QCD臨界点付近でのクォークスペクトルについて

北沢正清

（阪大理）

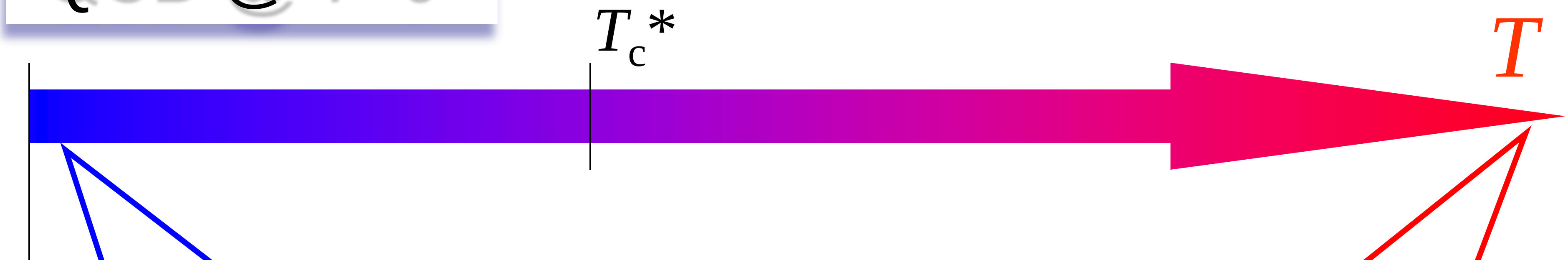
国広悌二、根本幸雄

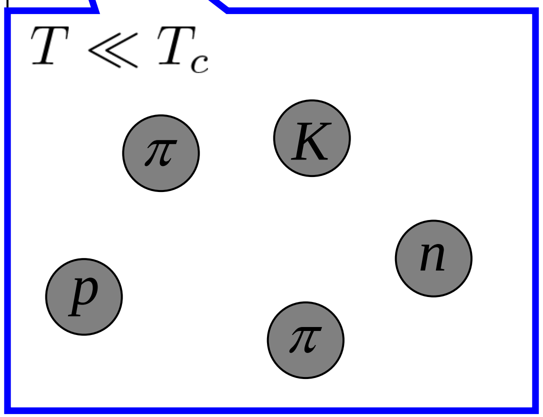
MK, Kunihiro, Nemoto, in prep.

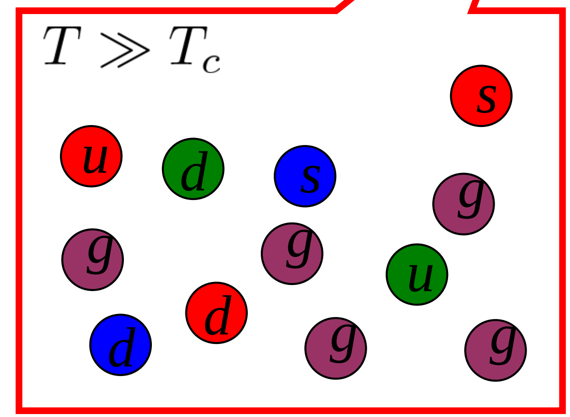
20aSB4

日本物理学会2013年秋季大会、2013/9/20、高知大学

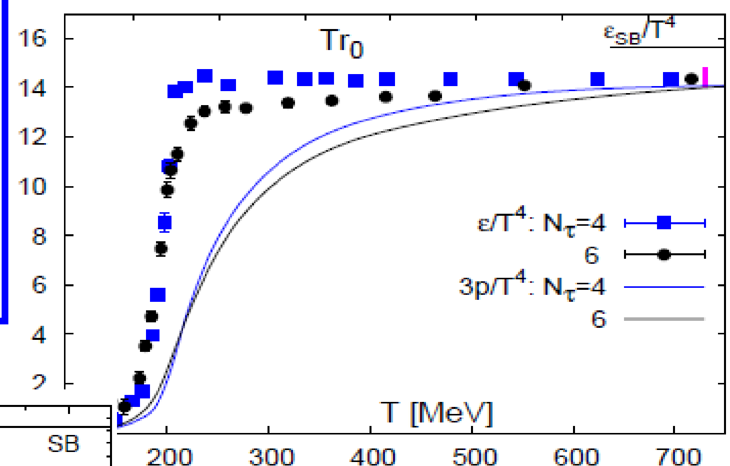
QCD @ T>0

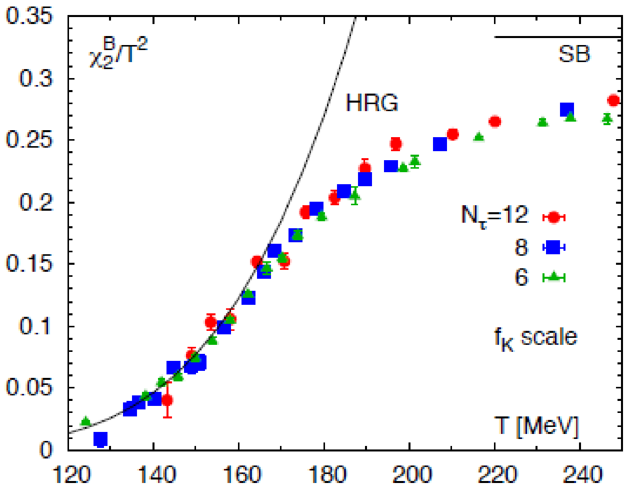






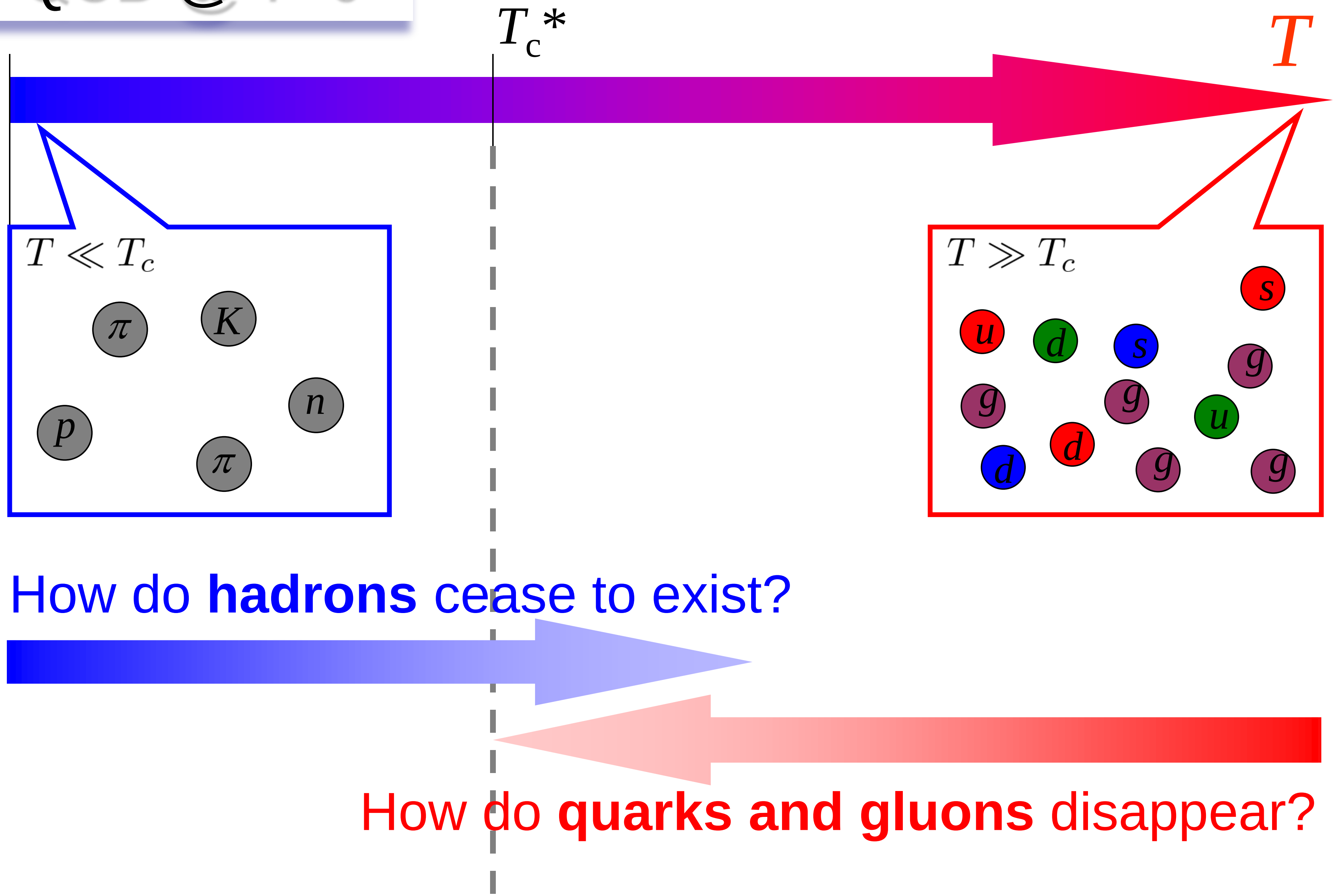
QCD EoS





Success of HRG model for higher-order cumulants below Tc

QCD @ T>0

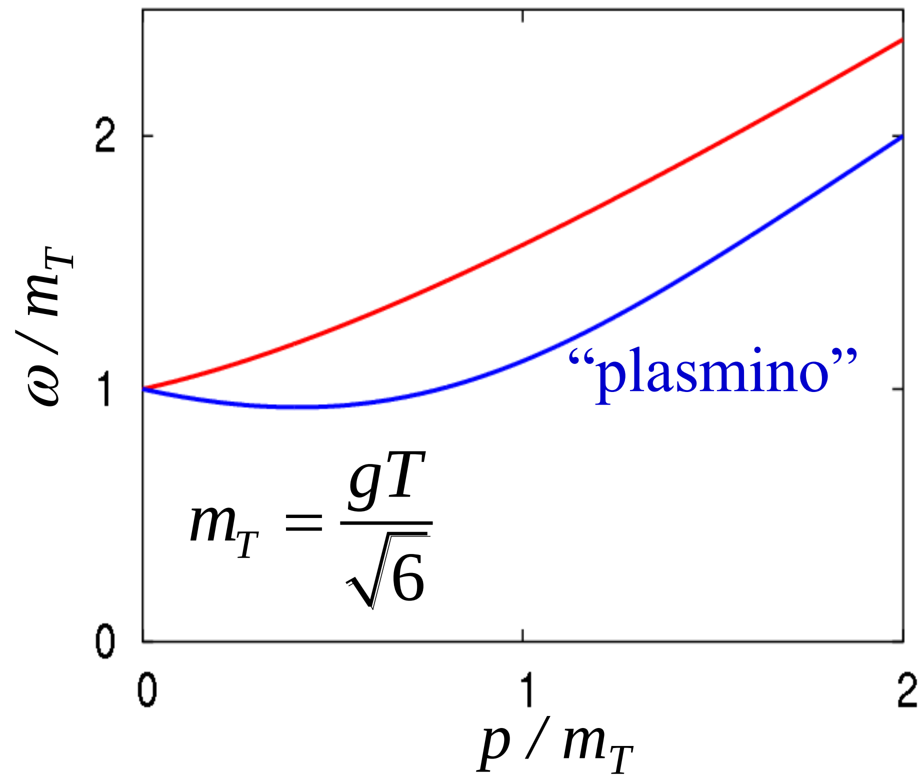


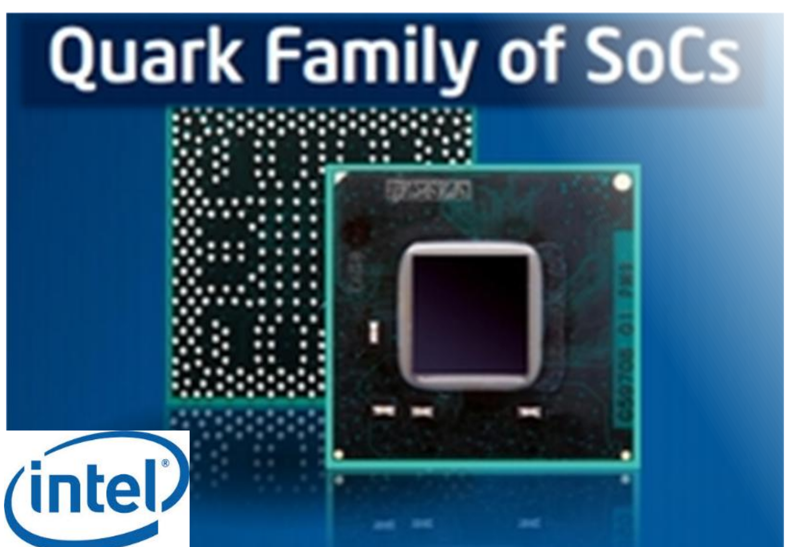
T_c*
T
$T \ll T_c$
π
K
n
p
π
$T \gg T_c$
s
u
d
s
g
g
g
u
d
d
g
g
How do **hadrons** cease to exist?
How do **quarks and gluons** disappear?

Quarks at Extremely High T

Klimov '82, Weldon '83
Braaten, Pisarski '89

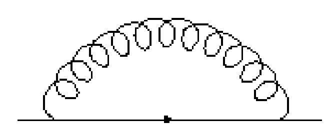
- 2 collective excitations having "thermal mass" $\sim gT$
- width $\sim g^2T$
- Minimum of the plasmino mode at nonzero ***p***





$$S(\omega,\mathbf{p}) = \frac{1}{\omega\gamma_0 - \mathbf{p}\cdot\boldsymbol{\gamma} - \Sigma(\omega,\mathbf{p})}$$

$$\Sigma(\omega,\mathbf{p}) =$$



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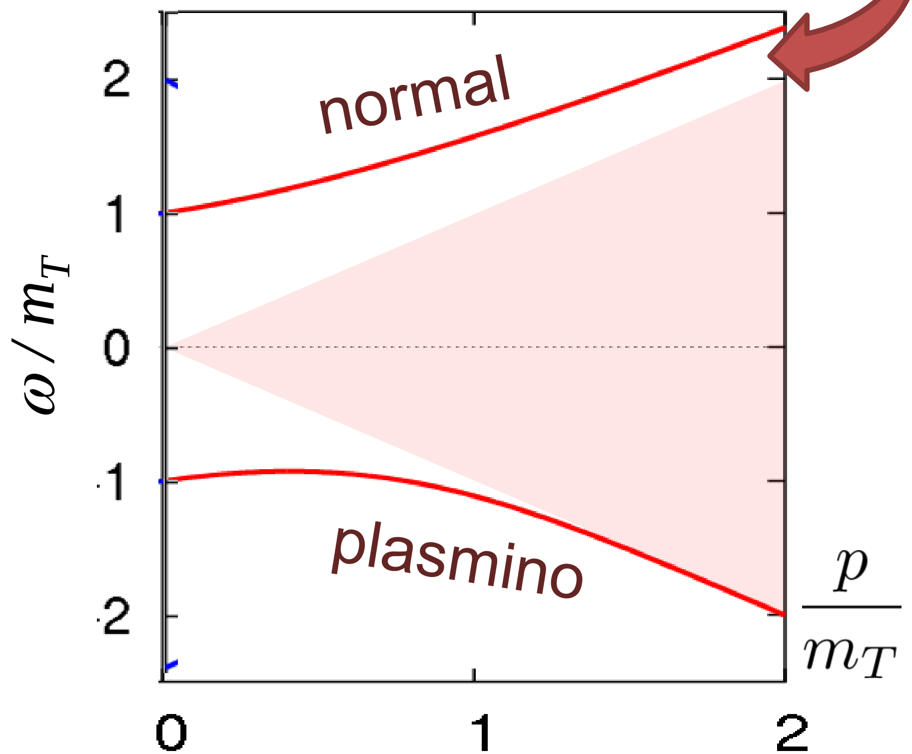
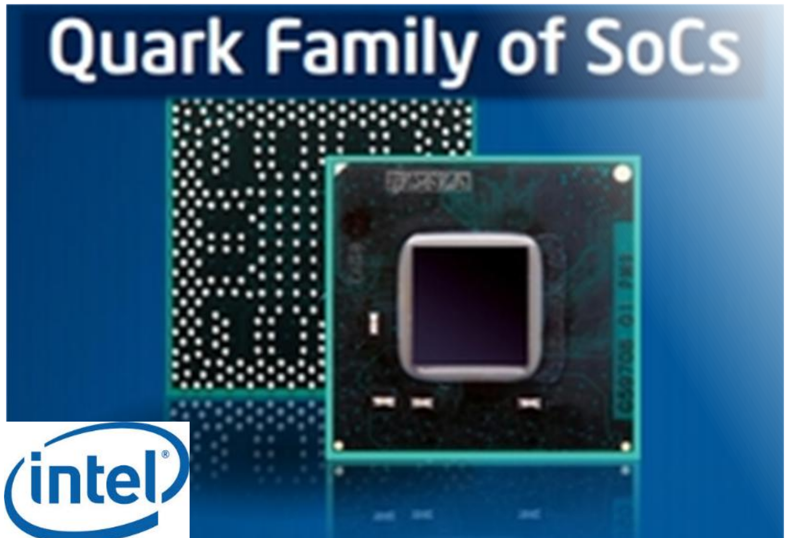
$$\Lambda_\pm(\mathbf{p}) = \frac{1 \pm \gamma_0 \mathbf{p}\cdot\vec{\gamma}}{2}$$

$$S(\omega, p) = S_+(\omega,\mathbf{p})\Lambda_+(\vec{\mathbf{p}})\gamma^0 + S_-(\omega,\mathbf{p})\Lambda_-(\vec{\mathbf{p}})\gamma^0$$



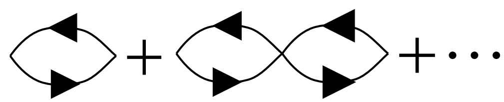


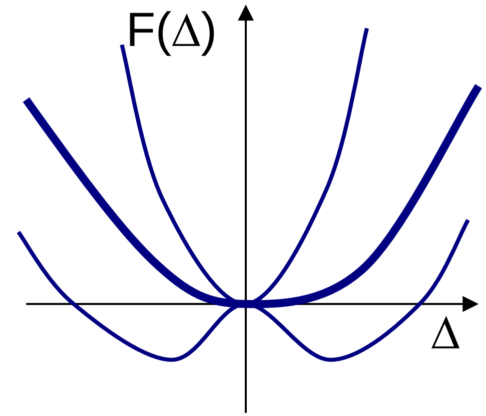
Soft Modes of Chiral Transition

Hatsuda, Kunihiro,1985

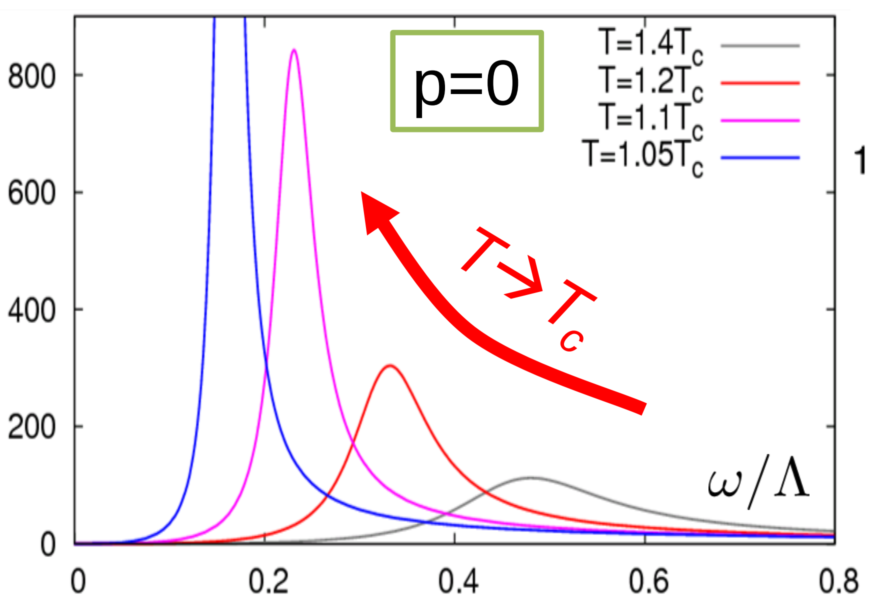
Large fluctuations of order parameter near T_c

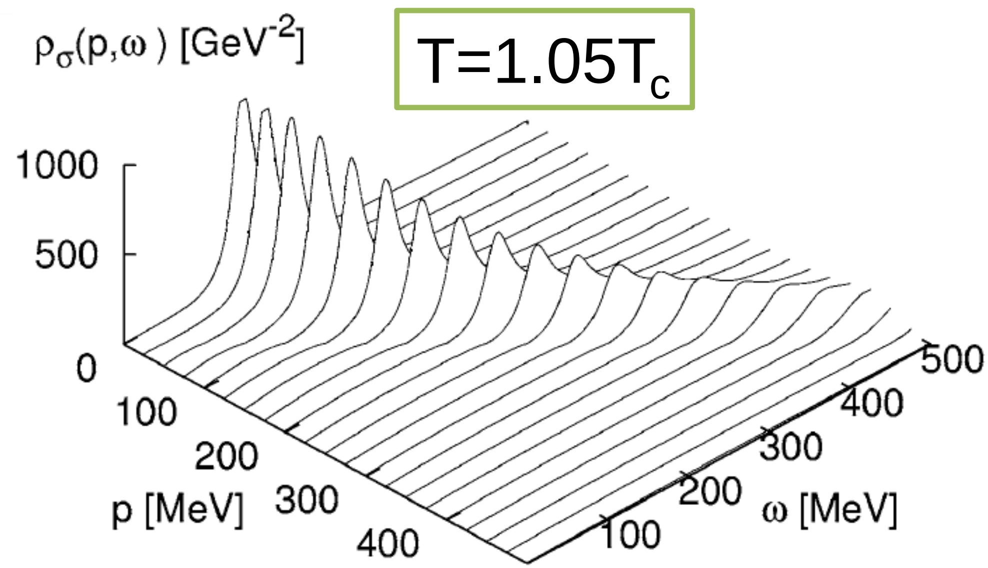
➡ Chiral transition : σ, π -modes

$D_{\sigma,\pi}(\omega, p) =$ 



Spectral Function





Quark Propagator near T_c

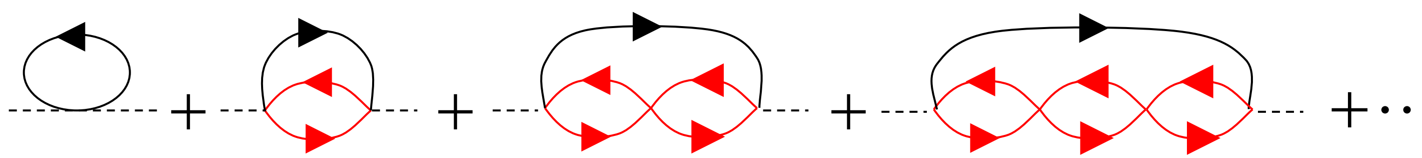
MK, Kunihiro Nemoto, 2006

- NJL model
- 2-flavor
- chiral limit (m_0=0)

$$G(\mathbf{k}, i\omega_n) = \frac{1}{G^0(\mathbf{k}, i\omega_n) - \Sigma(\mathbf{k}, i\omega_n)}$$

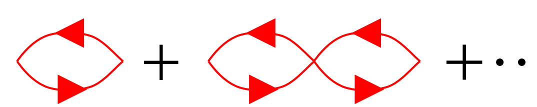
Quark Self-Energy

$\Sigma(\mathbf{k}, i\omega_n) =$



$$= T\sum_m \int \frac{d^3 q}{(2\pi)^3} \Xi(\mathbf{k}-\mathbf{q}, \omega_n - \omega_m) G^0(\mathbf{q}, \omega_m)$$

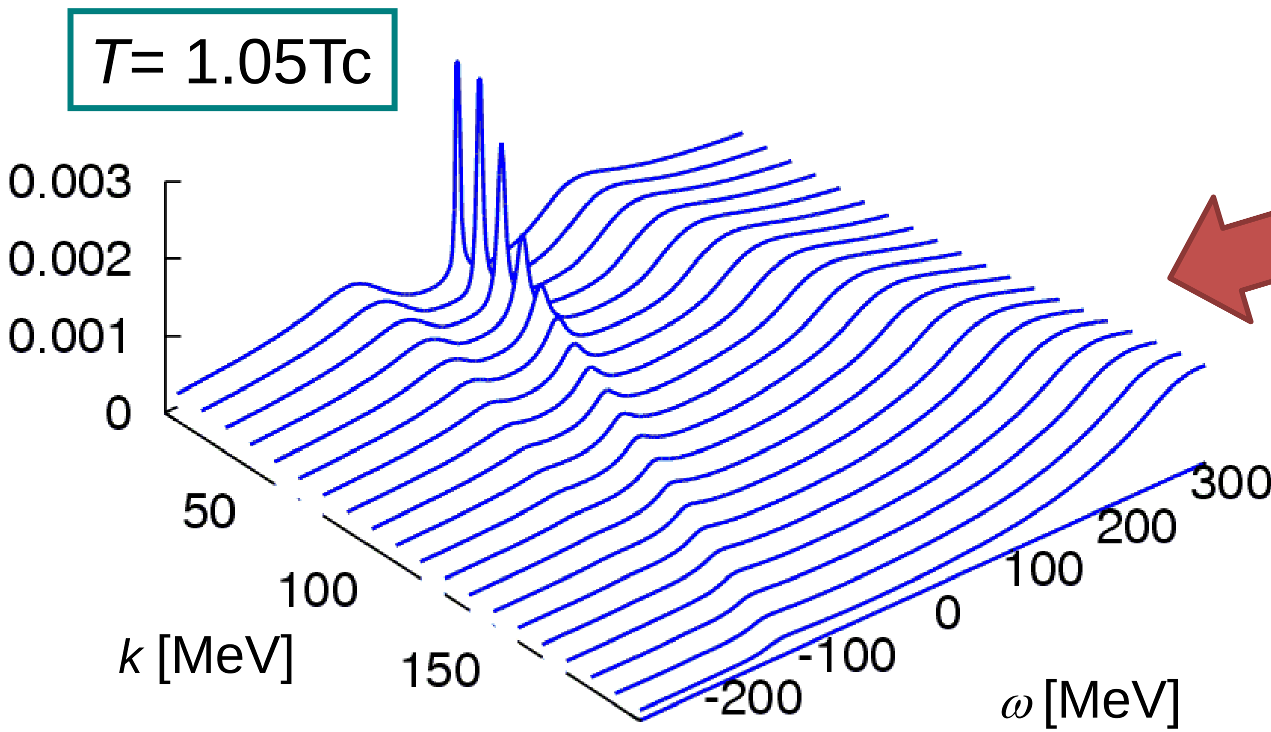
$\Xi(\mathbf{k}, i\omega_n) = 1 +$

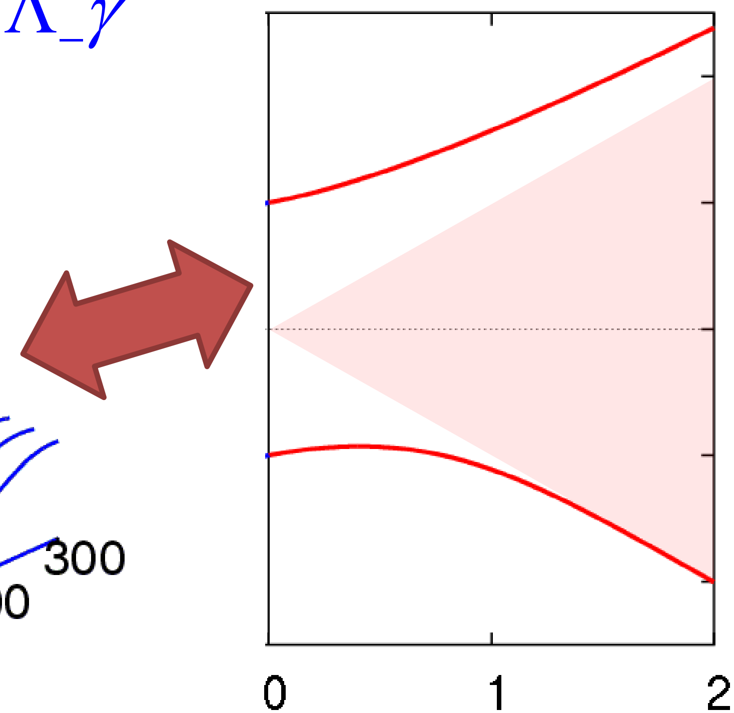


Quark Spectrum near T_c

MK, Kunihiro Nemoto, 2006

$$A(\mathbf{p}, p^0) = \rho_+(\mathbf{p}, p^0)\Lambda_+\gamma^0 + \rho_-(\mathbf{p}, p^0)\Lambda_-\gamma^0$$





- Three-peak structure emerges
- Sharpest peak around the origin

Fermion & Boson System

Yukawa model

$$L = i\bar{\psi}(i\gamma \cdot \partial - m_f - g\sigma)\psi + \frac{1}{2}(\partial_\mu \sigma \partial^\mu \sigma + m_b^2 \sigma^2)$$

"fermion (m_f) + boson (m_b)"

- Fermion spectrum at 1-loop order:
  - Klimov, 1982; Weldon, 1983 $m_f = 0, m_b = 0$
  - Baym, Blaizot, Svetitsky, 1992 $m_f \neq 0, m_b = 0$
  - MK, Kunihiro, Nemoto, 2007 $m_f = 0, m_b \neq 0$
  - MK, Kunihiro, Mitsutani, Nemoto, 2008 $m_f \neq 0, m_b \neq 0$

Fermion Spectrum

MK, Kunihiro, Nemoto, 2007

- Yukawa model, $m_f = 0, g = 1$

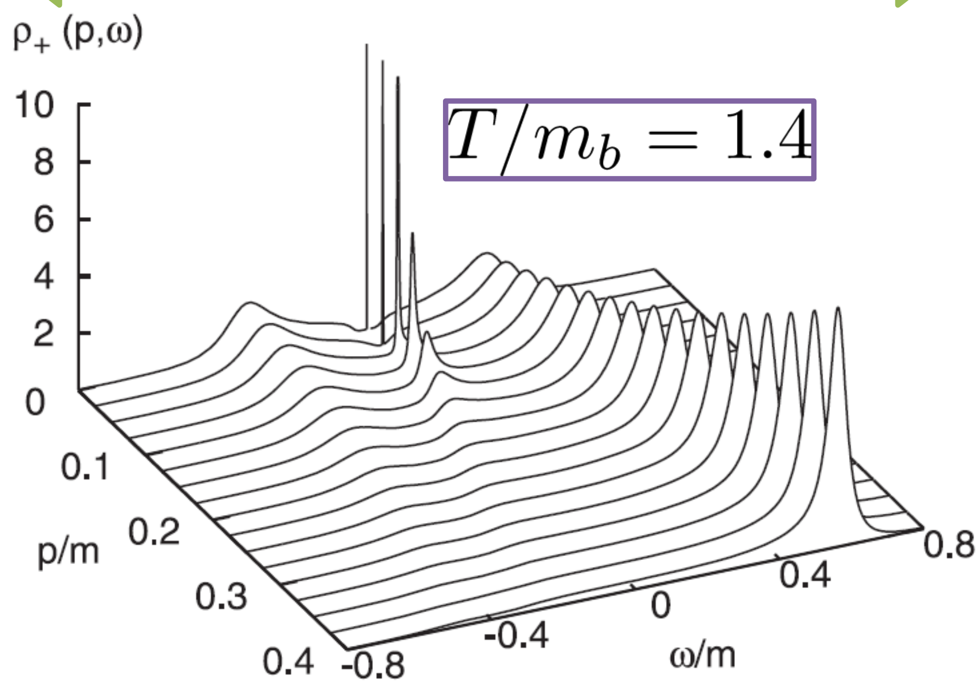
$T/m_b \simeq 0$

massless free fermion

T/m_b

$T/m_b \to \infty$

normal & plasmino with m_T

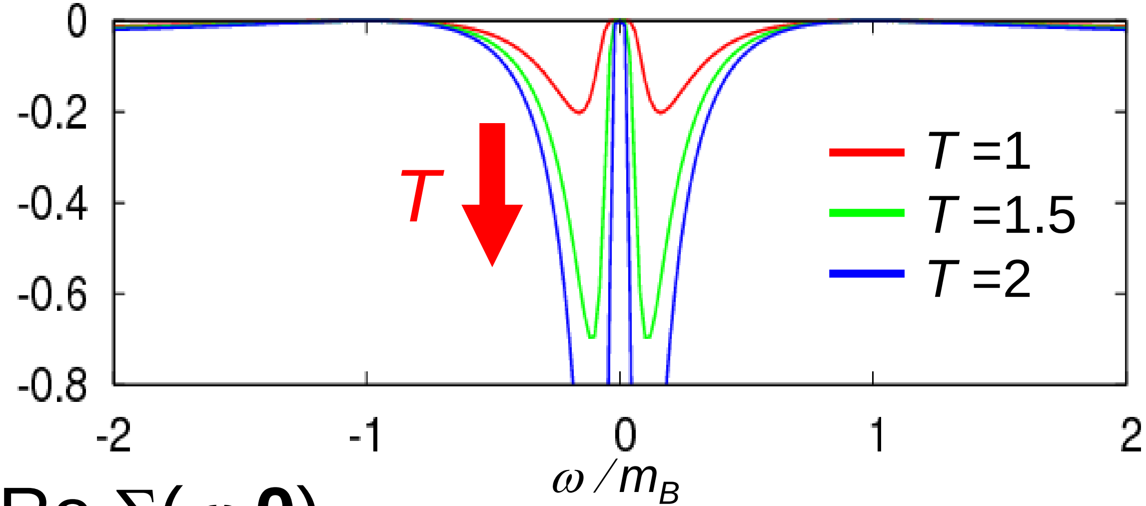


Three peak structure emerges for $T \sim m_b$

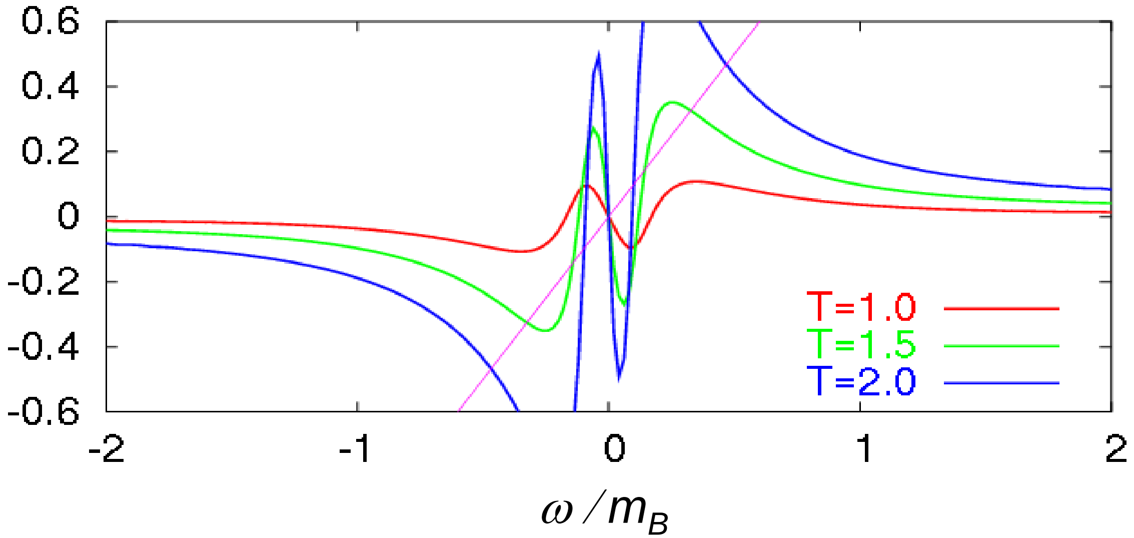
Low energy peak ceases to exist for $m_f > 0.2 m_b$

Quark Self-Energy at p=0

Im $\Sigma(\omega,\mathbf{0})$



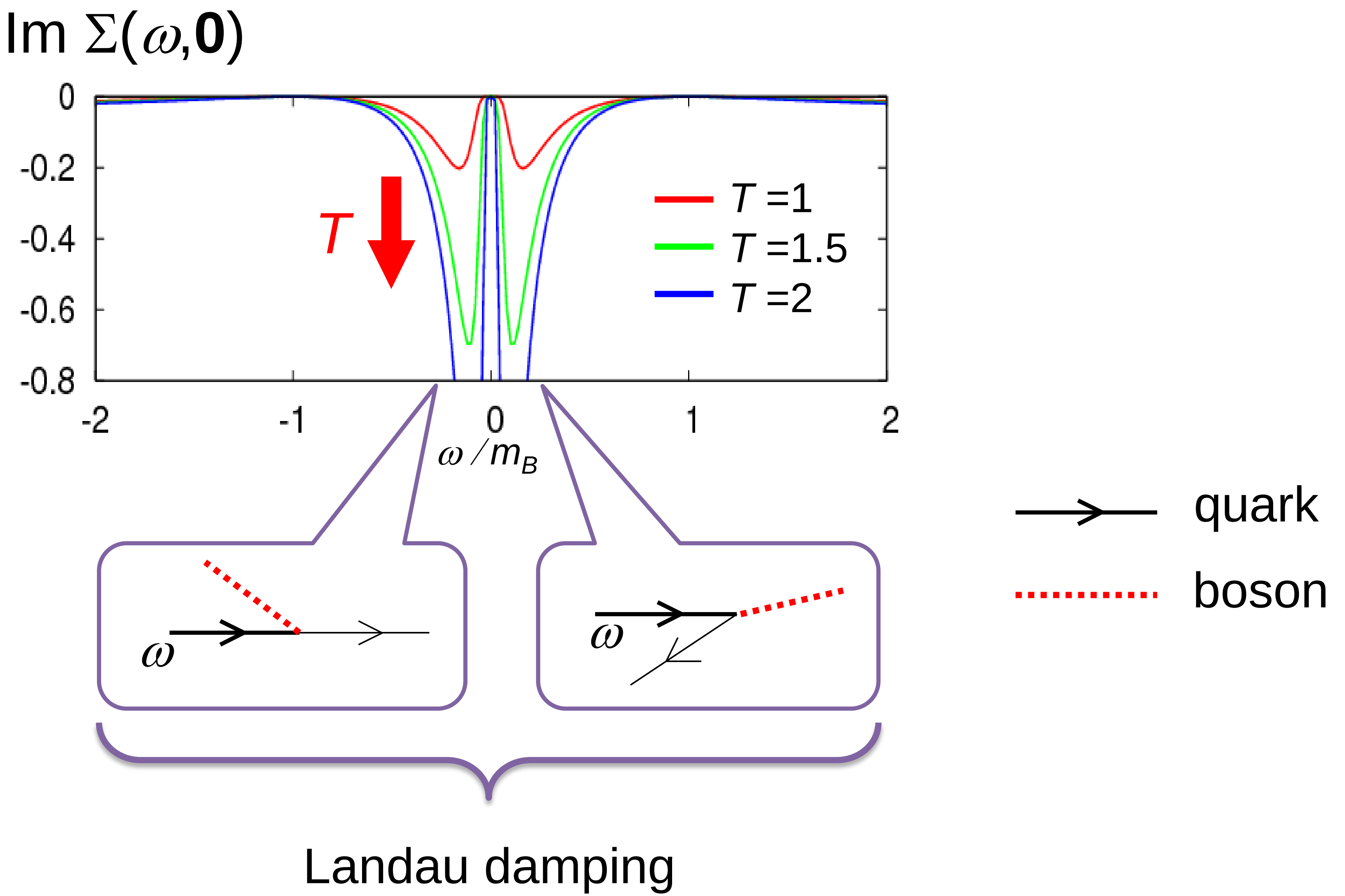
Re $\Sigma(\omega,\mathbf{0})$



- Two peaks develop at low energy.

- Two “oscillating behavior” grows as *T* is raised.

Landau Damping



Introducing Nonzero m_0

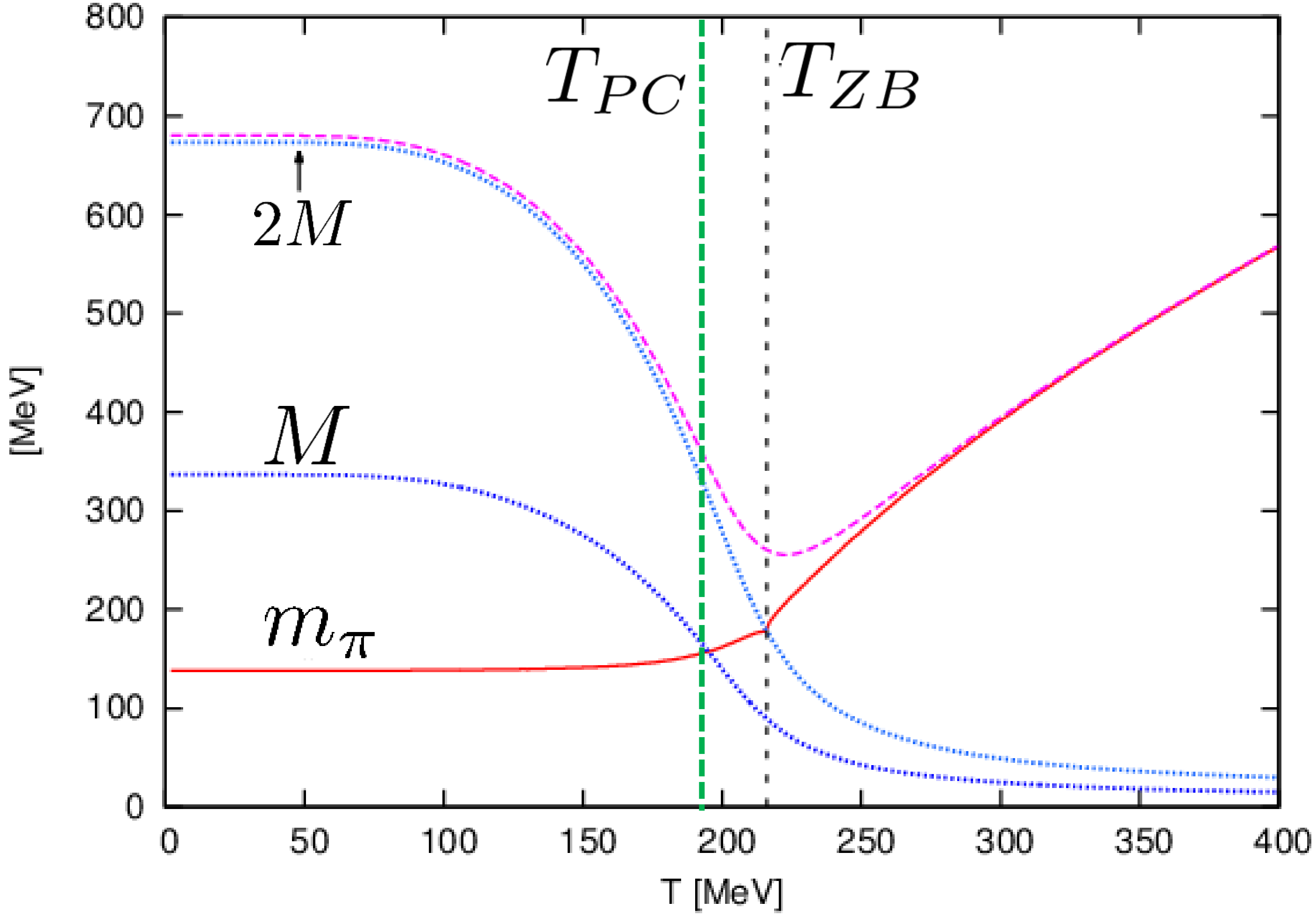
2-flavor NJL model

$$L = i\bar{\psi}(i\gamma \cdot \partial - m_0)\psi + G_S((\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\boldsymbol{\tau}\psi)^2)$$

What's NEW!

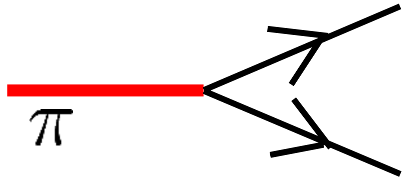
- Effect of m_0
  - Phase transition becomes crossover.
  - Constituent quarks stay massive.
  - Soft modes do not become massless.

Stable π modes above T_{PC}

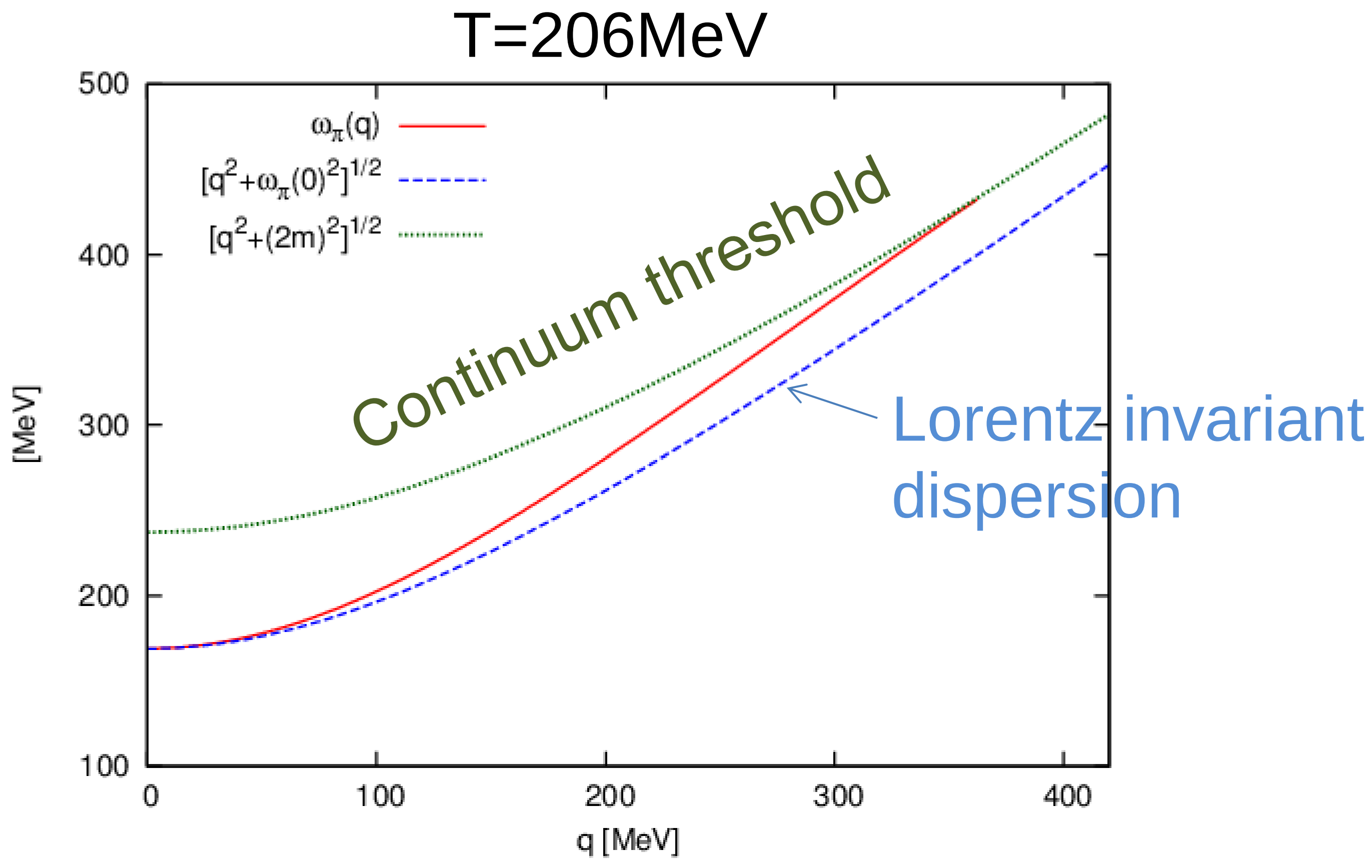


π modes can be stable even above T_{PC}

for $m_\pi < 2M$



Pion Dispersion Relation

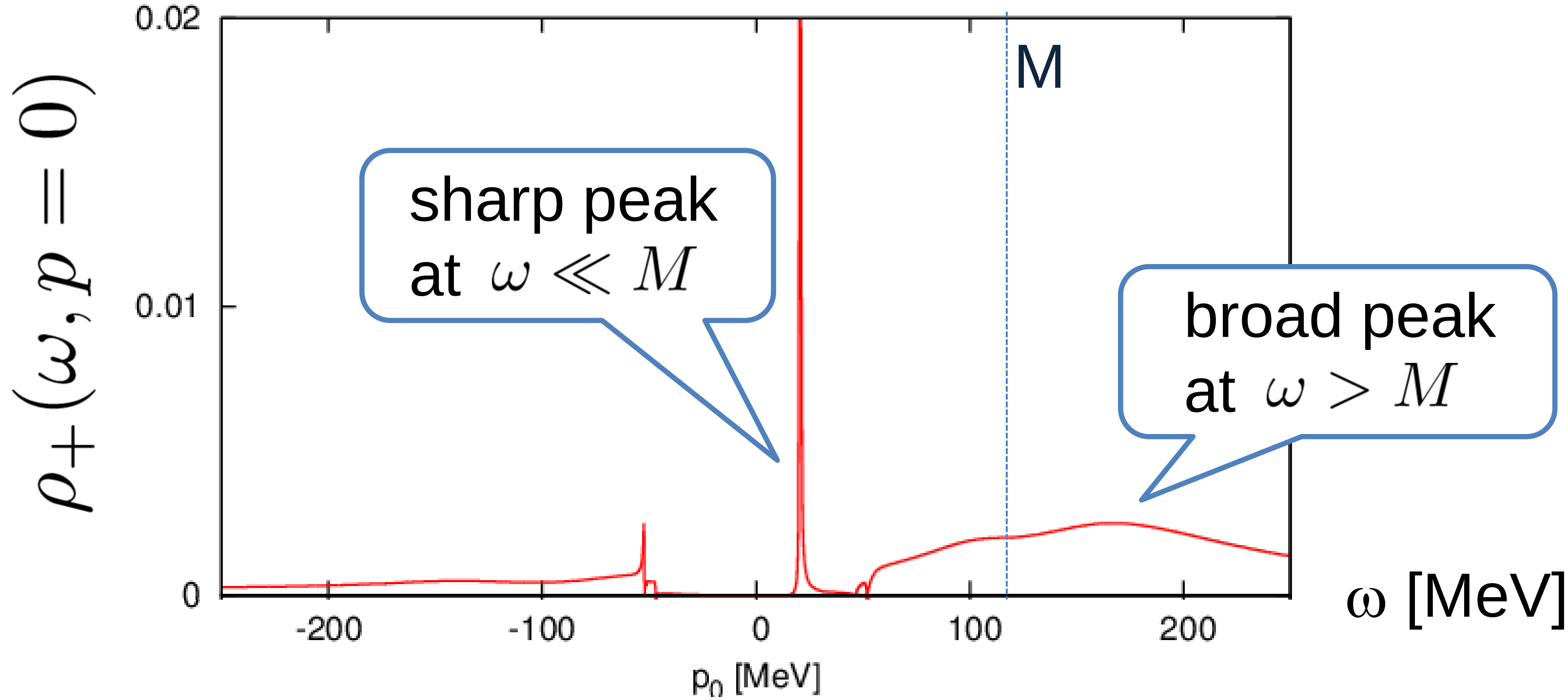


- Dispersion relation of stable pion deviates from Lorentz form.
- Pionic modes become unstable at nonzero p.

Quark Spectrum

$$\frac{M}{m_\pi} \simeq \frac{120}{150} \simeq 0.8$$

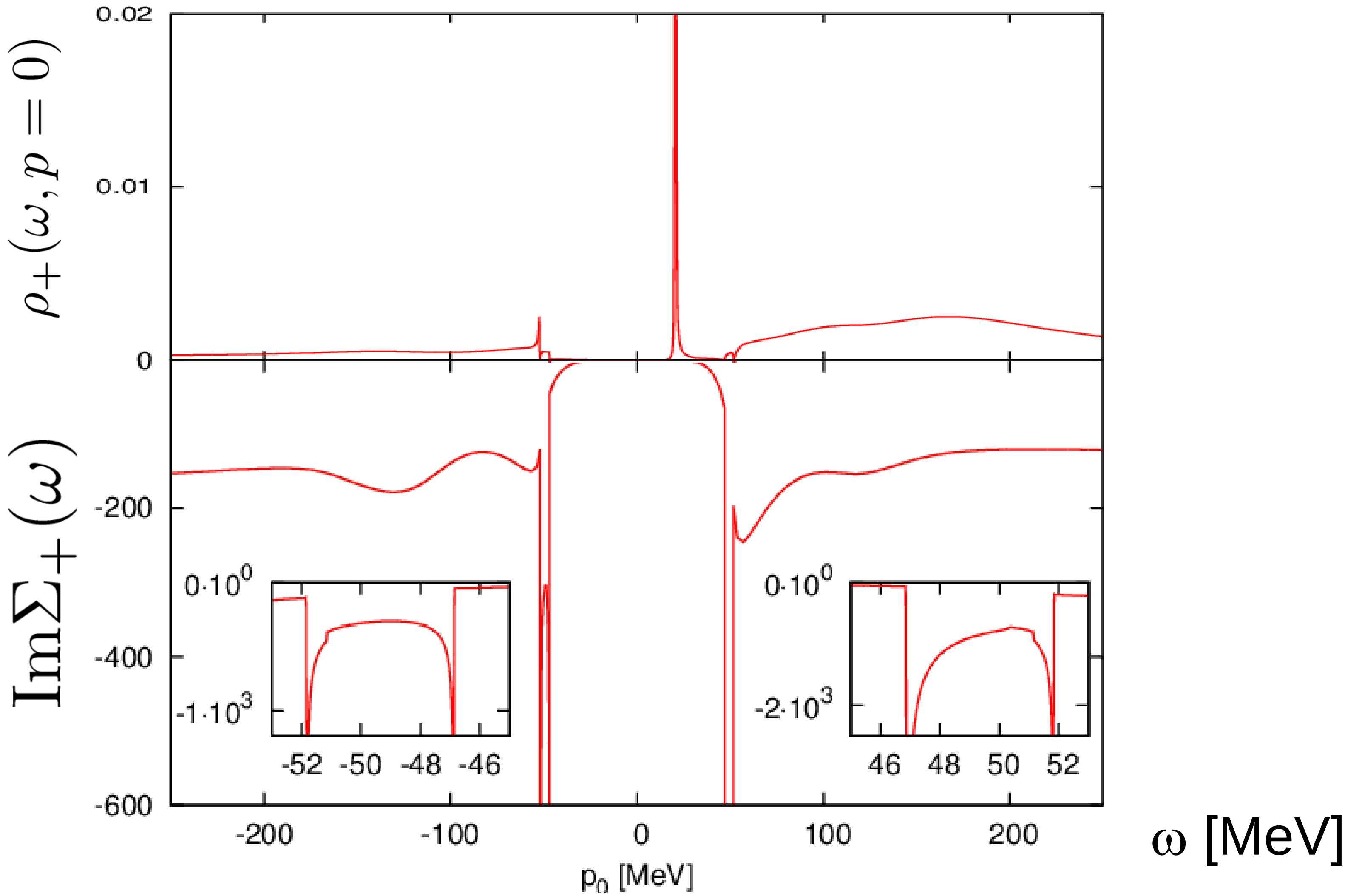
T=206 MeV, p=0



- Strong modification of the quark spectrum
- Appearance of sharp peak at low energy

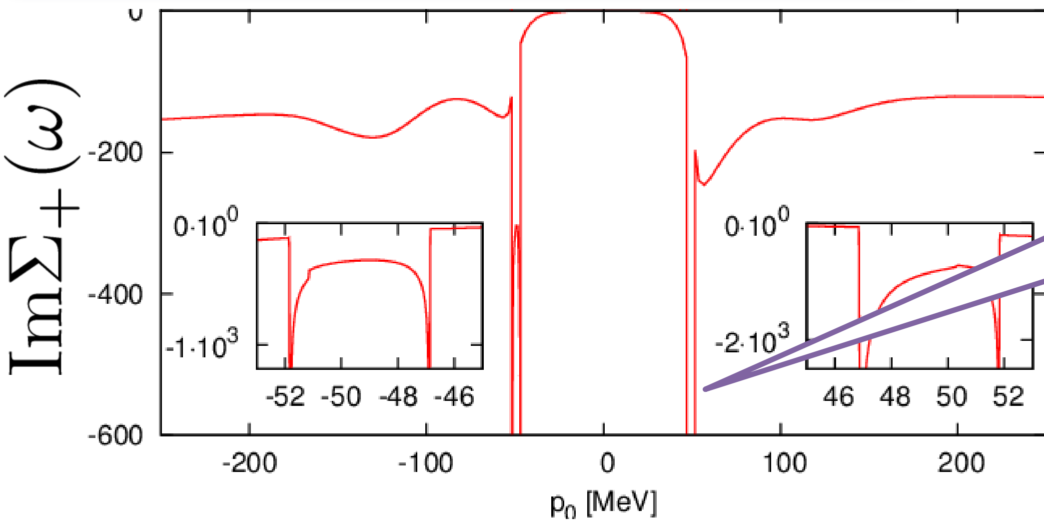
Im Σ

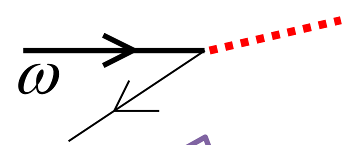
T=206 MeV, p=0



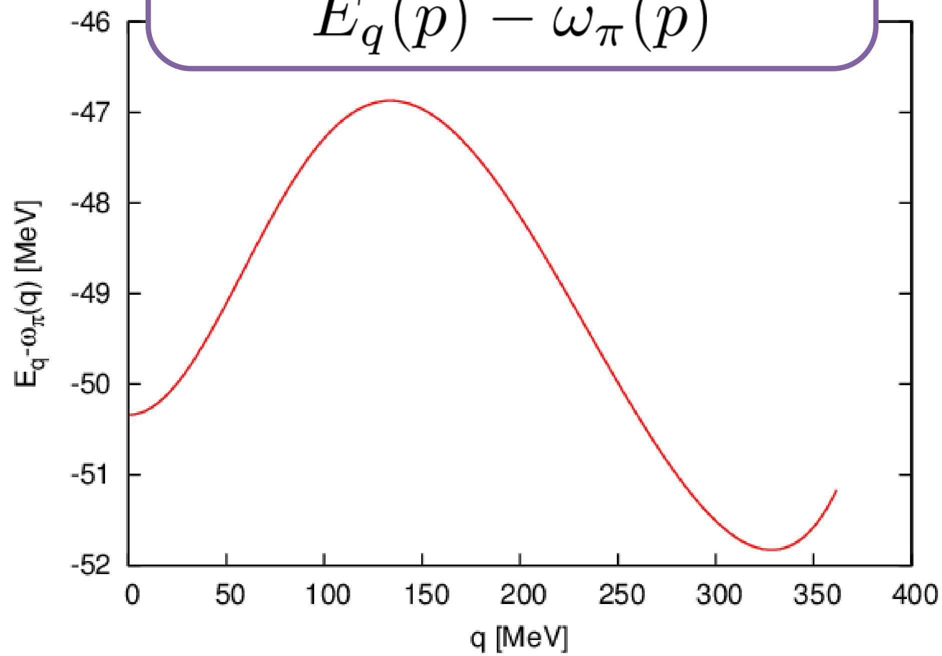
☐ There exist divergences in Im $\Sigma_+(\omega)$!

van Hove Singularity





Relative group velocity of quarks and pions
$E_q(p) - \omega_\pi(p)$



Zeros of group velocity

Divergences of joint DoS

van Hove singularity

Summary

We have studied quark spectrum near but above T_{PC} coupled with the chiral soft modes off the chiral limit.

Effects of nonzero m_0

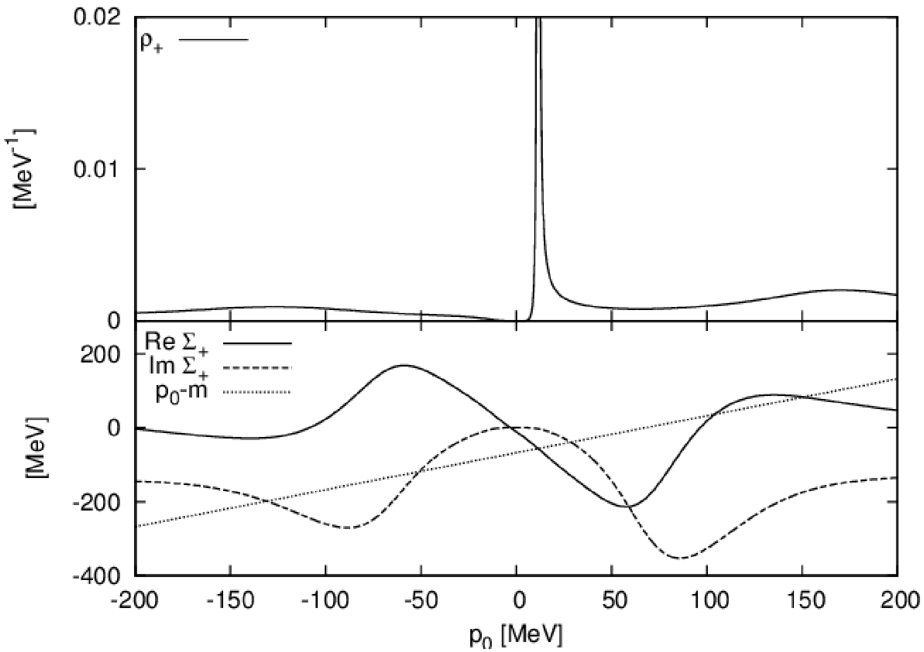
nonvanishing masses of
- constituent quarks
- soft modes

pionic modes:
- stable even above TPC
- non-relativistic dispersion

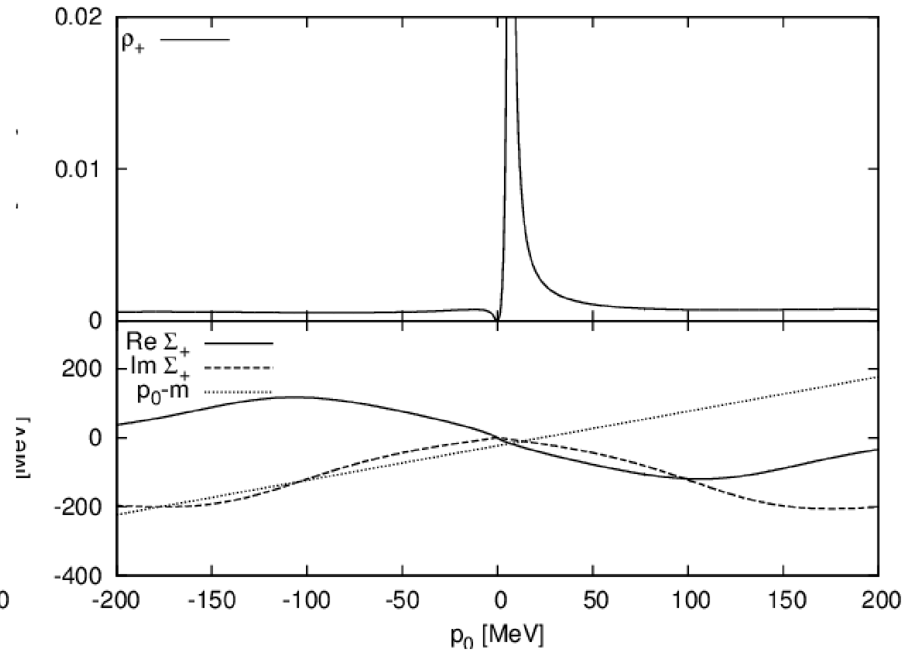
- Quark spectrum is significantly modified by the van Hove singularity induced by the scattering of quarks and pions.
- Quark spectrum near TPC can have a sharp peak with a small energy.

T Dependence of Quark Spectrum

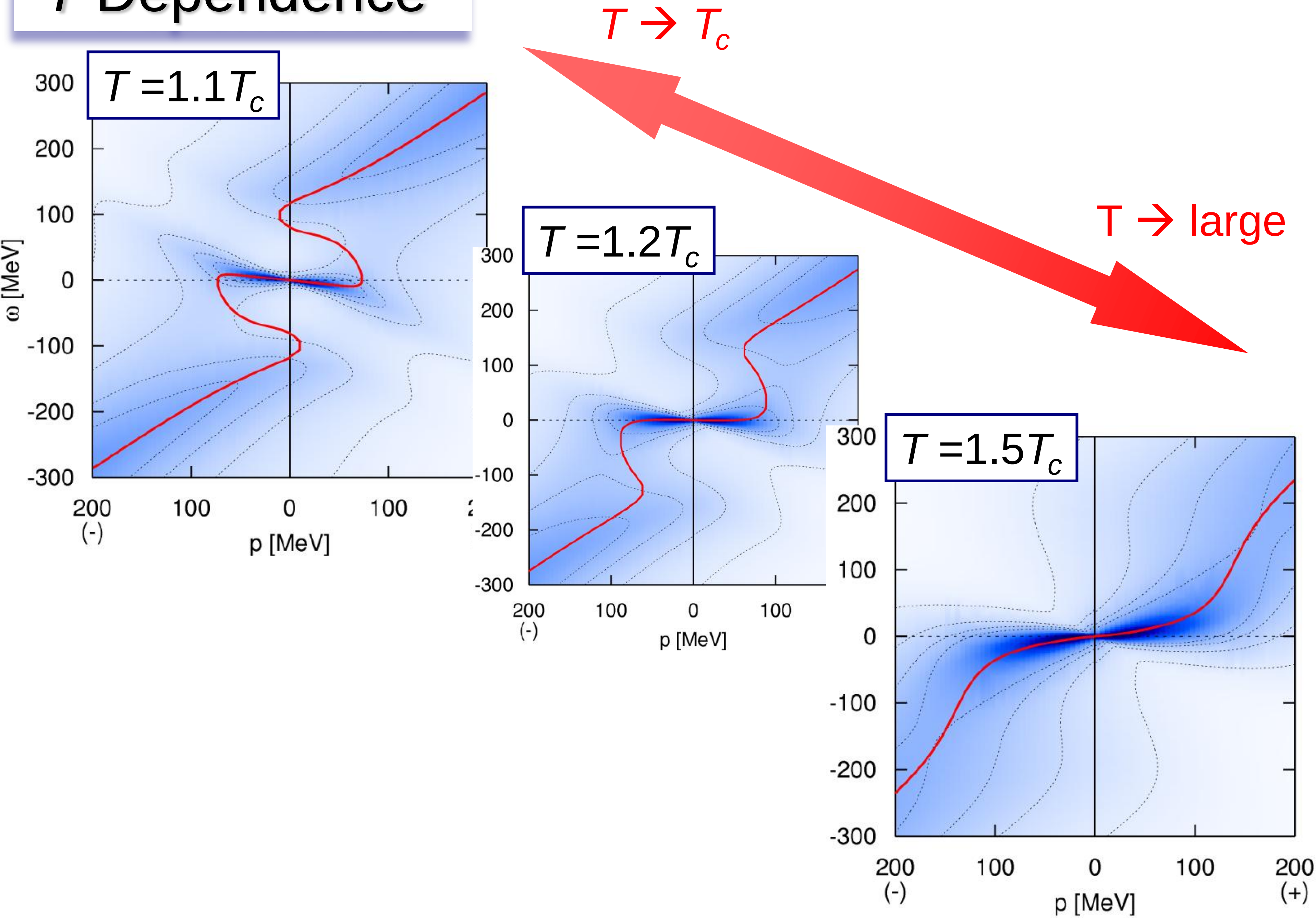
$T = 1.05T_{\mathrm{ZB}}$



$T = 1.4T_{\mathrm{ZB}}$



T Dependence



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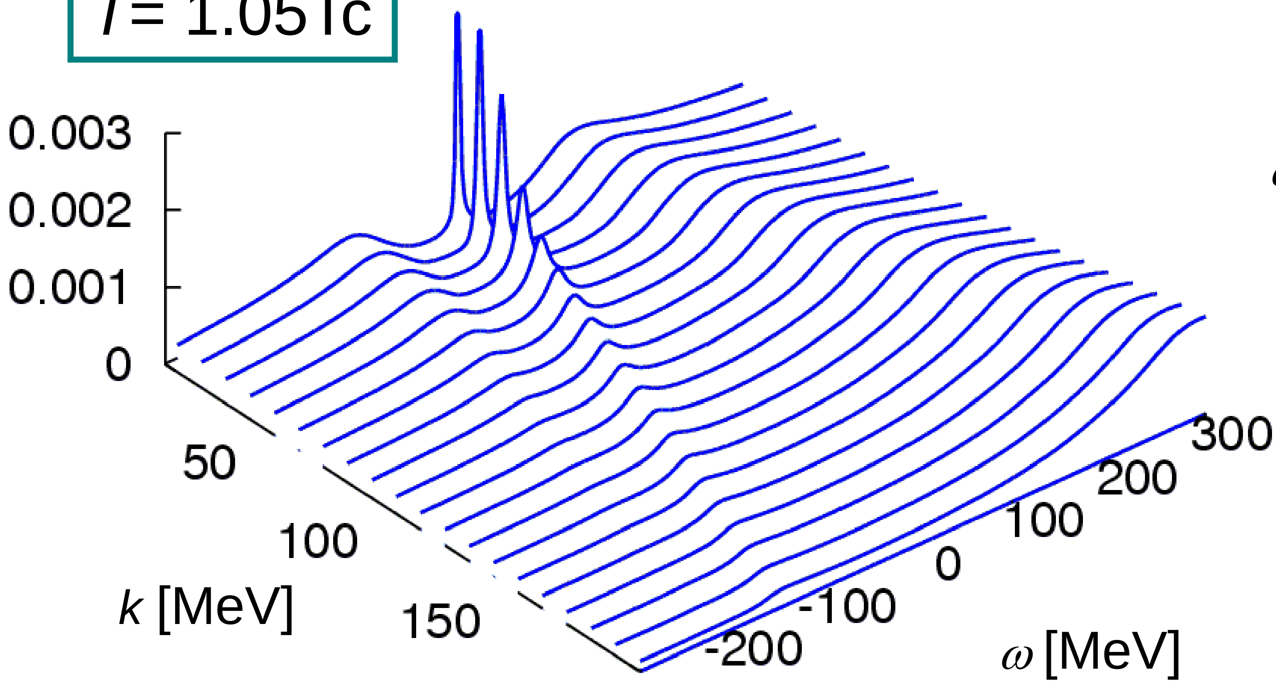
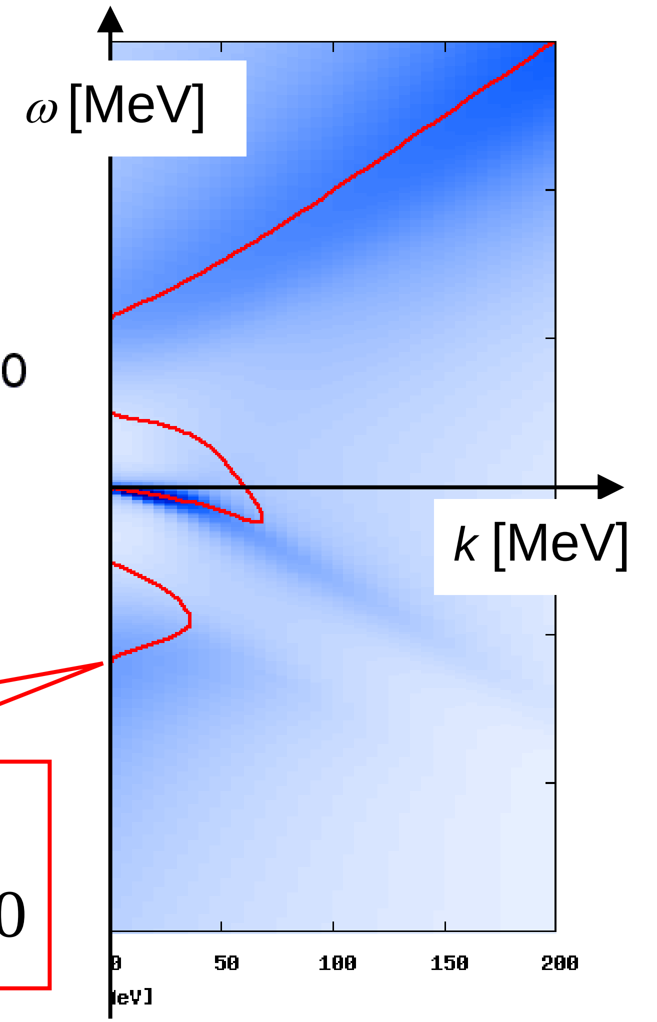
T= 1.05Tc





Quasi-dispersion relation

$$\mathrm{Re}\left[S_+(\omega,\mathbf{p})\right]^{-1} = \omega - |\mathbf{p}| - \mathrm{Re}\,\Sigma_+(\omega,\mathbf{p}) = 0$$