Charmonium spectral functions at finite momenta in the quark-gluon plasma from lattice QCD

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LQGP collaboration

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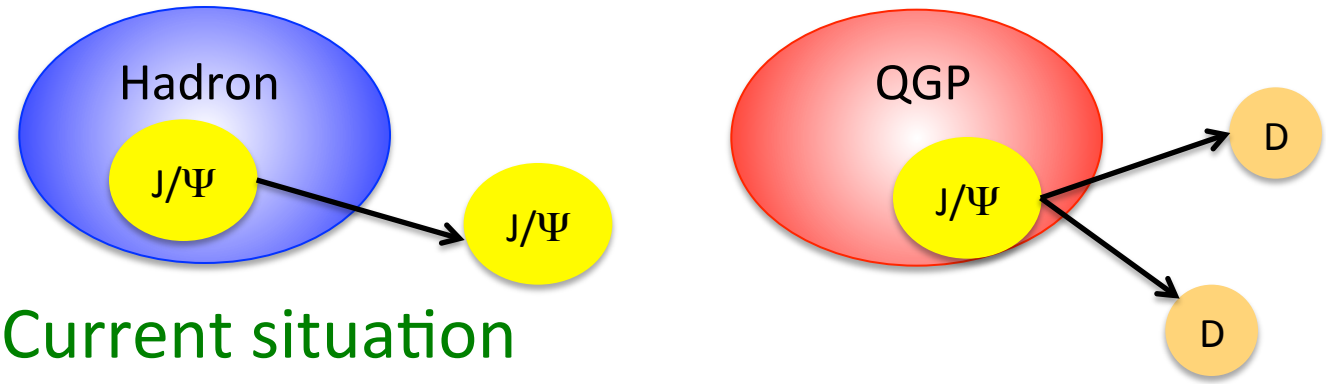
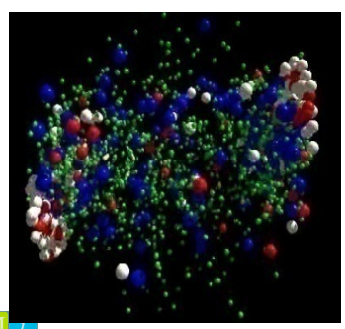
J/Ψ Suppression

- QGP signature in heavy ion collisions

Matsui and Satz, Miyamura… '86



- Current situation
  - Experiments: SPS, RHIC, LHC
  - Lattice QCD: η_c, J/Ψ survive at T ~1.7T_c, *Asakawa,Hatsuda,Umeda,…..*
- Relativistic heavy ion collisions



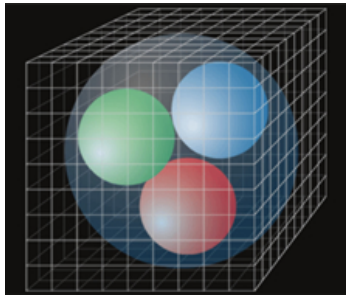
space-time expansion

temperature ~ 200 MeV @ RHIC

charmonia ~ 3.0 GeV

➡ Charmonium spectral functions at finite momenta

Lattice QCD



- First principle calculation
- Useful tool for analyses of non-perturbative aspects: sQGP
- Monte Carlo simulations, numerical experiments

$$\langle A \rangle = \frac{1}{Z} \int dU d\bar{\psi} d\psi e^{-S_G - S_F} A(\bar{\psi}, \psi, U)$$

ex. A: correlators

S_G :gauge action $S_F = \bar{\psi} W \psi$:fermion action

$$\langle A \rangle = \frac{1}{Z} \int \det W dU e^{-S_G} A(\bar{\psi}, \psi, U)$$

det W =1 : quenched approximation

Charmonia in Heavy Ion Collisions

- Spectral functions with finite momenta
- Ill-posed problems

$$C(t,\vec{p}) = \int d\omega \rho(\omega,\vec{p}) K(t)$$

correlators on lattice

noisy, discrete $\sim O(10)$

spectral function

continuous

$\sim O(10^3)$

kernel

Maximum Entropy Method

$$C(T,\vec{p}) = \sum_{x} \exp(i\vec{p}\cdot\vec{x}) \langle O_\Gamma(\vec{x},t)\Gamma O_\Gamma^\dagger(\vec{0},0)\rangle$$

$$O_\Gamma(\vec{x},t) = \bar{\Psi}(\vec{x},t)\Gamma\psi(\vec{x},t)$$

Maximum Entropy Method

Asakawa, Hatsuda, Nakahara

$$C(t,\vec{p}) = \int d\omega \rho(\omega,\vec{p}) K(t)$$

- Bayes' theorem

$$P[\rho|CH] = \frac{P[C|\rho H]P[\rho|H]}{P[C|H]}$$

C: lattice data
H: all definitions and prior knowledge

χ^2-likelifood function

$$P[C|\rho H] = \exp(-L)/Z_L$$

Shannon-Jaynes entropy

$$P[\rho|H] = \exp(\alpha S)/Z_S$$

$$S = \int \left[A(\omega) - m(\omega) - A(\omega)\log\left(\frac{A(\omega)}{m(\omega)}\right)\right]$$

m: default model

$$P[\rho|CH] \propto \exp(\alpha S - L)$$

- MEM solution: maximum of $\alpha S - L$
- Error analysis : essential in MEM analysis

Parameters

Asakawa and Hatsuda, PRL

- Actions
  - standard plaquette action, Wilson fermion
  - quenched approximation ← heavy flavor
- Lattice sizes
  - anisotropic lattice: $\xi = a_\sigma / a_\tau = 4$
  - $\beta = 7.0$, $a_\tau = 9.75 \times 10^{-3}$ fm
  - large spatial volume: N_σ X $N_\tau = 64^3$ X N_τ, $P_{min} \sim 0.5$ GeV

PACS-CS@Tsukuba
Blue Gene@KEK
ϕ@Nagoya

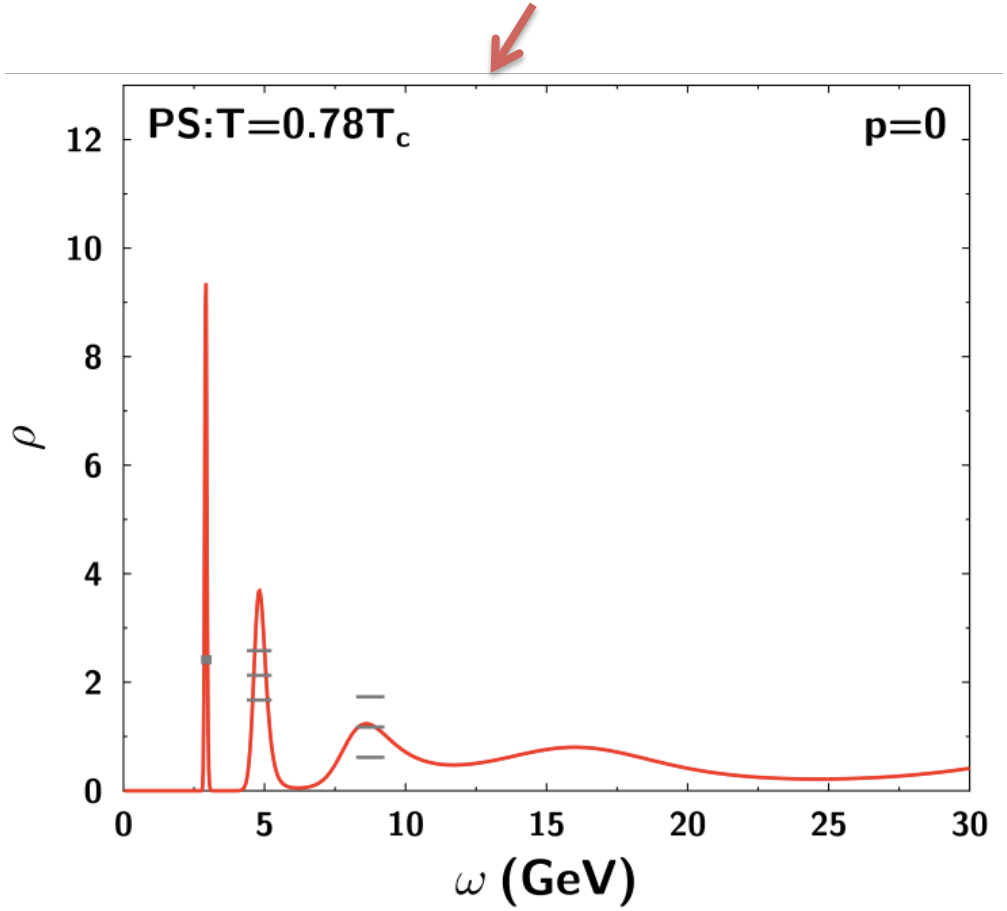
N_t (T/Tc)	96 (0.78)	54 (1.38)	46 (1.62)	44 (1.70)	42 (1.78)	40 (1.87)	32 (2.33)
# of conf.	260	400	400	400	400	400	400

heat bath : overrelaxation=1:4

1000 sweeps between measurements

η_c at T=0.78Tc

N_t (T/Tc)	96 (0.78)	54 (1.38)	46 (1.62)	44 (1.70)	42 (1.78)	40 (1.87)	32 (2.33)

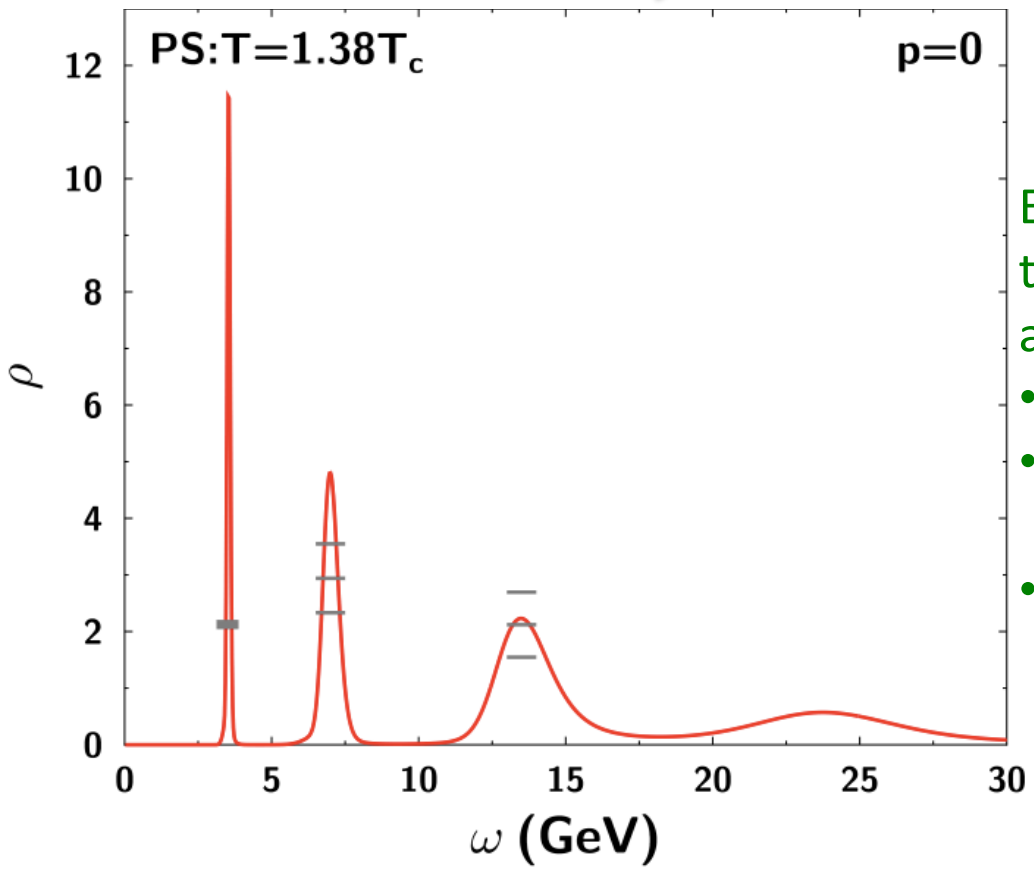


κ=0.08285 η_c

- The first peak ~ 2.9(2)GeV
  Consistent with experimental value
- The second peak
  resonance ?
- Other structure: lattice artifact

η_c at T=1.38Tc

N_t (T/Tc)	96 (0.78)	54 (1.38)	46 (1.62)	44 (1.70)	42 (1.78)	40 (1.87)	32 (2.33)

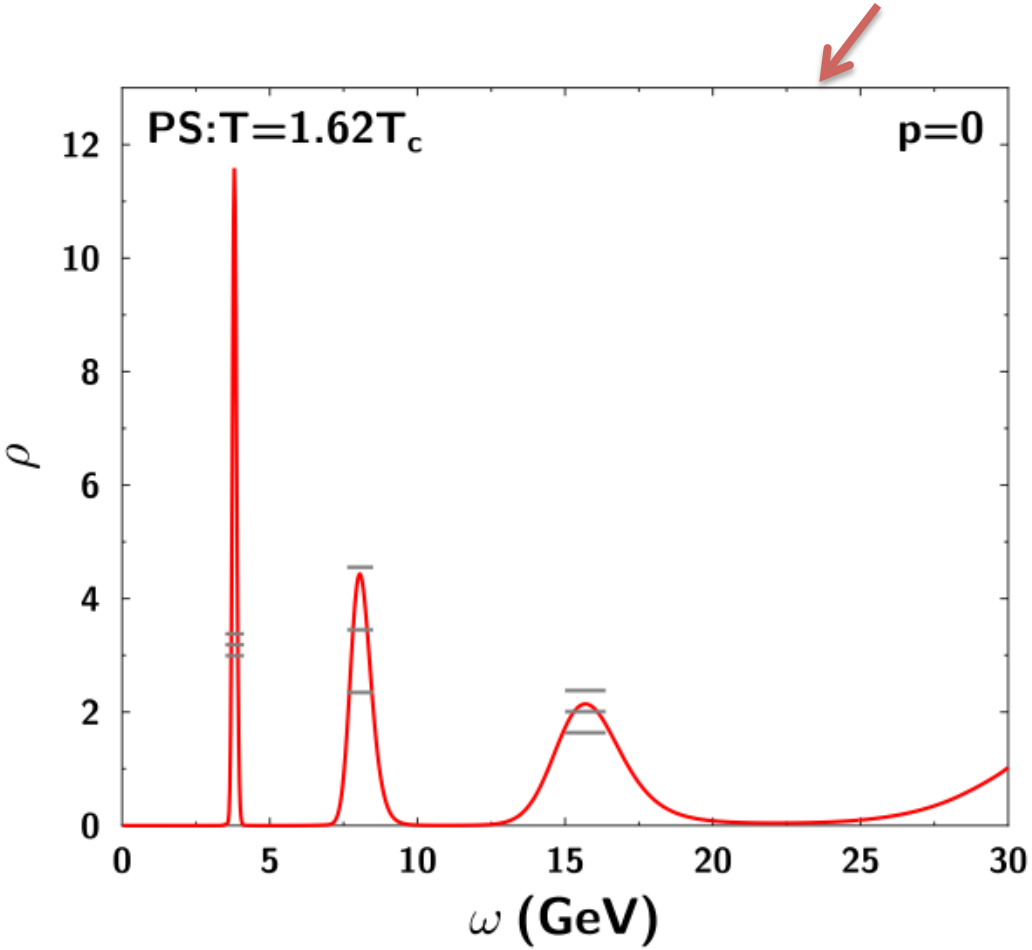


Even above the Tc
the qualitative feature of ρ is the same as that at T=0.78 Tc.

- The first peak
- The second peak resonance ?
- Other structure: lattice artifact

η_c at T=1.62Tc

N_t (T/Tc)	96 (0.78)	54 (1.38)	46 (1.62)	44 (1.70)	42 (1.78)	40 (1.87)	32 (2.33)

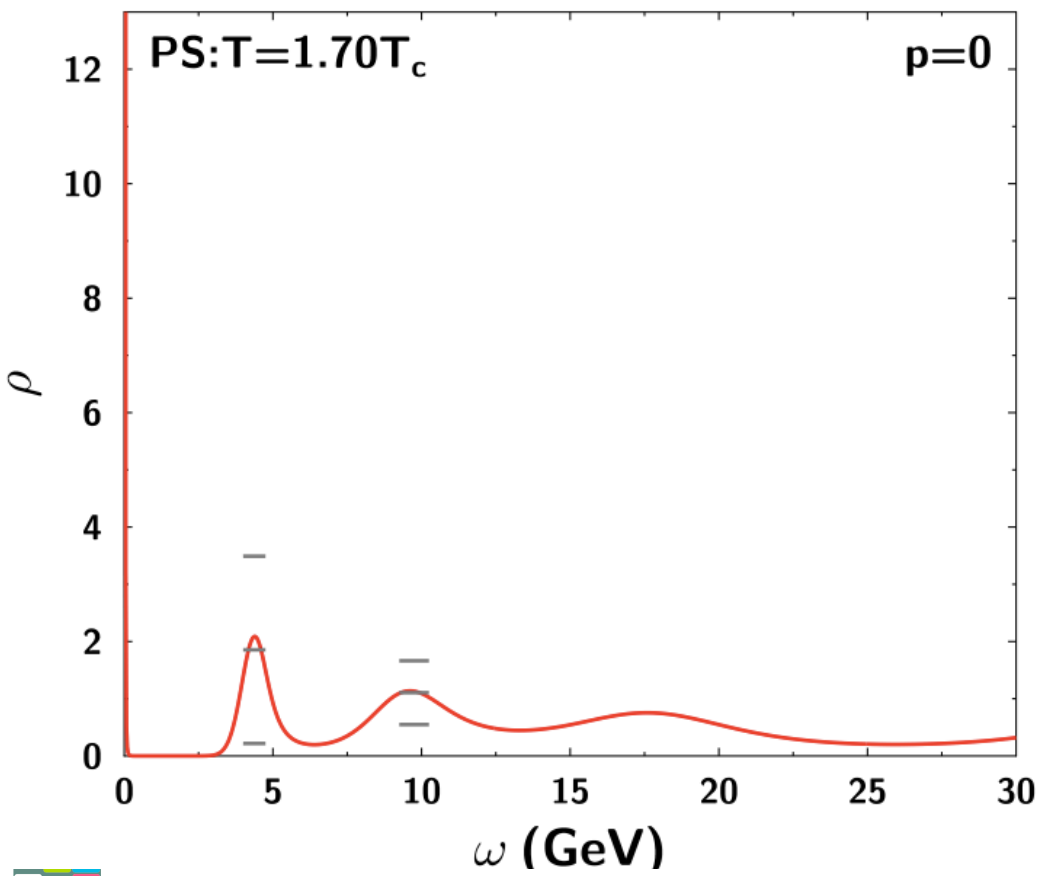


Even above the Tc
The first peak exists clearly.

- The first peak
- The second peak
  lattice artifact ?
- Other structure: lattice artifact

η_c at T=1.70Tc

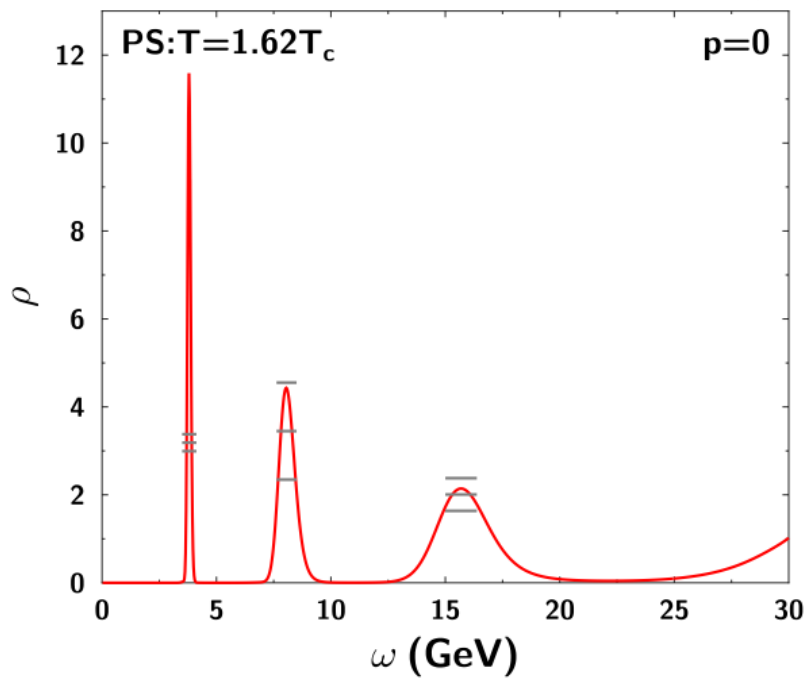
N_t (T/Tc)	96 (0.78)	54 (1.38)	46 (1.62)	44 (1.70)	42 (1.78)	40 (1.87)	32 (2.33)

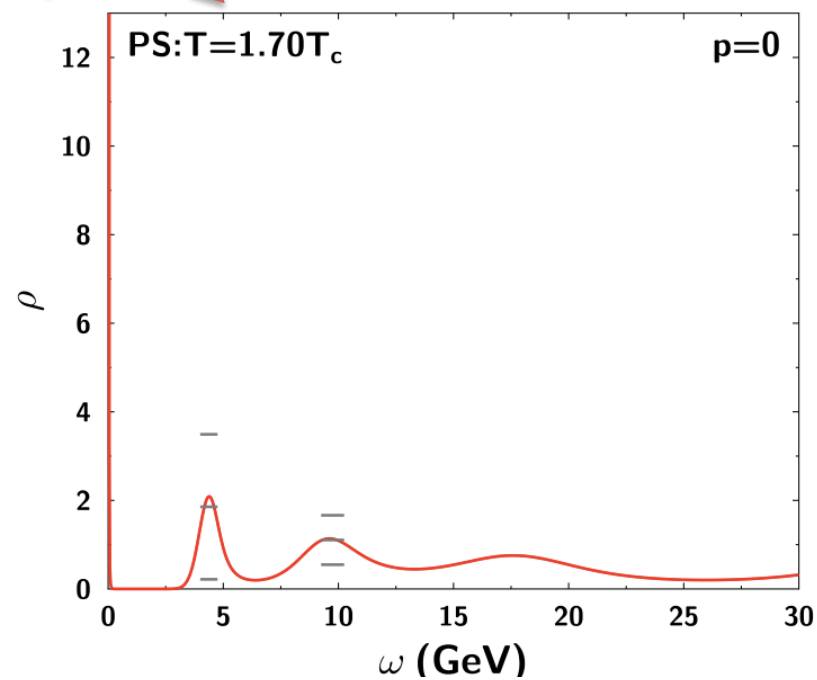


At T=1.70 Tc
the spectral function dramatically changes.
From comparison with error bars, at T=1.70Tc η_c melts.

Melting Temperature

N_t (T/Tc)	96 (0.78)	54 (1.38)	46 (1.62)	44 (1.70)	42 (1.78)	40 (1.87)	32 (2.33)

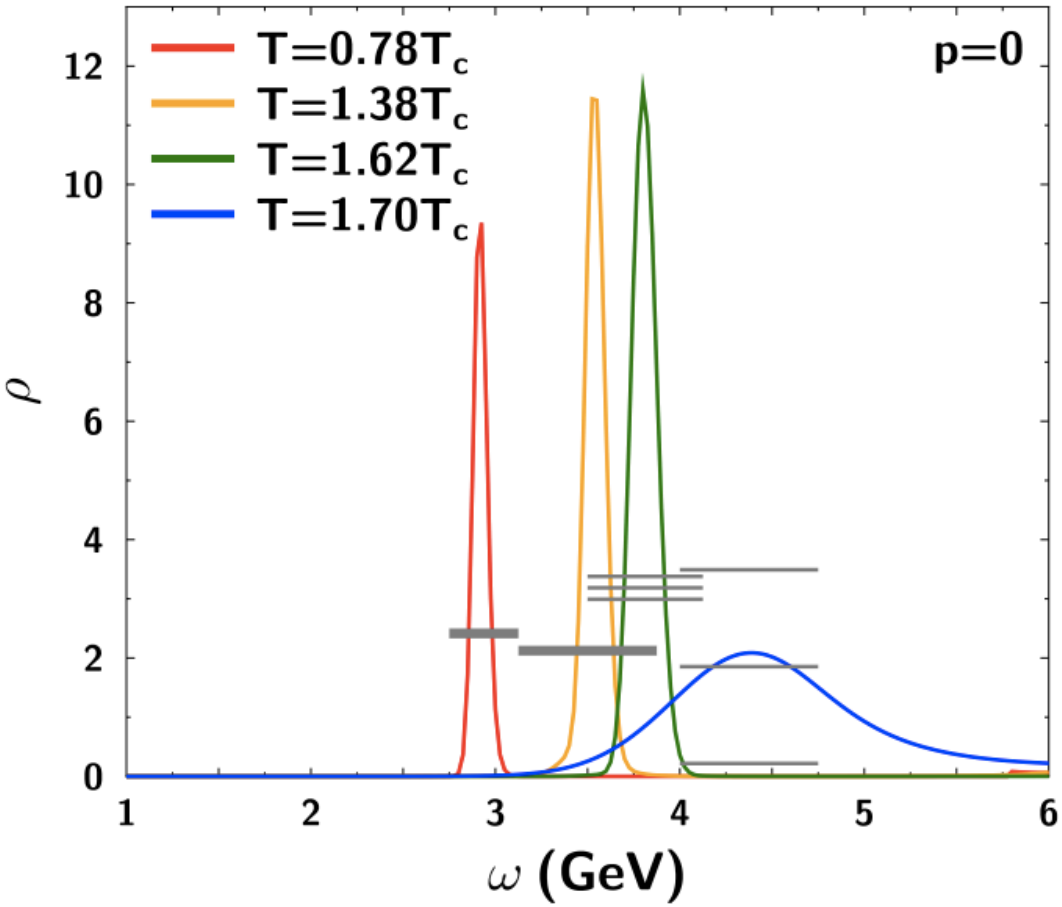


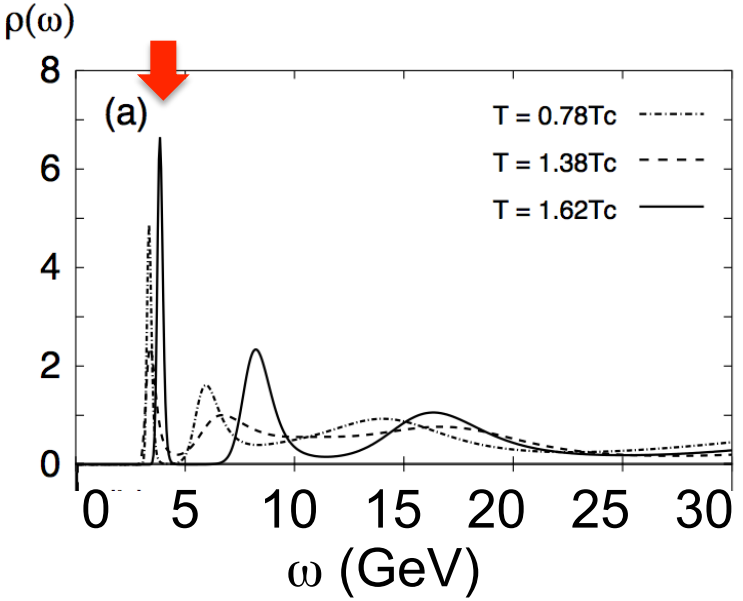


η_c melts between *T=1.62 Tc and T=1.70 Tc.*

Temperature Dependence of ρ

N_t (T/Tc)	96 (0.78)	54 (1.38)	46 (1.62)	44 (1.70)	42 (1.78)	40 (1.87)	32 (2.33)

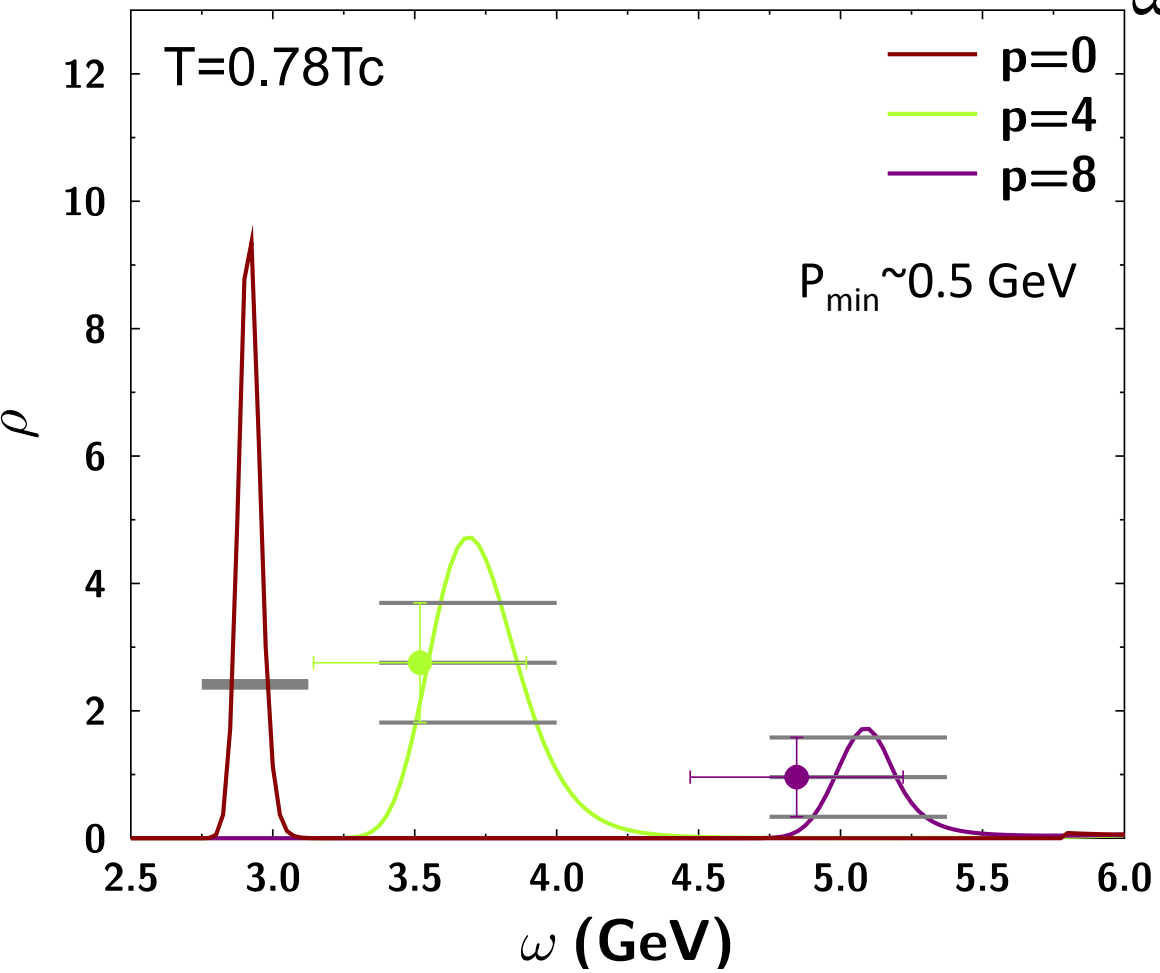




Asakawa and Hatsuda, PRL

The mass of η_c increases with temperature.

Dispersion Relations at $T<T_c$



$$\omega^2 = m|^2_{p=0} + \hat{p^2}_{\rm lattice}$$

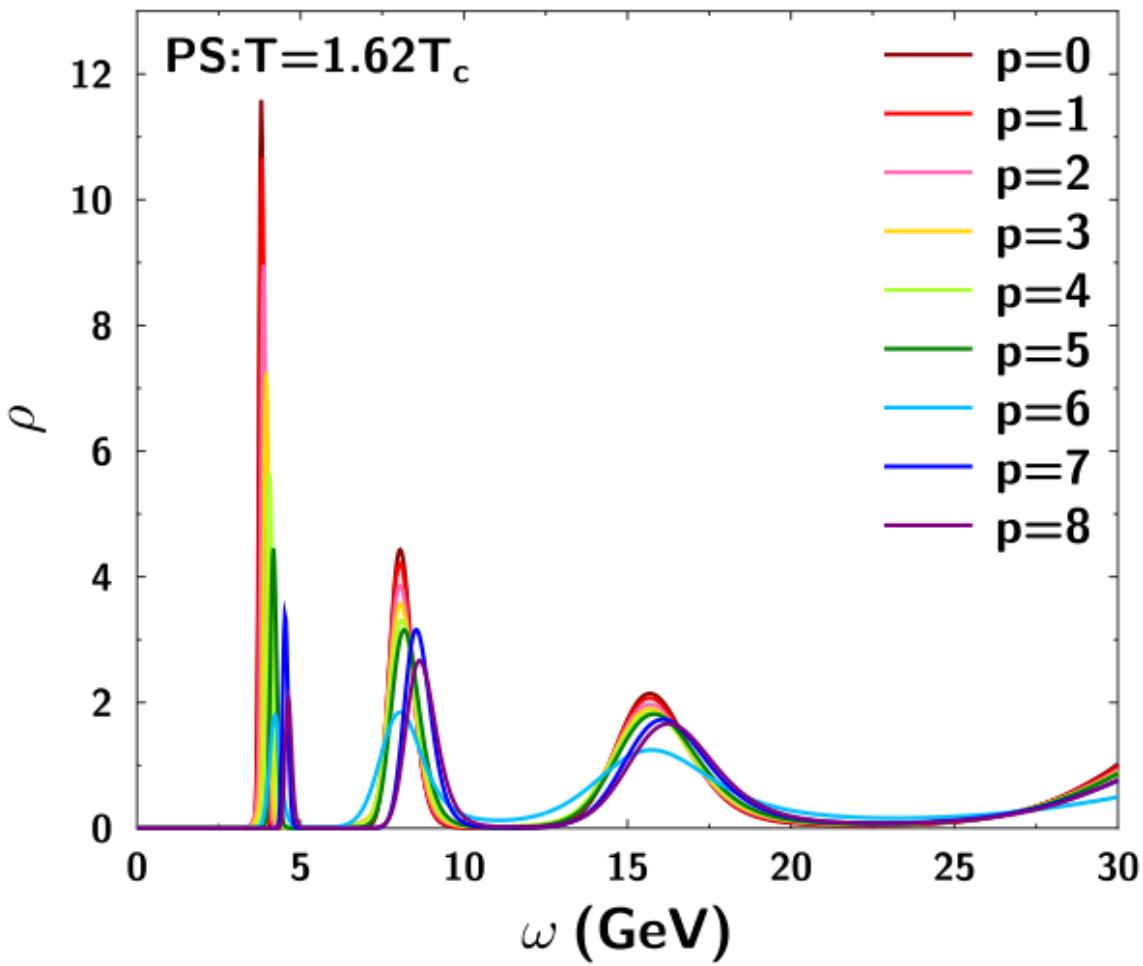
free bosons:

$$\hat{p^2}_{\rm lattice} = \frac{2}{a_\sigma}\sin(pa_\sigma/2)$$

The dispersion relation at T=0.78Tc on the lattice is consistent with that of vacuum.

Spectral functions at P≠0 (T=1.62Tc)

N_t (T/Tc)	96 (0.78)	54 (1.38)	46 (1.62)	44 (1.70)	42 (1.78)	40 (1.87)	32 (2.33)

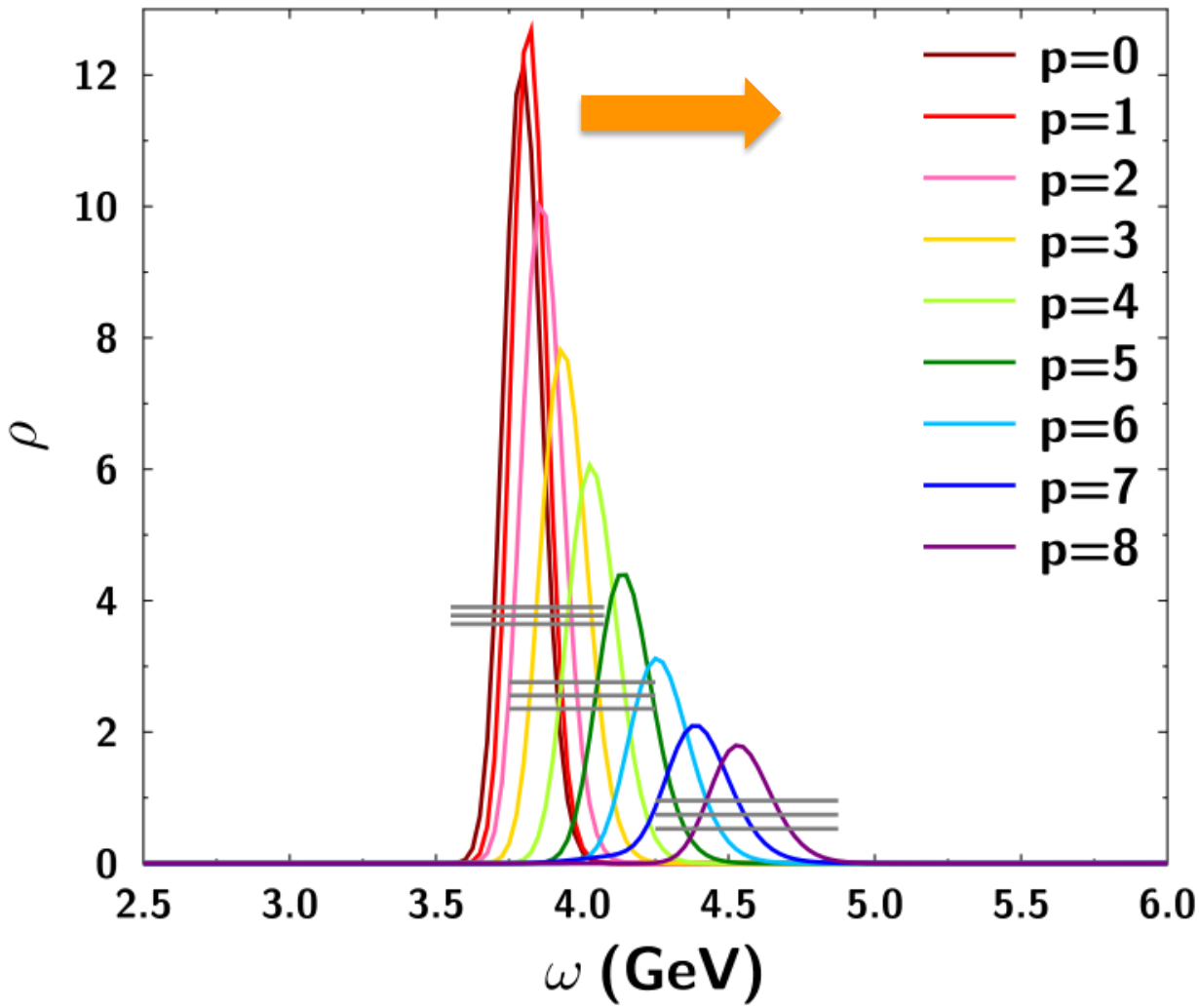


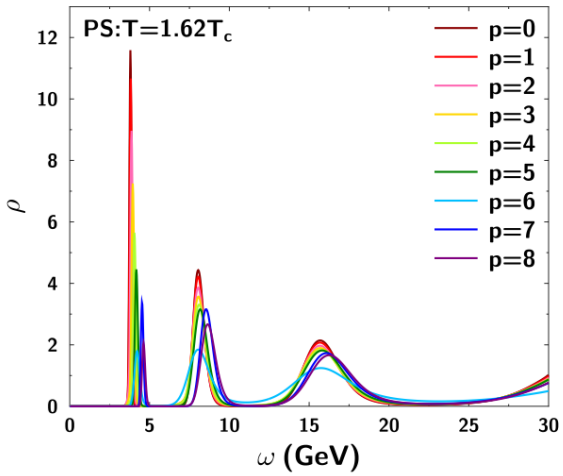
P_{min}~0.5 GeV

Qualitatively
the shape of spectra
functions at p≠0
is almost the same.

1st peak at finite momenta

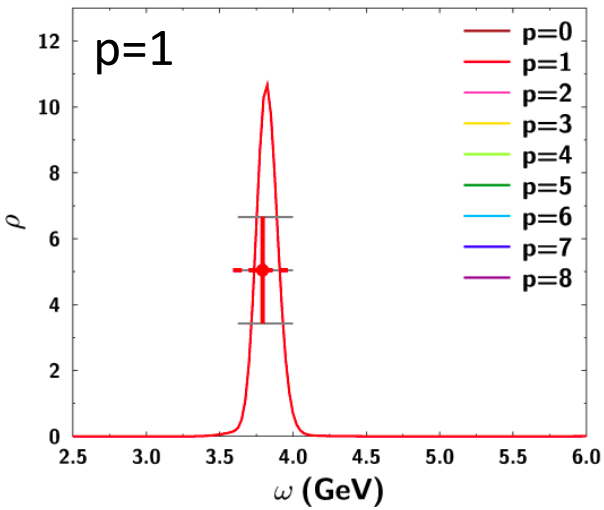
T=1.62Tc





- η_c is stable even at higher momentum.
- The strength of the peak becomes smaller at higher momentum.
- The peak shifts to larger ω at high momentum.

Dispersion Relation



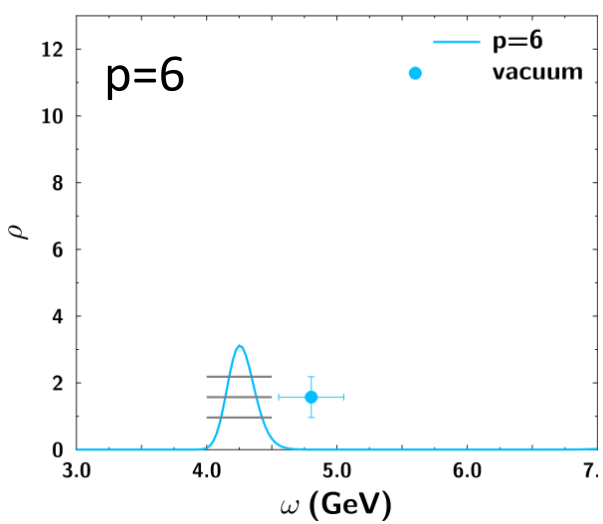
$$\omega^2 = m|^2_{p=0} + \hat{p^2}_{\rm lattice}$$

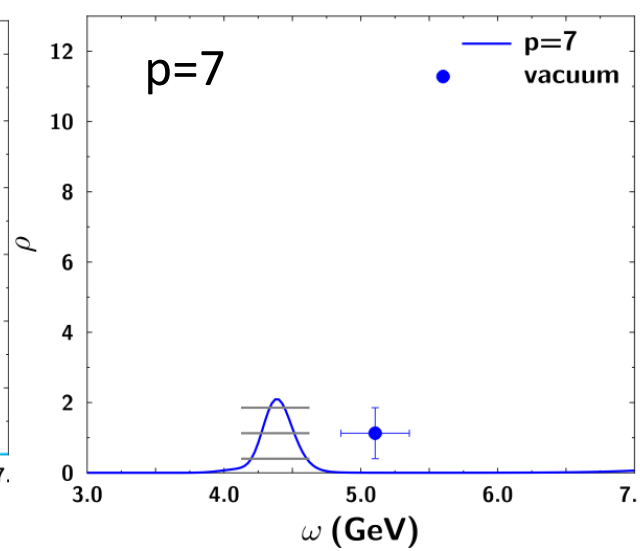
free bosons: $\hat{p^2}_{\rm lattice} = \frac{2}{a_\sigma}\sin(pa_\sigma/2)$

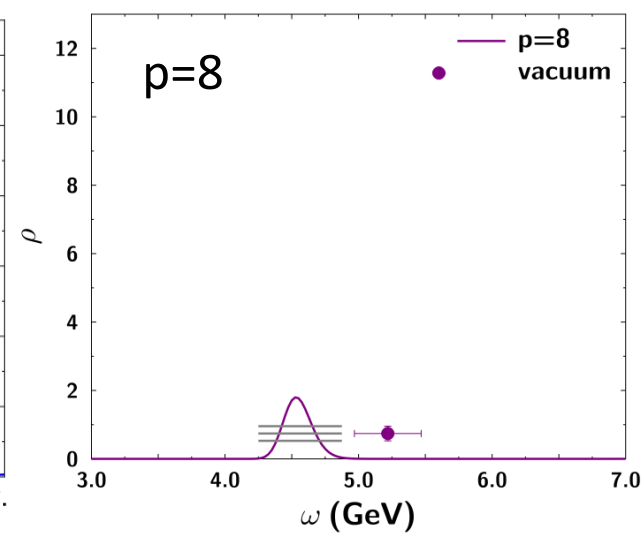
- The deviation from dispersion relation at vacuum starts to appear around p~3.0 GeV.

  ➔ medium effect

  different from dispersion relation at $T<T_c$







Summary

- Charmonium in Relativistic Heavy Ion Collisions
  - η_c (PS channel) at P=0
    - η_c melts between *T=1.62 Tc* and *T=1.70 Tc*
    - Mass of η_c increases with temperature (*T < 1.7 Tc*)
  - η_c at finite momenta
    - *At T=1.62 Tc* medium effects appears in dispersion relations

- Work in progress
  - J/Ψ (vector channel)

- Future
  - dilepton productions
    experimental data (NA60@SPS, PHENIX, STAR@RHIC, LHC)
    ex. light mesons (ρ, ω...)