Heavy Quarkonium in QGP on the Lattice

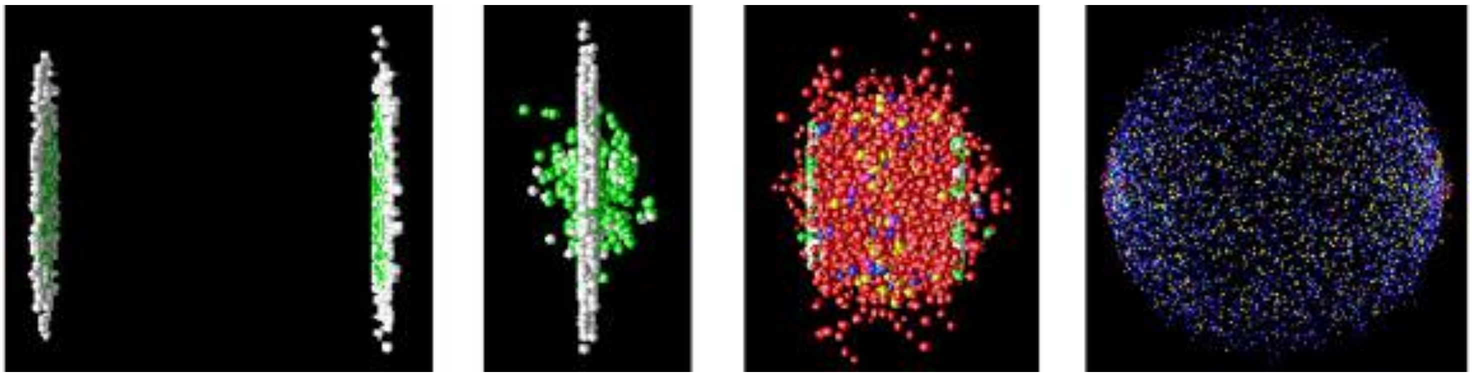
Takashi Umeda

HIROSHIMA UNIVERSITY

3rd Asian Triangle Heavy-Ion Conference
CCNU, Wuhan, China, October 18-20, 2010

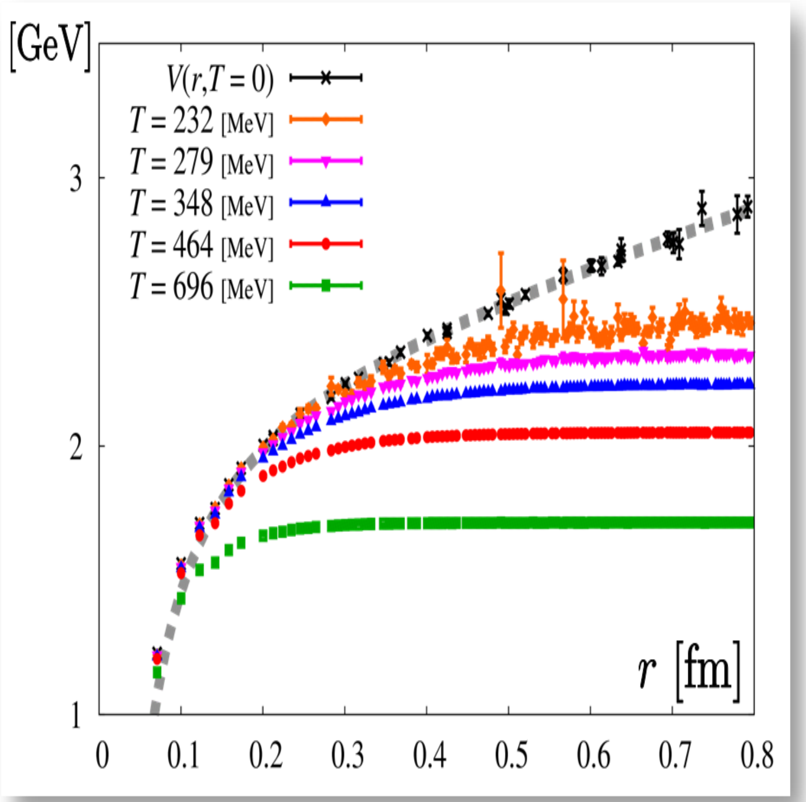
Contents of this talk

from the Phenix group web-site



- Introduction
  - -- J/ψ suppression
  - -- Lattice studies with Maximum Entropy Method (MEM)
  - -- Sequential J/ψ dissociation
- Zero mode contributions
- Other approaches to study charmonium dissociation
- Summary

J/ψ suppression as a signal of QGP



Static quark free energy
WHOT-QCD Collab. ('07)

N_f=2+1 QCD result

Confined phase:
- linear raising potential
  - → bound state of c – $\bar{c}$

De-confined phase:
- Debye screening
  - → scattering state of c - $\bar{c}$ (J/ψ dissociation)

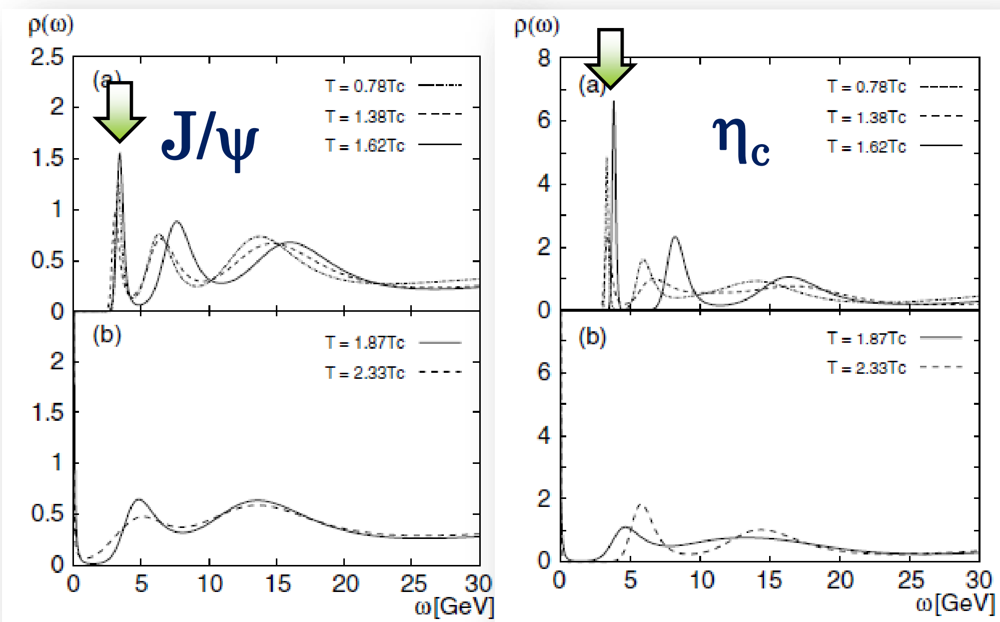
T.Hashimoto et al.('86), Matsui&Satz('86)

Maximum Entropy Method (MEM)

$$G(\tau) = \sum_{\vec{x},i} \langle J_i(\vec{x},\tau) J_i^\dagger(\vec{x},0)\rangle = \int_0^\infty d\omega \frac{e^{-\omega\tau}}{1-e^{-\frac{\omega}{T}}} \rho(\omega)$$

Charmonium correlator on the lattice

Spectral function (SPF)



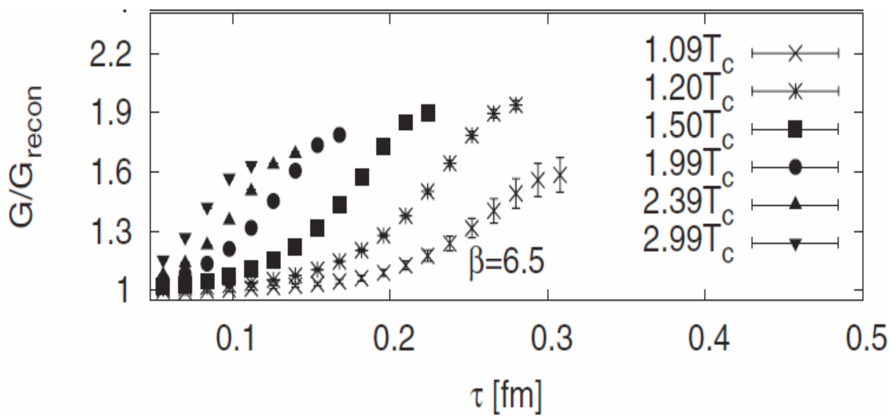
Charmonium spectral func.
Asakawa & Hatsuda ('04)

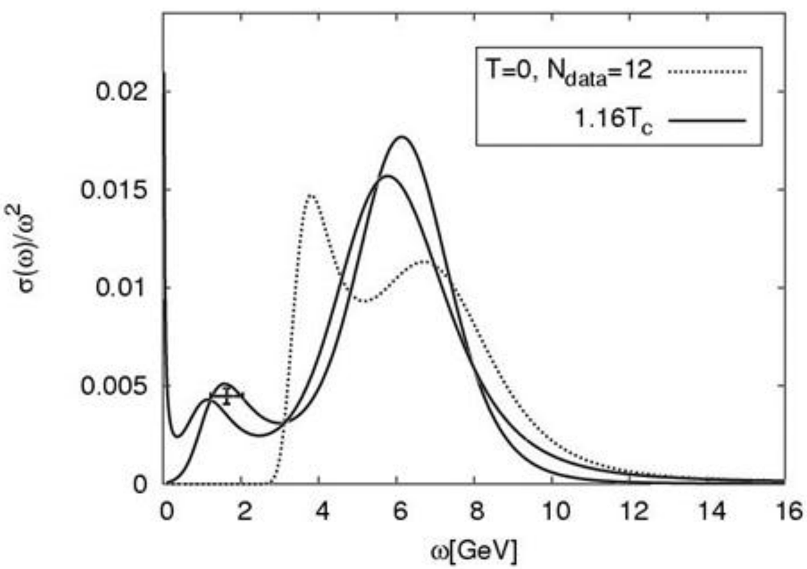
Quench QCD (N_f=0)

Maximum Entropy Method

J/ψ & η_c
survive till 1.62 T_c
dissociate at 1.87T_c

P-wave states (χ_c) in charmonium





Results on P-wave states

A.Jakovac et al. ('07)

G_{recon} is a charmonium correlator constructed with SPF at T=0.
No change in SPF at T>0 leads to $G/G_{recon} = 1$

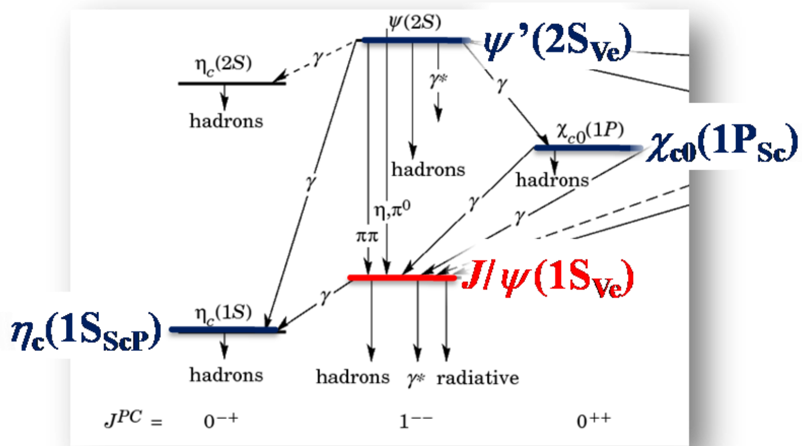
- Drastic change in χ_c correlator above T_c
- MEM results indicate χ_c dissociation just above T_c (?)

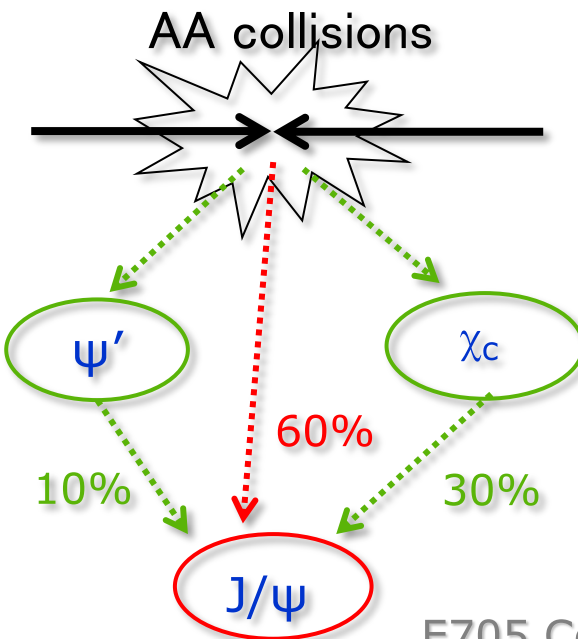
"Default model" is input information for MEM analysis
Default model dependence is one of systematic errors

Possible J/ψ suppression scenario

Sequential charmonium dissociation

F. Karsch et al. ('05)



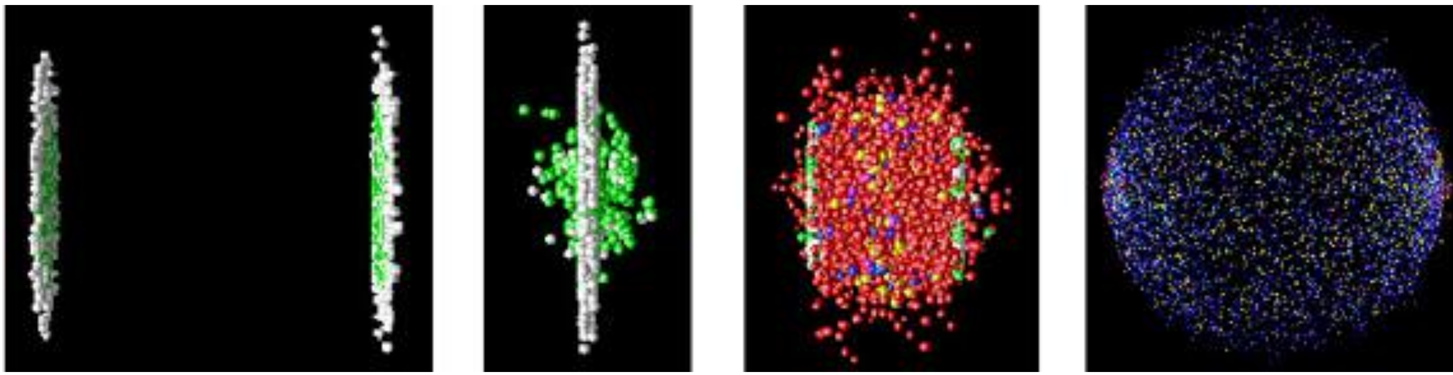


E705 Collab.('93)

When χ_c or/and ψ' dissociate just above T_c,
part of J/ψ suppression occurs
even if J/ψ survives in QGP.

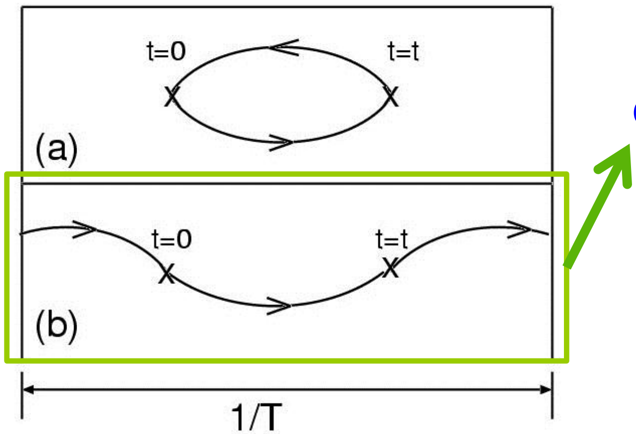
Contents of this talk

from the Phenix group web-site



- Introduction
  - -- J/ψ suppression
  - -- Lattice studies with Maximum Entropy Method (MEM)
  - -- Sequential J/ψ suppression
- Zero mode contributions
- Other approaches to study charmonium dissociation
- Summary

Zero mode in meson correlators



$\exp(-m_q t) \times \exp(-m_q(L_t - t)) = \exp(-m_q L_t)$

zero mode

$L_t = 1/T$ = temporal extent

m_q is single quark energy

T. Umeda ('07)

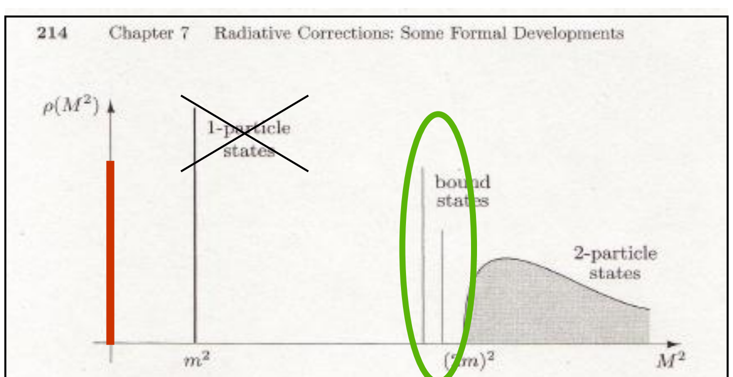


Figure 7.2. The spectral function $\rho(M^2)$ for a typical interacting field theory. The one-particle states contribute a delta function at m^2 (the square of

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

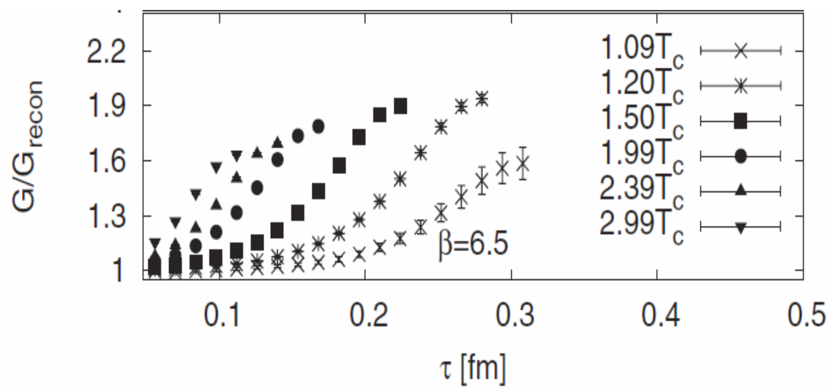
- The zero mode is part of Landau dumping but it is not relevant whether charmonium dissociates or survives.
- One can remove the zero mode effects by derivative of correlators

$$G(\tau)/G_{recon}(\tau) \longrightarrow G'(\tau)/G'_{recon}(\tau)$$

Zero mode in meson correlators

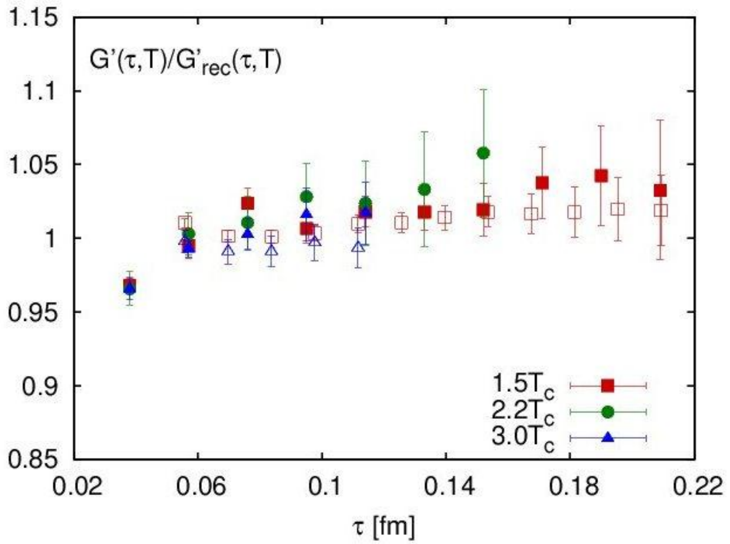
Spectral changes in χ_{c0}

w/ zero mode



A.Jakovac et al. ('07)

w/o zero mode



Mocsy & Petreczky ('08)

- The drastic change of correlators is due to the zero mode
- No change in χ_c SPF within statistical errors

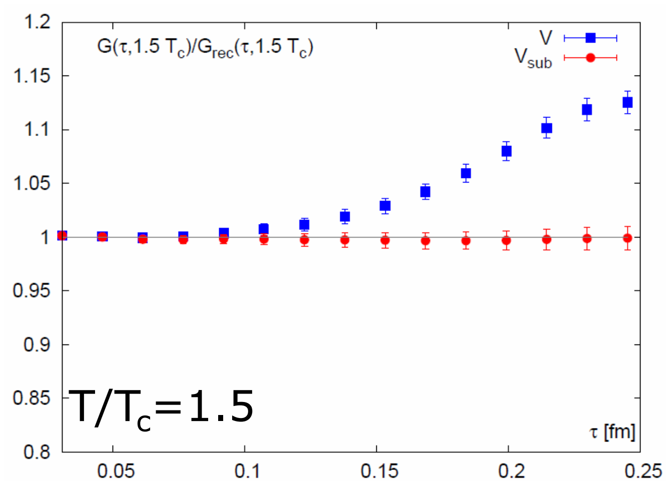
G_{recon} is a charmonium correlator constructed with SPF at T=0.
No change in SPF at T>0 leads to G/G_{recon} = 1

J/ψ results taking account of zero mode

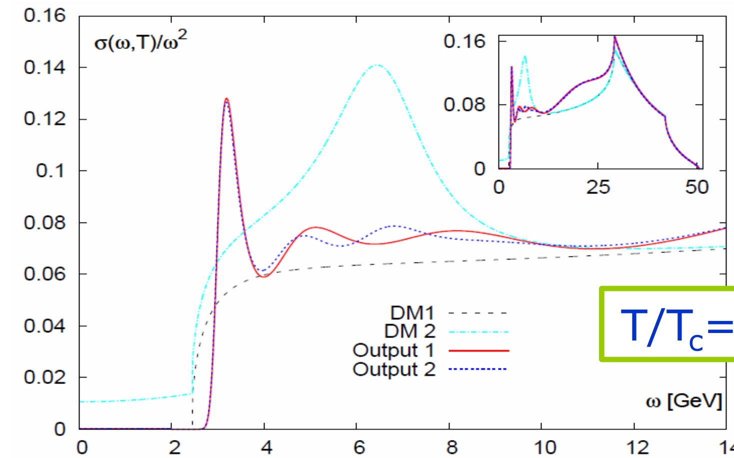
Zero mode in J/ψ correlator

H.Ding et al. ('09)

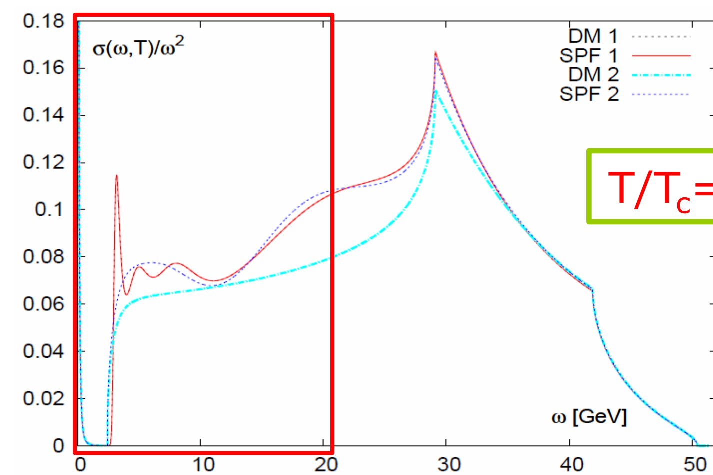
Spectral changes in J/ψ
w/ & w/o zero mode



No change in J/ψ SPF
within statistical error



$T/T_c=0.75$



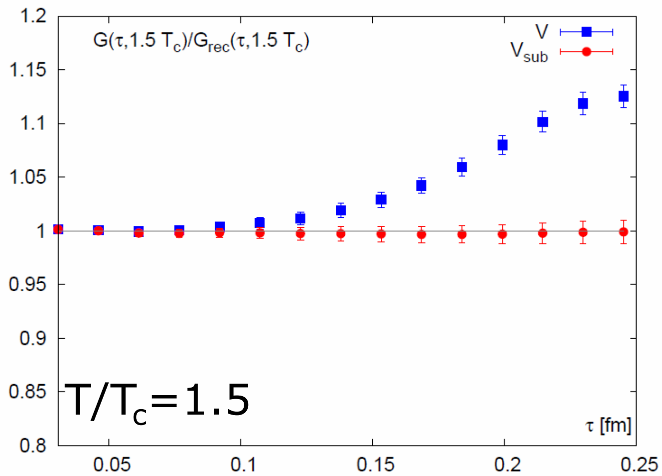
$T/T_c=1.5$

J/ψ results taking account of zero mode

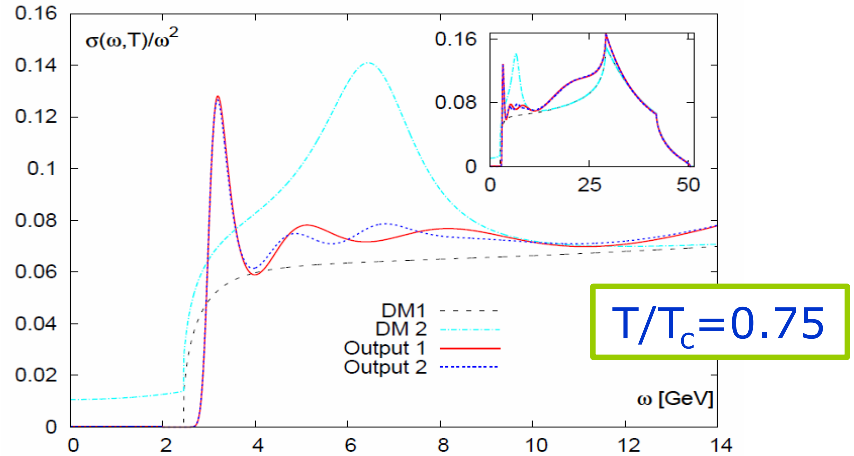
Zero mode in J/ψ correlator

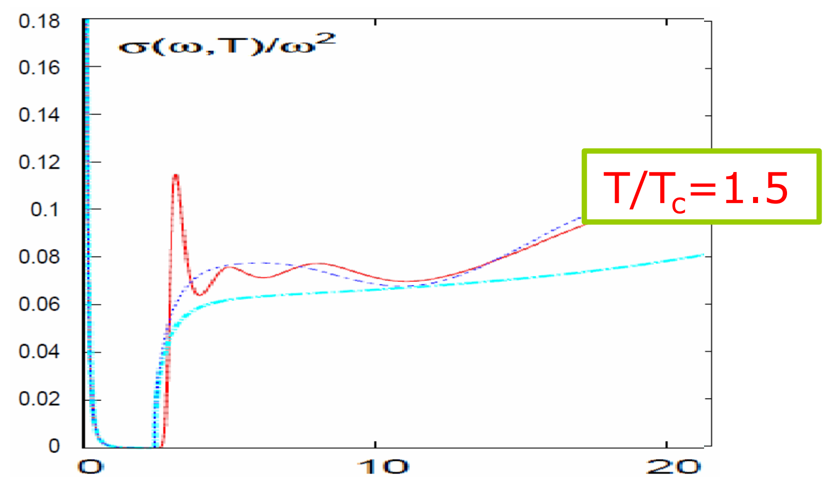
H.Ding et al. ('09)

Spectral changes in J/ψ
w/ & w/o zero mode



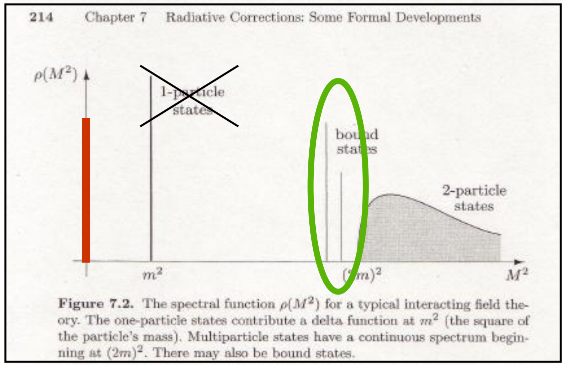
No change in J/ψ SPF
within statistical error

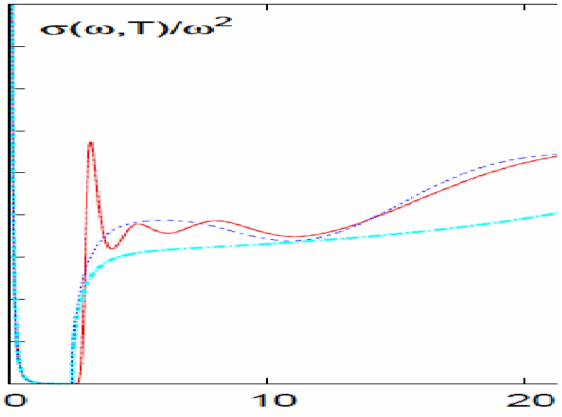




Zero mode & MEM results

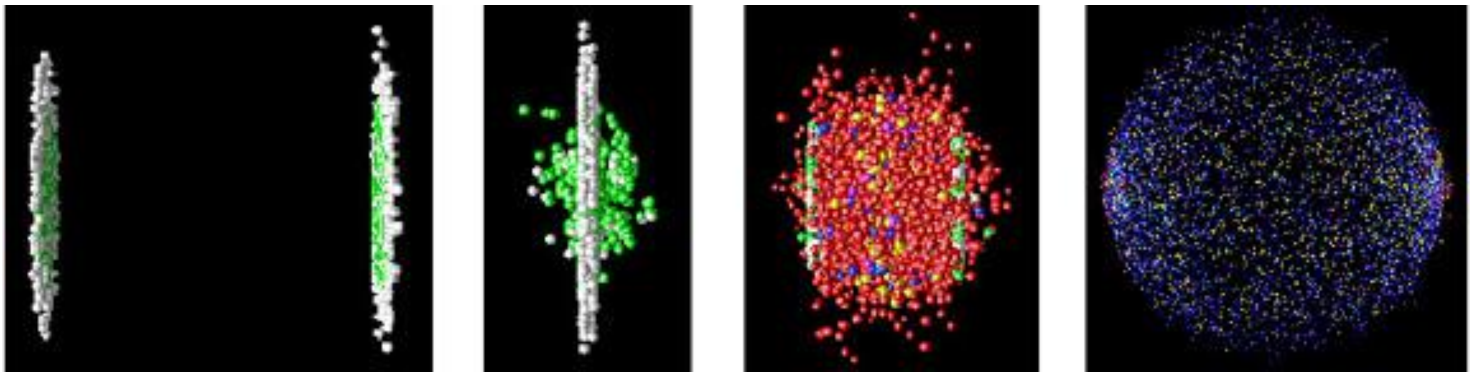
- No significant change in correlators at T>0
  except for the zero mode effect.
- Zero mode is not relevant to
  charmonium dissociations.
- The default model is necessary in MEM analysis.
  No good default model for charmonium SPFs.
  default model dependence
  → a systematic error in MEM
- T. Ding et al. ('09) shows that
  both SPFs w/ & w/o J/ψ peak can be
  extracted from common charmonium
  correlator at 1.5T_c by MEM.





Contents of this talk

from the Phenix group web-site



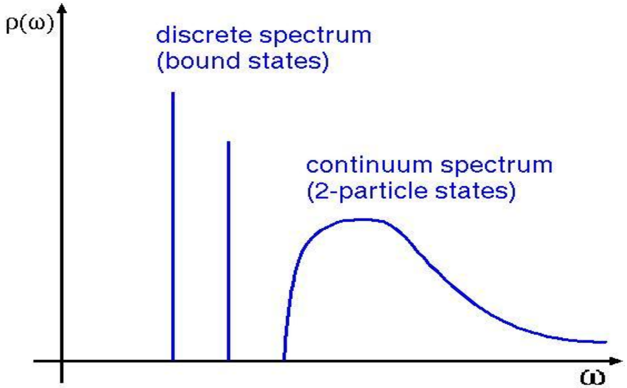
- Introduction
  - -- J/ψ suppression
  - -- Lattice studies with Maximum Entropy Method (MEM)
  - -- Sequential J/ψ suppression
- Zero mode contributions
- Other approaches to study charmonium dissociation
- Summary

Spectral functions in a finite volume

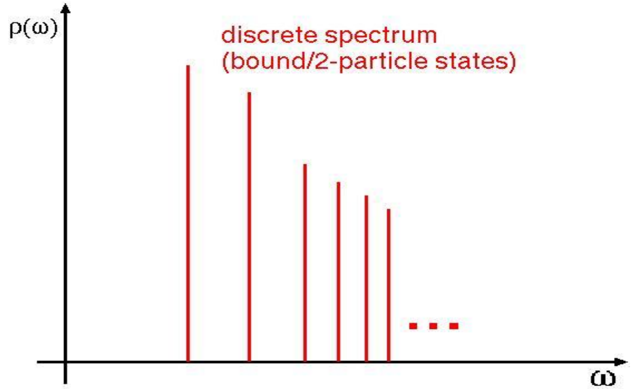
Momenta are discretized in finite ($V=L^3$) volume

$p_i/a = 2n_i\pi/L$ ($n_i=0,\pm1,\pm2,\ldots$) for Periodic boundary condition

infinite volume case



finite volume case

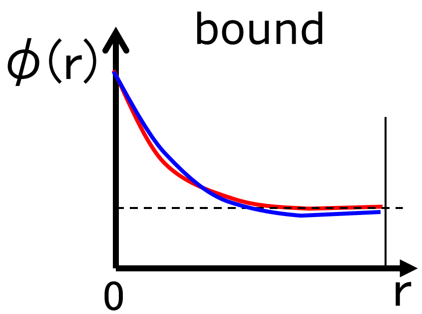


In a finite volume (e.g. Lattice simulations),
discrete spectra does not always indicate bound states !

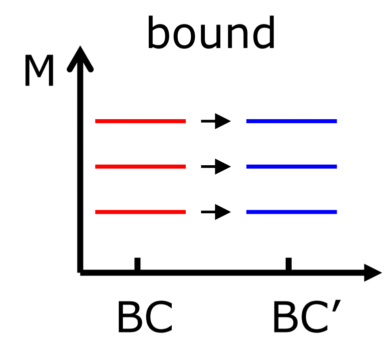
Other approaches to study charmonium dissociation

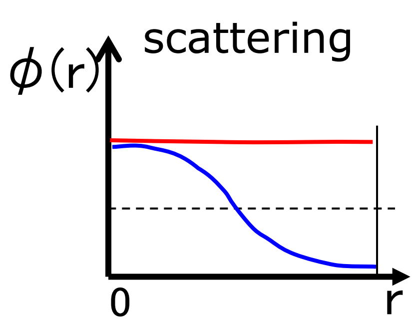
Quark boundary conditions (B.C.) in space
(finite volume on the lattice)

H. Iida et al. ('06)

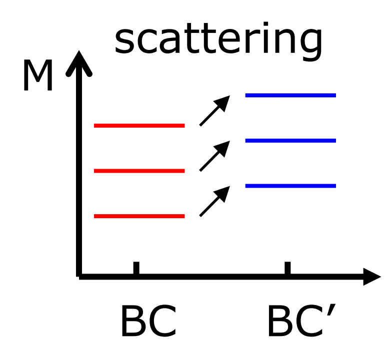


The wave functions are localized,
their energies are insensitive to B.C.

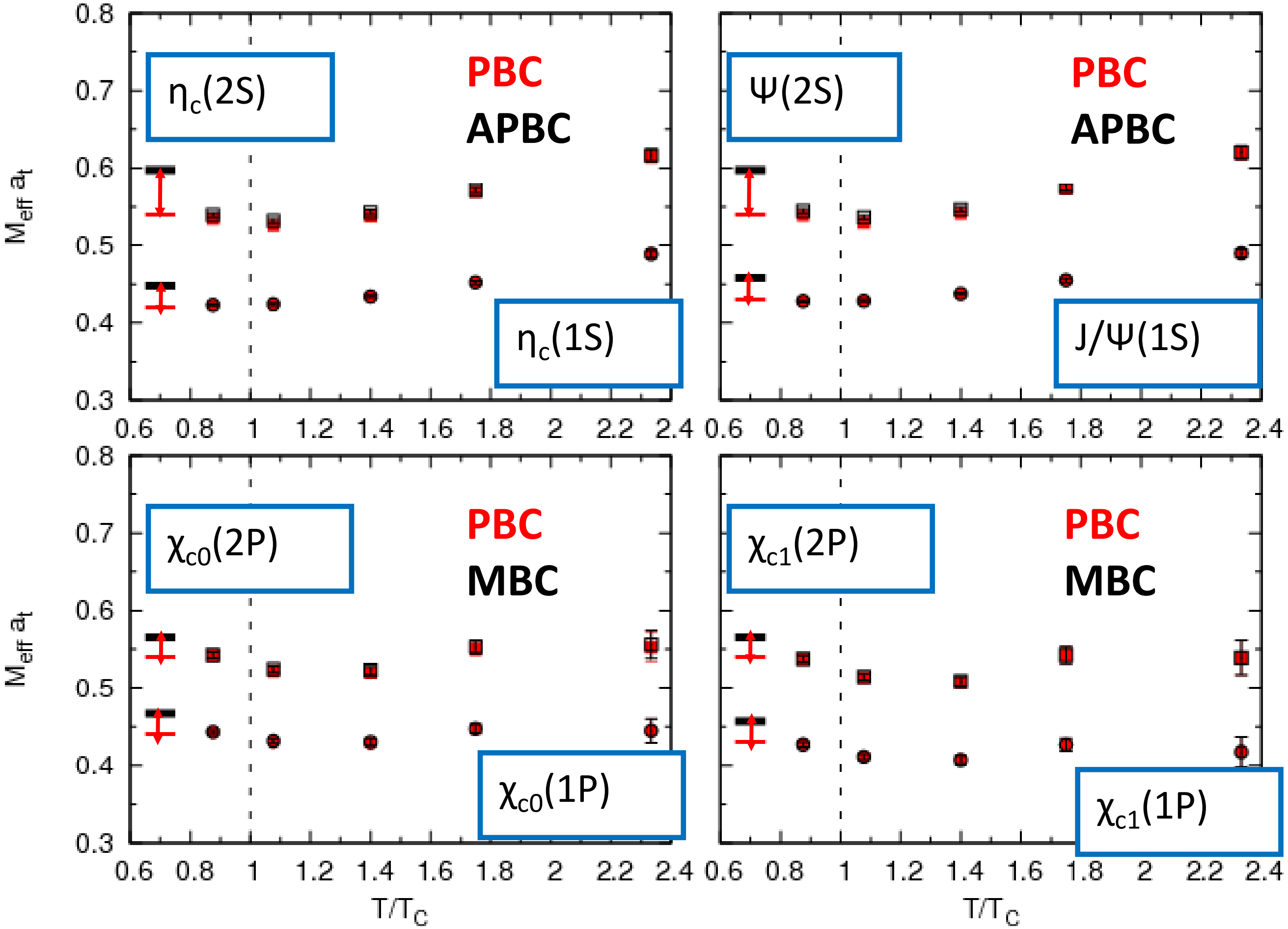




The momenta depends on BC,
the scattering state energies
are sensitive to B.C.



Charmonium spectra in various boundary conditions



$$q(x_i + L_i) = b_i q(x_i)$$

$b_i = 1$: periodic

$b_i = -1$: anti-periodic

PBC : b=(1, 1, 1)

APBC : b=(-1,-1,-1)

MBC : b=(-1, 1, 1)

an expected gap in $V=(2\text{fm})^3$ (free quark case) ~ 200MeV

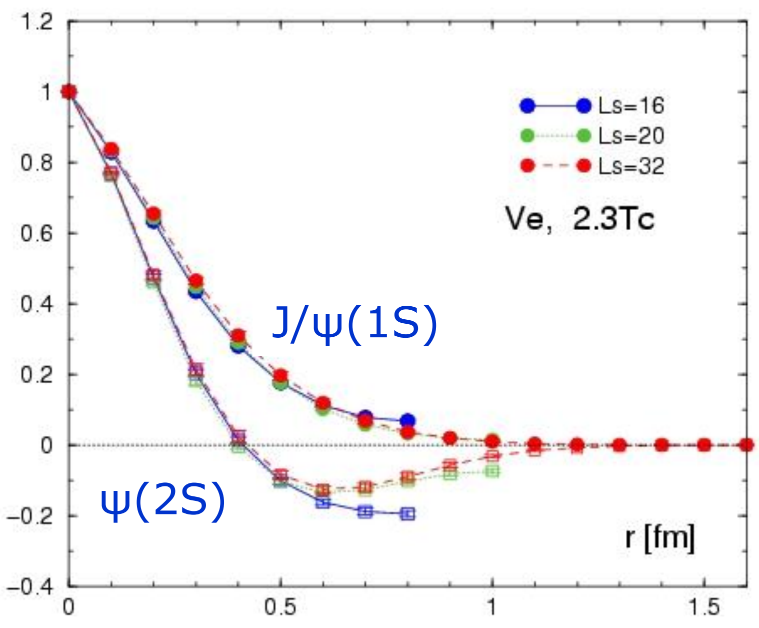
- No significant differences in the different B.C.

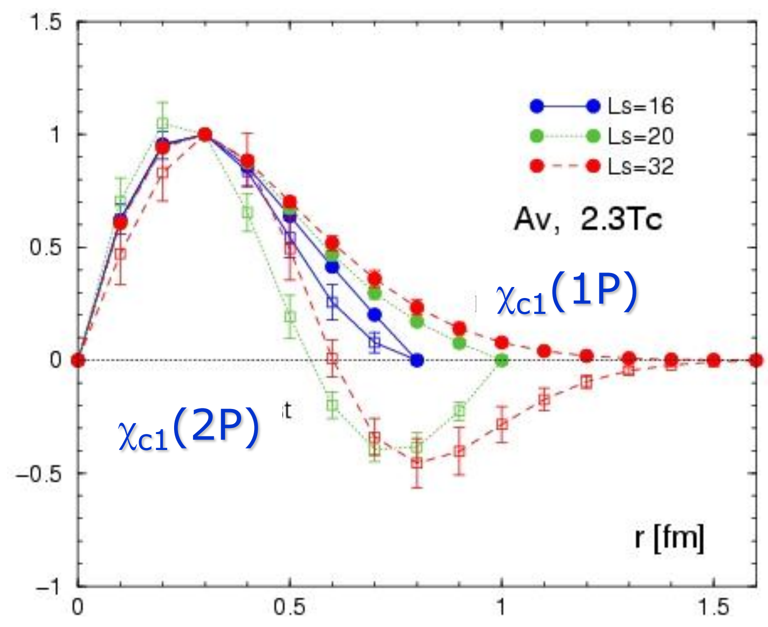
H. Ohno et al. ('08)

Charmonium wave function on the lattice

(Bethe-Salpeter) “Wave function” at $T=2.3T_c$

H. Ohno et al. (’08)





- Clear signals of bound states even at $T=2.3T_c$

Summary on lattice studies of charmonium dissociations

- Because of MEM results on the lattice,
  - J/ψ state survives till $1.5T_c$ or more
    and, dissociates around $1.5\text{-}2.0T_c$
  - χ_c states dissociate just above T_c

  are widely believed.

- Analysis taking the zero mode into account
  → No significant spectral changes in QGP (except for zero mode)

- MEM results include large default model dependence

- Other approaches to study charmonium dissociation
  indicate no clear signal of dissociation

Summary and Outlook

- Puzzle of J/ψ suppression in QGP
  J/ψ should dissociate at very high temperature
  because of the asymptotic freedom.

- Lattice QCD has never seen such evidences yet (except for MEM).
  High temperature calculations are time consuming on the lattice.

- Non-MEM studies at very high temperature (T/T_c=3~5) are desired.

Thank you for your attention !

Buckup slides

Wave functions at finite temperature

Temp. dependence of (Bethe-Salpeter) "Wave function"

$$BS(\vec{r},t) = \sum_{\vec{x}} \langle \bar{q}(\vec{x}+\vec{r},t)\Gamma q(\vec{x},t)\bar{q}(\vec{0},0)\Gamma q(\vec{0},0)\rangle$$
$$\Psi(|\vec{r}|,t) = BS(\vec{r},t)/BS(\vec{r}_0,t)$$

$$\Gamma = \begin{cases} \gamma_5 & \text{(Ps)} \\ \gamma_i & \text{(Ve)} \quad (i=1,2,3) \\ \sum_j \left(\overrightarrow{\partial}_j\gamma_j - \overleftarrow{\partial}_j\gamma_j\right) & \text{(Sc)} \\ \sum_{j,k}\epsilon_{ijk}\left(\overrightarrow{\partial}_j\gamma_k - \overleftarrow{\partial}_j\gamma_k\right) & \text{(Av)} \quad (i=1,2,3) \end{cases}$$

using the eigen functions of the variational method
→ we can extract the wave functions of each states

Summary and future plan

We investigated T_{dis} of charmonia from Lattice QCD
using another approach to study charmonium at T>0
without Bayesian analysis

- boundary condition dependence
- Wave function (Volume dependence)

No evidence for unbound c-c quarks up to T = 2.3 Tc

→ The result may affect the scenario of J/ψ suppression.

<u>Future plan</u>

- Interpretations of the experimental results on J/ψ suppression
- Higher Temp. calculations (T/Tc=3~5)
- Full QCD calculations (Nf=2+1 Wilson is now in progress)

Maximum Entropy Method (MEM)

<u>Other lattice studies:</u>

T.Umeda et al.('02), S.Datta et al.('04),
Asakawa&Hatsuda('04), A.Jakovac et al.('07), G.Aatz et al.('06)

→ all calculations conclude that J/ψ survives till $1.5T_c$ or higher