Quarkonium states at finite temperature

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The aim of this talk

- In the QGP phase, heavy quarkonium states exist or not ?
- If it exists, what temperature does it dissolve at ?

First principle calculation is possible by Lattice QCD,

but it is applicable for only rather ideal system, for example,

- thermal equilibrium,
- homogeneous in finite volume with periodic b.c.,
- etc...

Some of them are different from that of actual experiments.

One of the most important parts

of "J/ψ suppression" as a phenomenological model

Contents

- Introduction
- I. Spectral function (SPF) of charmonium at T>0
  - How to calculate SPFs on lattice
  - Maximum Entropy Method
  - Numerical results
- II. Wave function
  - t-dependence of Wave function at T>0
  - Numerical results
- Summary

part-I : Spectral function

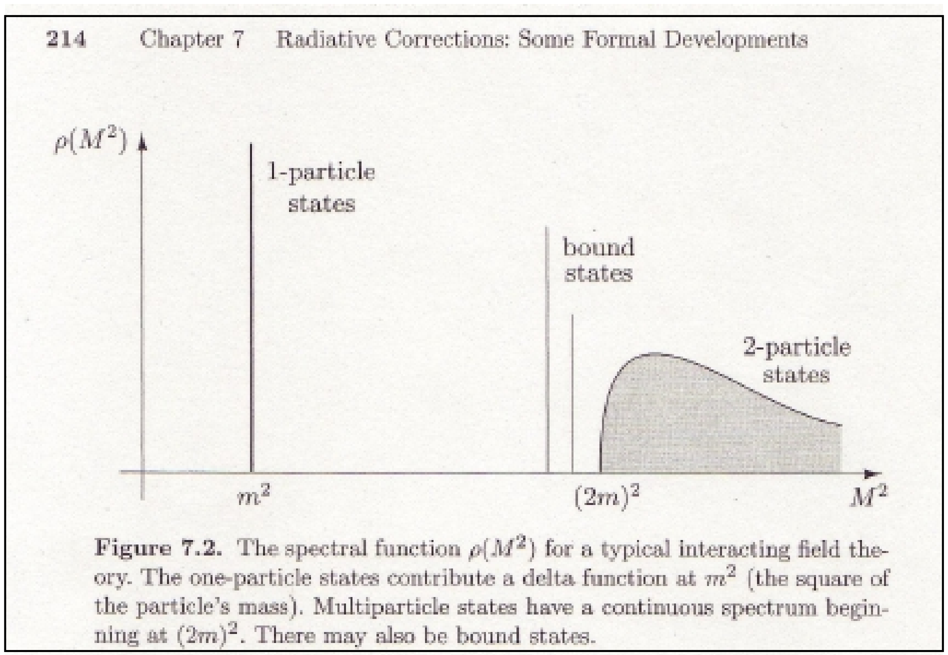
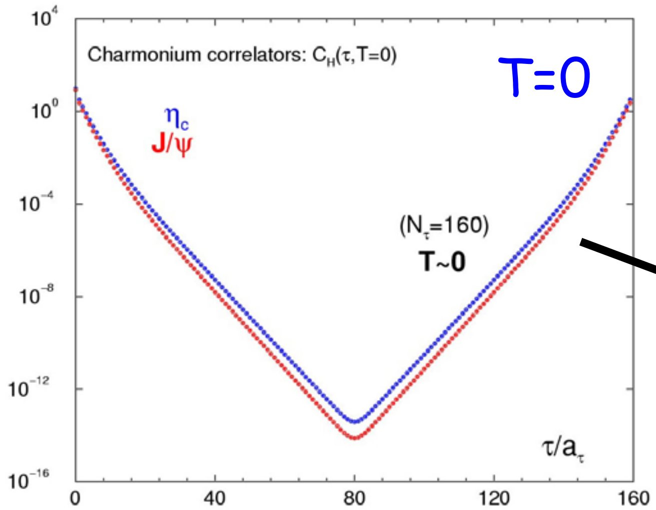

214 Chapter 7 Radiative Corrections: Some Formal Developments

Figure 7.2. The spectral function $\rho(M^2)$ for a typical interacting field theory. The one-particle states contribute a delta function at m^2 (the square of the particle's mass). Multiparticle states have a continuous spectrum beginning at $(2m)^2$. There may also be bound states.

from "An Introduction to Quantum Field Theory"
Michael E. Peskin, Perseus books (1995)

How to calculate the SPFs on lattice

Thermal hadron correlation function (T: temperature)



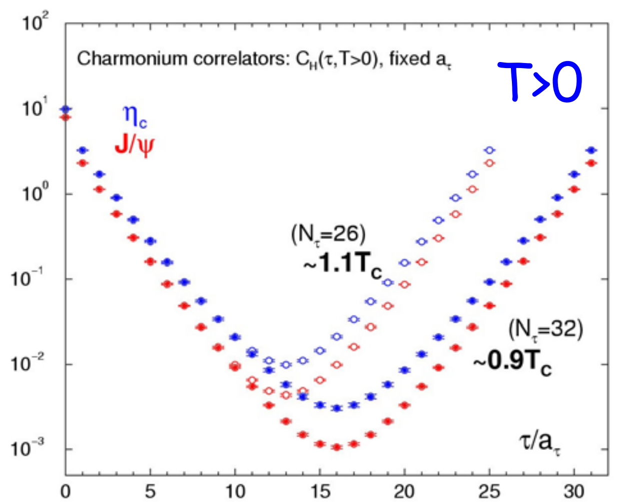
$$C_H(\tau,T) = \sum_{\vec{r}} \langle J_H(\tau,\vec{r}) J_H^{\dagger}(\tau,\vec{0}) \rangle$$

Spectral function

$$C_H(\tau,T) = \int_0^{\infty} d\omega \; \sigma_H(\omega,T) \frac{\cosh(\omega(\tau - \frac{1}{2T}))}{\sinh(\frac{\omega}{2T})}$$

"Inverse problem"

usually, brute force χ^2 analysis fails (ill-posed problem)



- Furthermore, in T>0 lattice QCD,

$$C_H(\tau,T), \;\; 0 \leq \tau/a_\tau \leq 1/T$$

where $T = 1/(a_\tau N_\tau)$

Maximum Entropy Method

MEM (based on Bayes' theorem)

M.Asakawa et al.
Prog.Part.Nucl.Phys.46(2001) 459

searches for the most probable shape of SPFs

by maximization of $Q = \alpha S - L$

L : Likelihood function (χ^2 term)

$$S = \int d\omega \left[\sigma_H(\omega) - m(\omega) - \sigma_H(\omega) \ln \frac{\sigma_H(\omega)}{m(\omega)} \right]$$

m(w) : default model func.

α : parameter → integrated out with a prior prob.

- Result depends on the default model function
- At high temperature
  - it is difficult to check the reliability even if MEM works.
  - melting of bound state? simple failure of MEM?

Papers for charmonium SPFs at T>0

- Umeda, Matsufuru and Nomura (quenched QCD)

  T.Umeda et al, Eur.Phys.J.C37S1 (2004) 9.(hep-lat/0211003)

- Bielefeld group (quenched QCD)

  S.Datta et al., Phys.Rev.D69(2004)094507.

- Asakawa and Hatsuda (quenched QCD)

  M.Asakawa and T.Hatsuda, Phys. Rev. Lett. 92 (2004) 012001

- Trin-lat group (2-flavors QCD)

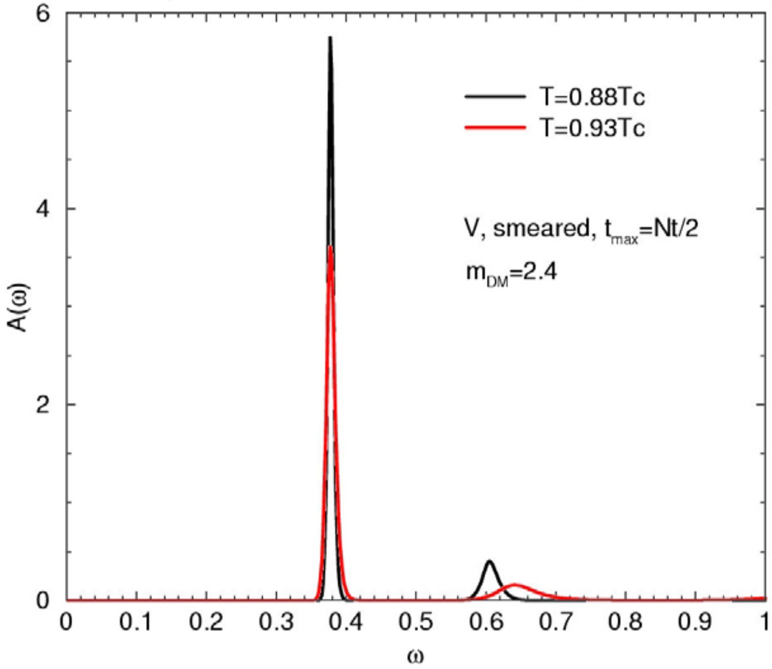
  R.Morrin et al., hep-lat/0509115 (Lattice'05)

- others

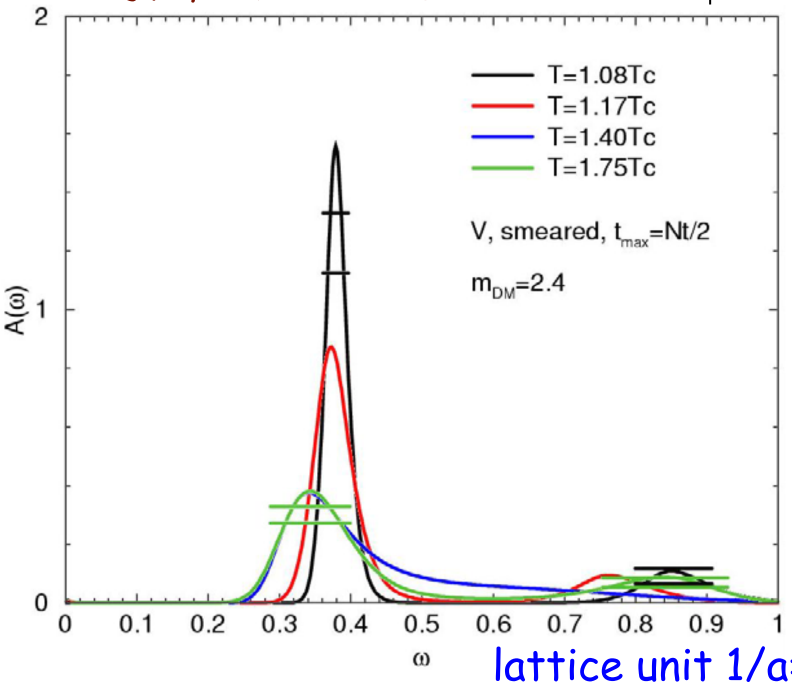
All studies supports existence of J/ψ at not so high-Temp.

Results by T.Umeda et al.

J/ψ below Tc



J/ψ above Tc



lattice unit 1/a=8GeV

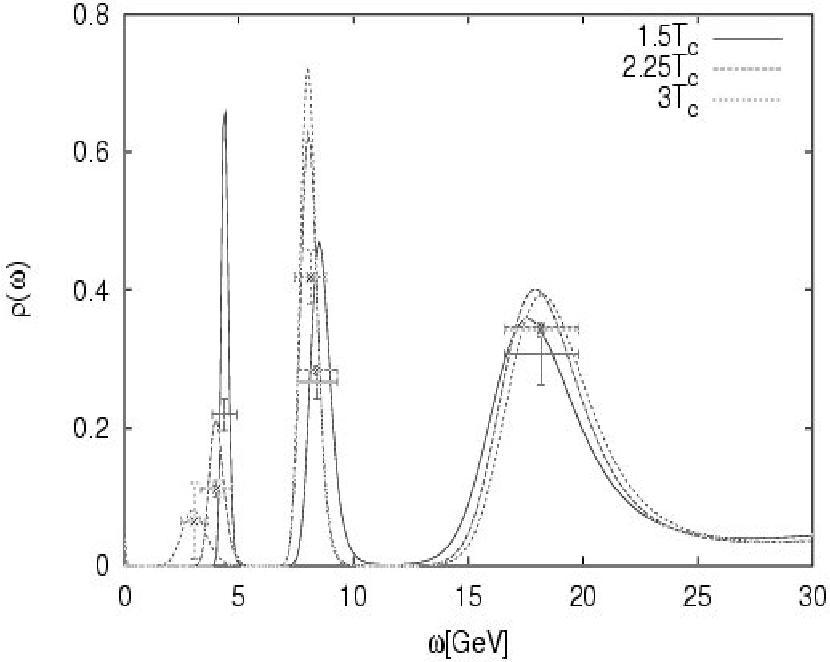
T<Tc : no mass shift, almost same SPF as T=0

T>Tc : peak structure survives up to 1.2Tc (?)

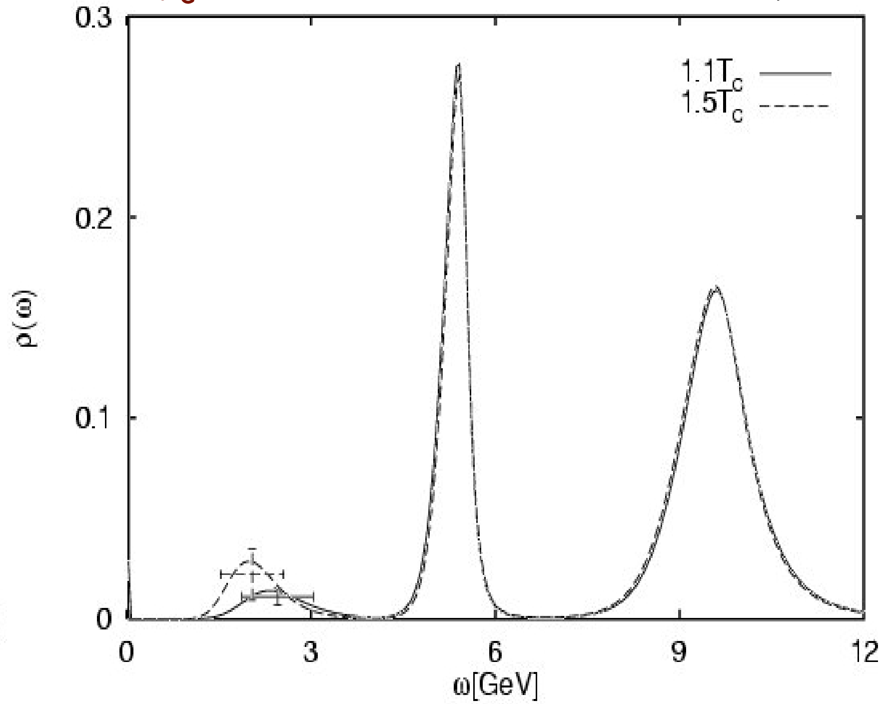
η_c : up to 1.4Tc, J/ψ : up to 1.2Tc (at least)

Bielefeld group results

J/ψ above Tc



χ_c above Tc

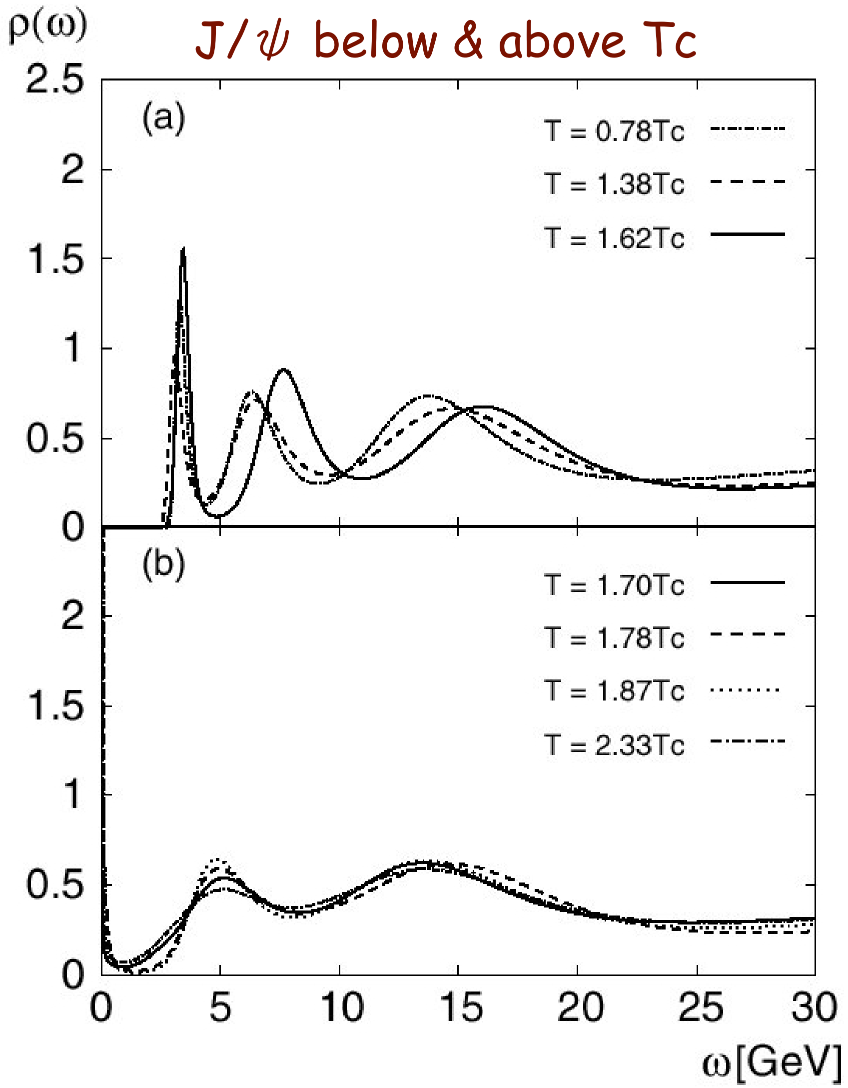


- J/ψ, η_c states survive up to $2.25T_c$
- χ_c state may dissolve just above T_c

(in pp collisions, about 40% of J/ψ production comes from decay of the excited states χ_c and ψ')

Hatsuda & Asakawa result

J/ψ below & above Tc



SPF has peak at
the same place as T=0
up to 1.6Tc
for J/ψ & η_c channels

Summary for spectral functions

- From these charmonium SPFs results,
  - J/ψ , η_c states survive even in QGP phase
  - Dissociation temp. may be 1.4~2 T_c (large uncertainty)
  - χ_c state may disappear just above T_c

- Many problems remain...
  - Most studies does not include dynamical quark effects
  - Reliability of the results at high temperature is not so good

At present we have only qualitative results !!

part-II : Wave function

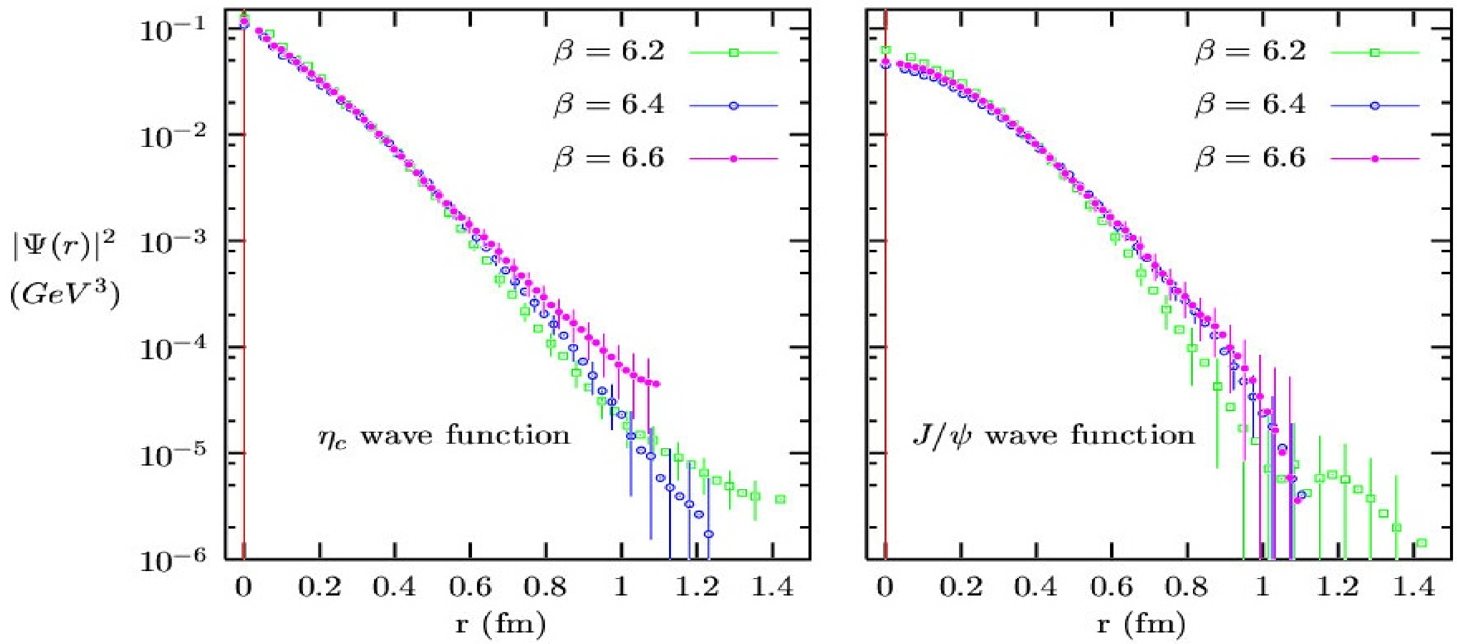


Figure 6: Scaling analysis of pseudoscalar (left) and vector (right) matter wave functions. The vertical scale is logarithmic.

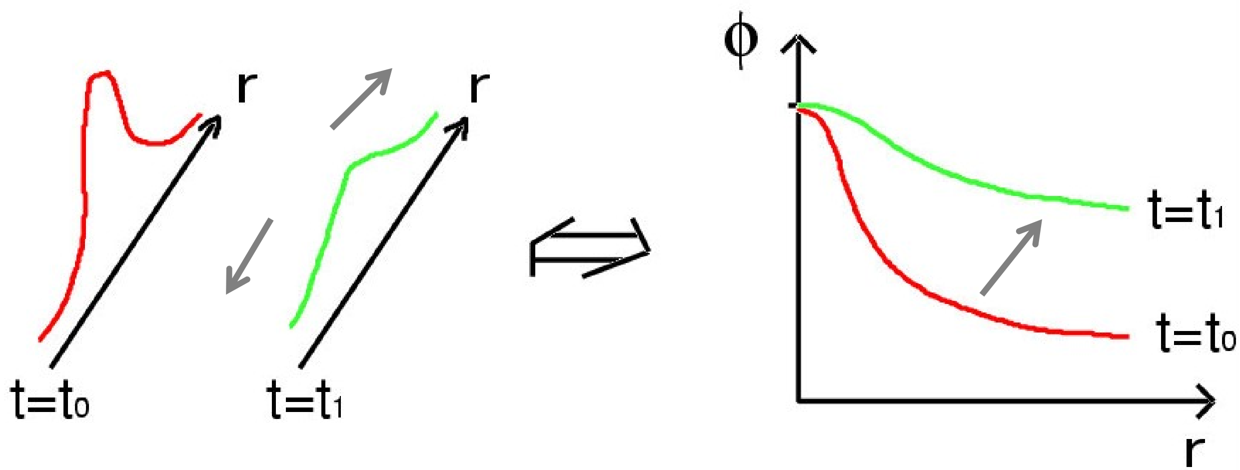
Charmonium wave functions at zero temperature from QCD-TARO Collab., JHEP 0308 (2003) 022.

Wave function

t-dependence of "Wave function" of charmonium
→ spatial correlation of c-bar{c} in QGP

$$\omega_\Gamma(r,t) = \sum_{\vec{x}} \langle \bar{c}(\vec{x}+\vec{r},t)\Gamma c(\vec{x},t) O^\dagger(0)\rangle$$: Wave function (BS amp. in Coulomb gauge)

$$\phi(r,t) \;=\; \omega_\Gamma(r,t)/\omega_\Gamma(0,t)$$: normalized $\omega_\Gamma(r,t)$ at spatial origin



When the wave function spreads out like free quarks,
$\phi(r,t)$ has gentle slope at large t.

Wave function

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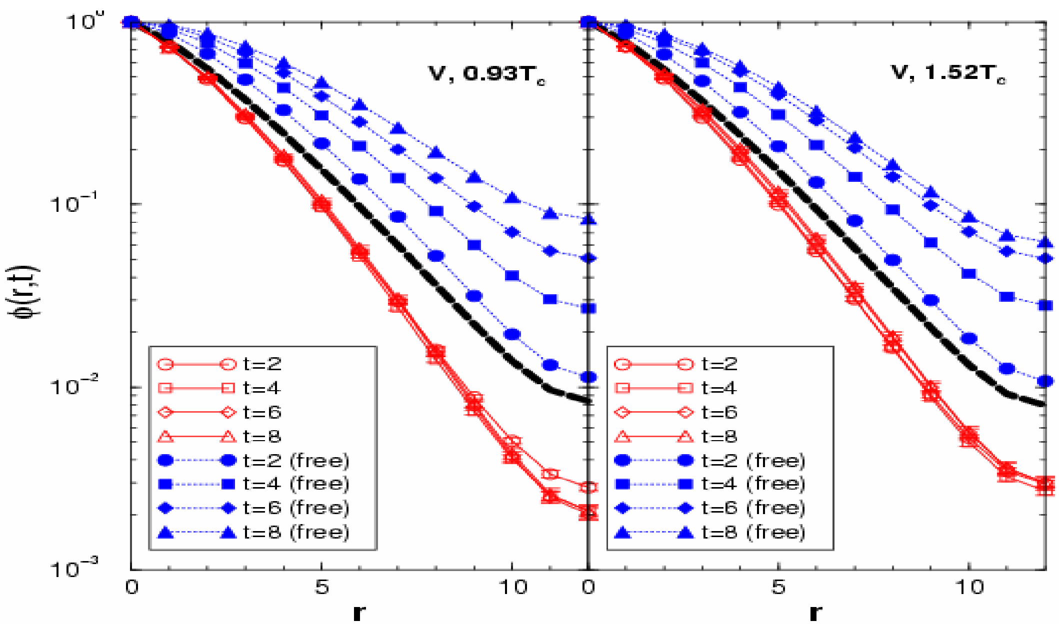

c-bar{c} has strong spatial correlation even at T=1.5Tc

T.Umeda et al. Int.J.Mod.Phy.A16(2001)2215

Summary of this talk

- From recent MEM results,
  J/ψ , η_c states survive even in QGP phase
  dissociation temp. may be 1.4~2 T_c (large uncertainty)
  χ_c state may disappear just above T_c
- Wave function shows
  strong spatial correlation even at $T=1.5T_c$

Next step

- Improvement of MEM analysis
  & dynamical quark effects
- New ideas ...