c.f. Manuel, PRD. 1998):

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

Higgs Effective Potential (R_ξ Gauge)

$$V_{\rm eff} = -\frac{\mu_0^2}{2}\left[1 - \frac{T^2(2\lambda + 3g^2/4 + g'^{\,2}/4)}{4\mu_0^2}\right] v^2(T) + \frac{\lambda}{4} v^4(T) \ , \qquad (5)$$

- The ξ dependences cancel out between the Nambu-Goldstone modes and the ghost contributions (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.

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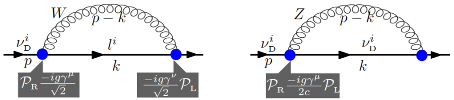
Neutrino Self-Energy and Spectral Density



- For the massless left-handed neutrinos, the finite-T effects are solely encoded in the coefficients in the decomposition

$$\Sigma^{(\nu)}_{\mathrm{ret}}(\mathbf{p},\omega;T) = \sum_{s=\pm}\left[\mathcal{P}_R\Lambda_{s,\mathbf{p}}\gamma^0\mathcal{P}_L\right]\ \Sigma^{(\nu)}_s(|\mathbf{p}|,\omega;T)\ , \tag{6}$$

$$\mathcal{P}_{L/R} = (1\mp\gamma_5)/2\ , \quad \Lambda_{\pm,\mathbf{p}} = (1\pm\gamma^0\boldsymbol{\gamma}\cdot\mathbf{p}/|\mathbf{p}|)/2\ . \tag{7}$$

- For the spectral density, similarly,

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

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

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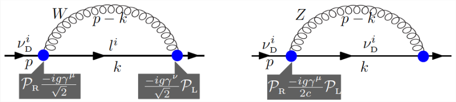

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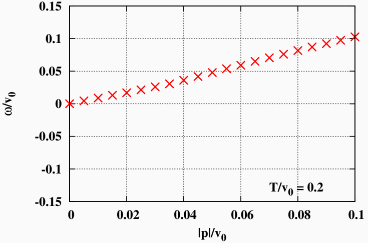
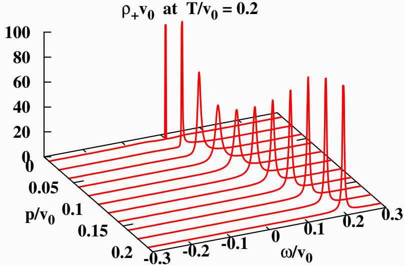
Low Temperature Region

$$T/v_0 = 0.2 \ , \quad T/M_W(T) \simeq 0.63 \ , \qquad (8)$$

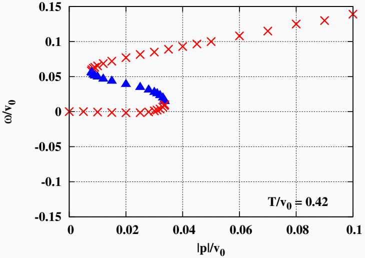


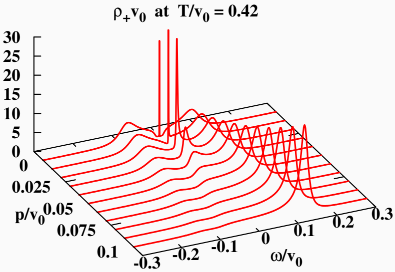


$$\omega - |\mathbf{p}| - \mathrm{Re}\ \Sigma_+(\omega, |\mathbf{p}|, T) = 0$$

Intermediate Temperature Region I

$$T/v_0 = 0.42 \ , \quad T/M_W(T) \simeq 1.45 \ , \tag{9}$$

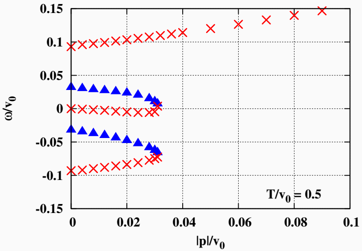


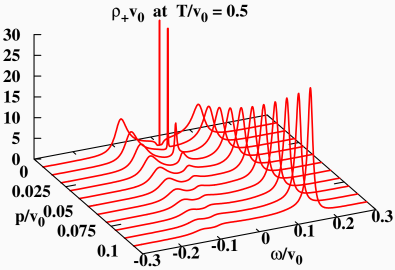


$$\omega - |\mathbf{p}| - \mathrm{Re}\ \Sigma_+(\omega, |\mathbf{p}|, T) = 0$$

Intermediate Temperature Region II

$$T/v_0 = 0.5\ , \quad T/M_W(T) \simeq 1.83\ , \tag{10}$$





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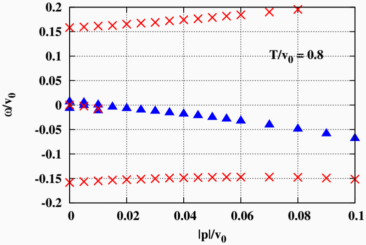
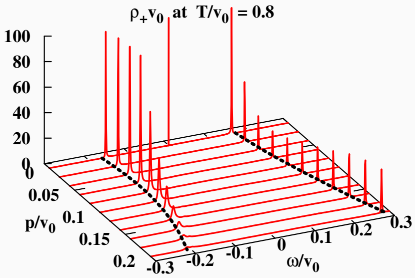
High Temperature Region

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





- 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).

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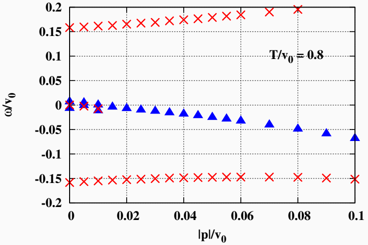

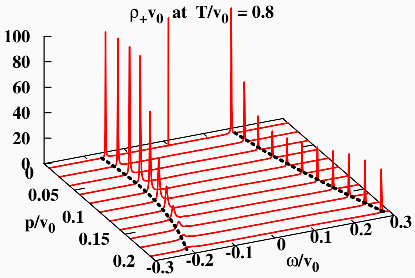

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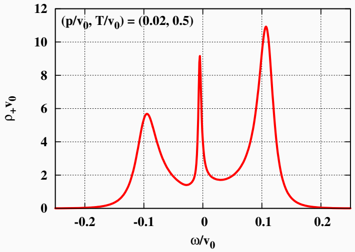
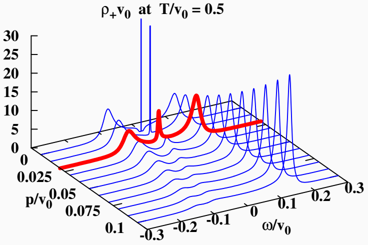
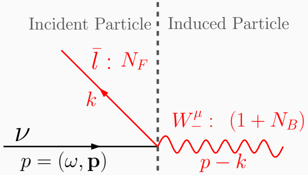
Spectral Density at $(|\mathbf{p}|/v_0, T/v_0) = (0.02, 0.5)$





Landau Damping

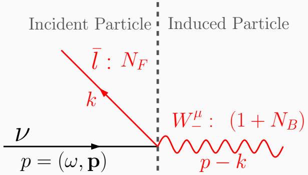


- Landau Damping (Fig.) makes the imaginary part being finite in the spacelike region:

$$\mathrm{Im}\Sigma_{+}^{(\nu)} \ni \int_k \delta\left[\omega+|\mathbf{k}|-\sqrt{|\mathbf{p}-\mathbf{k}|^2+M_{\mathrm{W,Z}}^2}\right] \times \left[N_{\mathrm{F}}(1+N_{\mathrm{B}})+N_{\mathrm{B}}(1-N_{\mathrm{F}})\right]\cdot\left[\cdots\right] . \qquad (11)$$

- For a small external momentum $(\omega,\mathbf{p})$ and a not small $M_{\mathrm{W,Z}}$, the phase space in $\int_k$ admitting the Landau Damping will be restricted.

Landau Damping



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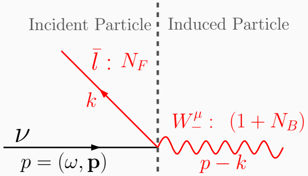
Landau Damping Suppression



$$G(x_0)=\int_{x_0}^{\infty}dx\;xN_{\mathrm{B}}(x)=\sum_{n=1}^{\infty}\frac{e^{-nx_0}}{n^2}\left[1+nx_0\right]\;,x_0=\frac{\omega^2-|\mathbf{p}|^2-M^2_{\mathrm{W,Z}}}{2T(\omega-|\mathbf{p}|)}>0\;.$$

c.f. HTL Limit $T\gg M_{\mathrm{W,Z}},\omega,|\mathbf{p}|$: $x_0\to 0$ and $G(x_0)\to\zeta(2)\gg 0$.

The condition $T\sim M_{\mathrm{W,Z}}$ and the resultant finite x_0 leads to $G(x)\ll\zeta(2)$
$\to$ the suppression of the Landau damping.

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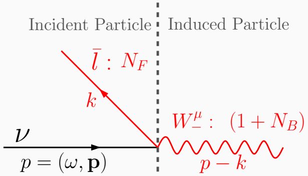

$$G(x_0) = \int_{x_0}^{\infty} dx\, x N_{\mathrm{B}}(x) = \sum_{n=1}^{\infty} \frac{e^{-nx_0}}{n^2}\left[1+nx_0\right] \;, x_0 = \frac{\omega^2 - |\mathbf{p}|^2 - M_{\mathrm{W,Z}}^2}{2T(\omega-|\mathbf{p}|)} > 0 \;.$$

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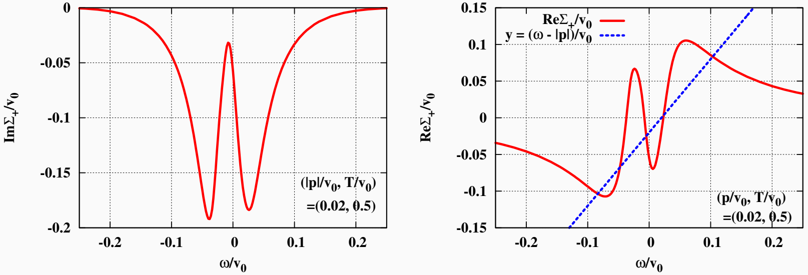
Self-Energy at Three-Peak Region

$$\frac{T}{v_0} = 0.5\ , \quad \frac{|\mathbf{p}|}{v_0} = 0.02\ . \tag{12}$$



In the right panel, the crossing points corresponds to the solutions of

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

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

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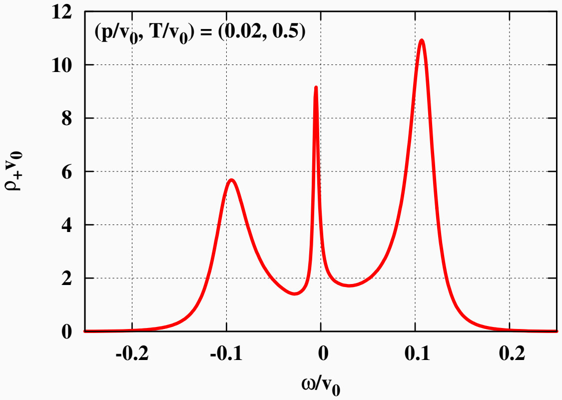
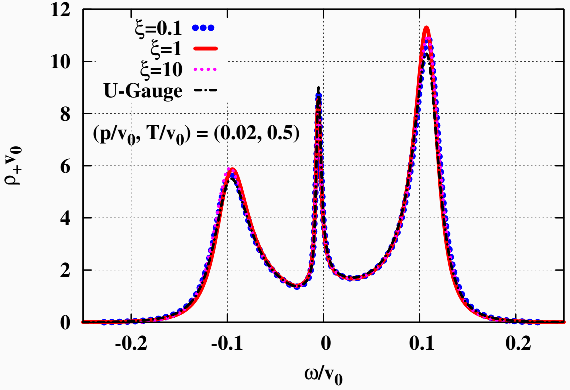


ξ Depenence of Three-Peak Spectral Density



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,

$$\left| \frac{1}{N_{\rm b}} \frac{dN_{\rm b}}{dt} \right| \geq H(T) \ , \tag{13}$$

where,

$$H(T) = 1.66 \sqrt{N_{\rm dof}} \frac{T^2}{M_{\rm PL}} \simeq T^2 \times 1.41 \times 10^{-18} \ ({\rm GeV}) \ , \tag{14}$$

$$\frac{1}{N_{\rm b}} \frac{dN_{\rm b}}{dt} = -1023 \cdot g^7 v(T) \exp\left[-1.89 \frac{4\pi v(T)}{gT} \right] \ , \tag{15}$$

and we obtain

$$T \geq T_* \simeq 160 \ {\rm GeV} \ , \quad T_*/v_0 \simeq 0.65 \ . \tag{16}$$

Sphaleron Freeze-out Temperature

The net baryon number N_b is produced in the sphaleron process when the changing rate of N_b is larger than the expanding rate of the universe,

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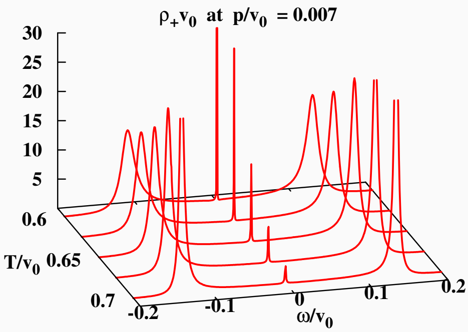
Neutrino Spectral Density around $T = T_*$



$$\frac{T_*}{v_0} \simeq 0.65 \; , \qquad \frac{T_*}{v(T)} \sim 1 \; . \tag{17}$$

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Summary

- We have investigated the spectral properties of standard-model left-handed neutrinos at finite T around the electroweak scale in a way where the gauge invariance is manifestly checked (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 collective excitation which involves the ultrasoft mode appears at temperature comparable to T_* within the present approximation. The three-peak collective modes could affect the leptogenesis at $T \gtrsim T_*$.
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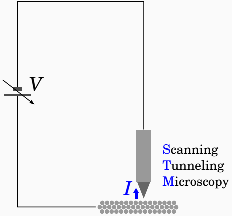

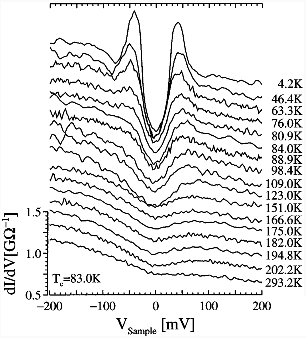

Slightly Underdoped Bi2212
STM Superconductor Scan

Renner et. al., Phys.Rev.Lett., 80 149, (2008).

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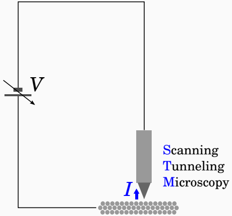

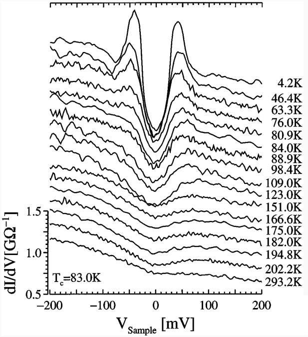

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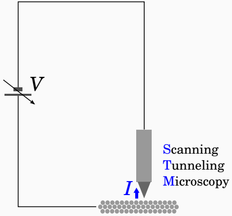

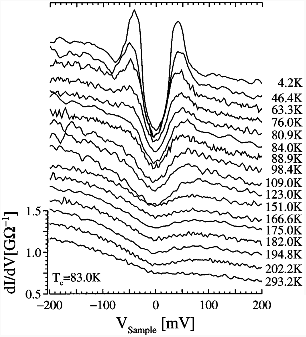

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