In-medium Spectral Functions in Lattice QCD

T. Hatsuda (Univ. Tokyo)

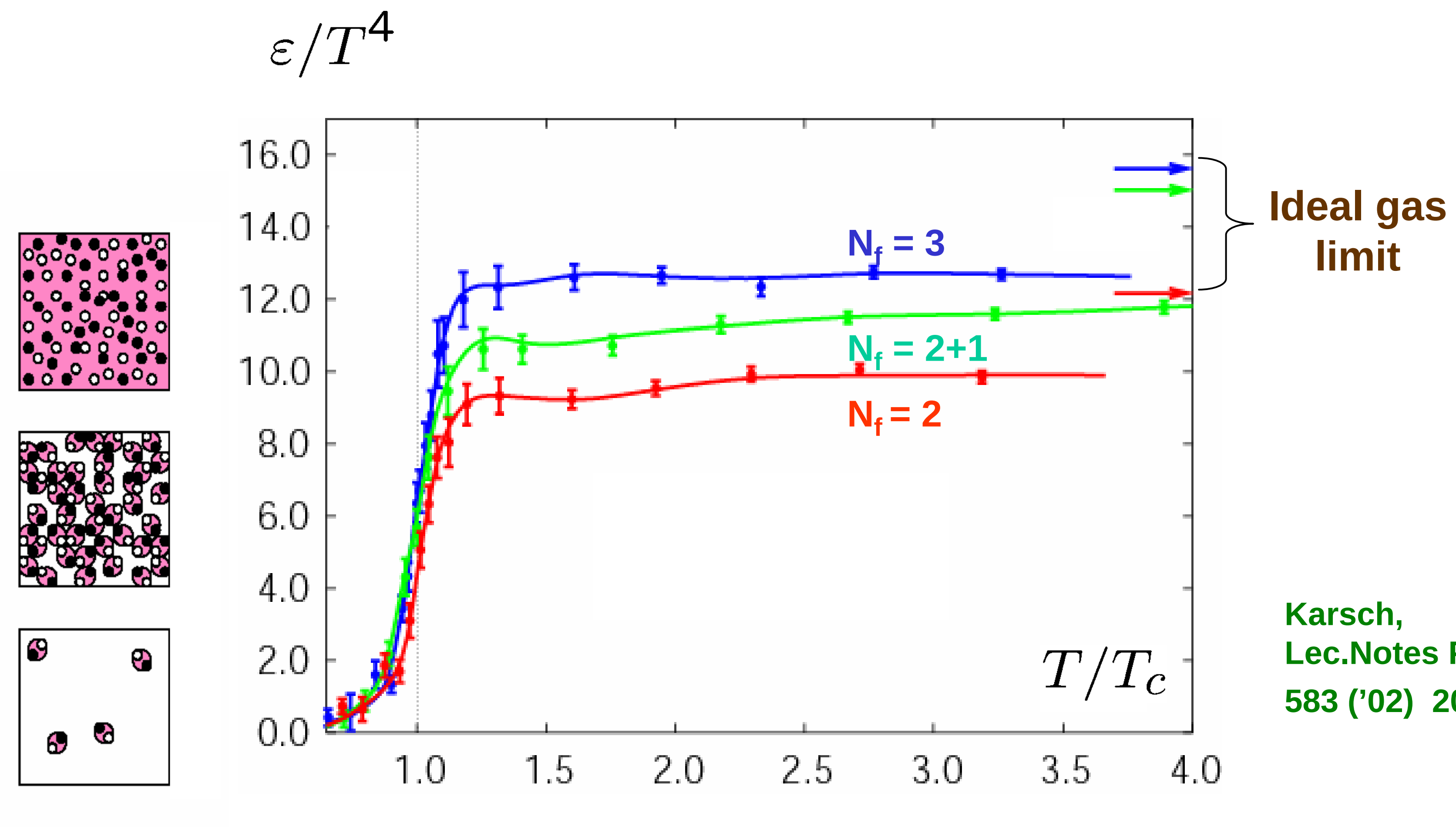
1. Are hadrons alive above T_c ?
   – original questions and ideas

2. Spectral functions in lattice QCD
   – general concepts

3. J/**ψ**, **η** $_c$ and **φ** in QGP
   – results of quenched lattice QCD simulations

4. Summary and outlook

Phase transition on the lattice



Karsch,
Lec.Notes Phys.
583 ('02) 209

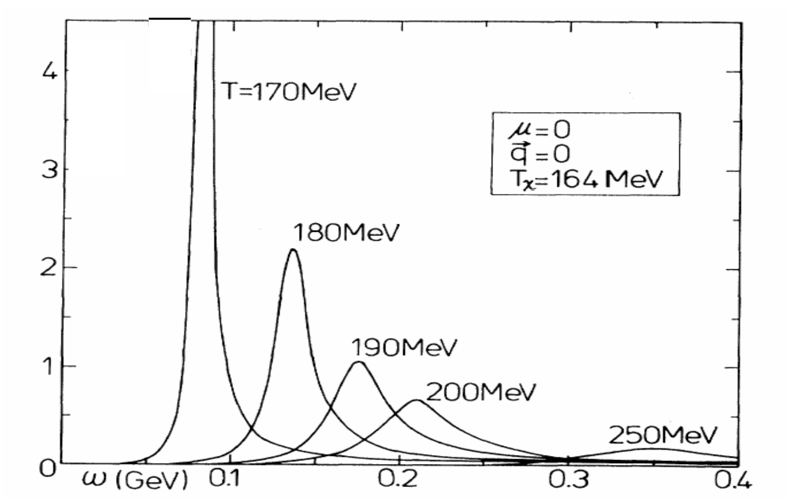
Hadrons above T_c ?

[Original questions in 1985]

1. Hadronic modes (σ, π) : para-pion by strong correlations above T_c

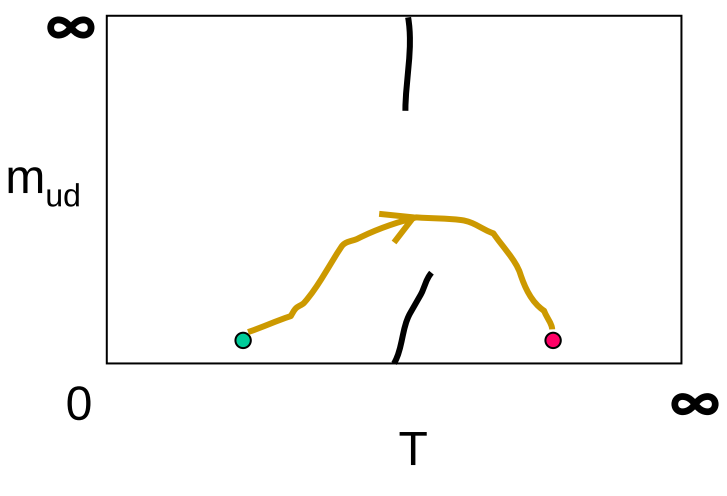
⇔ para-magnon
para-superconductivity
(pseudo-gap in high T_c SC)

Fluctuation effect in hot qurak matter:
Kunihiro and T.H., Phys. Rev. Lett. 55 (1985) 88



2. Light color-singlet modes by dynamical confinement above T_c

Conjecture concerning the modes of excitations in QGP:
DeTar, Phys. Rev. D32 (1985) 276



Fluctuation Effects in Hot Quark Matter: Precursors of Chiral Transition at Finite Temperature

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(Received 2 May 1985)

Fluctuations of the order parameter of chiral transition in a hot and dense quark gas are examined in the random-phase approximation with the use of a QCD-motivated effective Lagrangean. We show that there arise soft modes having a large strength and a narrow width above the critical temperature, which are analogous to the fluctuations of the order parameter in a superconductor above the critical point. It is argued that the modes contribute to the cooling of the quark-gluon

PHYSICAL REVIEW D VOLUME 32, NUMBER 1 1 JULY 1985

Conjecture concerning the modes of excitation of the quark-gluon plasma

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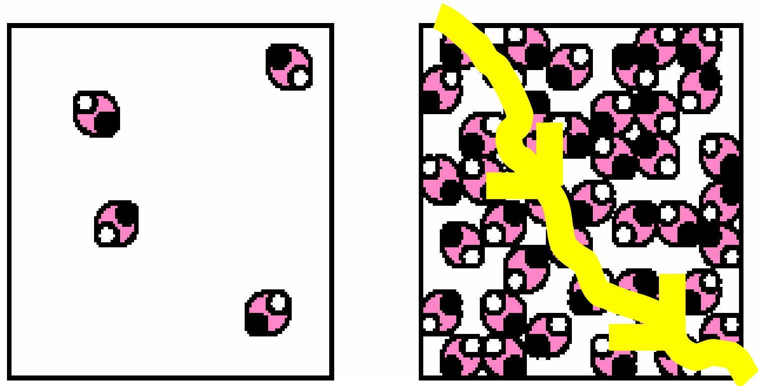
(Received 19 February 1985)

It is a widely held belief that at temperatures much higher than the confinement scale of quantum chromodynamics (QCD), quarks and gluons become free, giving rise to a new form of matter, called the quark-gluon plasma. It is conjectured here that the characterization of the plasma as a free or weakly interacting gas of quarks and gluons is valid only for short distances and short time scales of the order $1/T$, but that at scales larger than $1/g^2T$ (where g^2 is the running QCD coupling) the plasma exhibits confining features similar to that of the low-temperature hadronic phase. The confining features are manifest in the long-range, i.e., long-wavelength, low-frequency, modes of the plasma.

3. Percolation picture and hadrons above T_c

T.H., ('97)

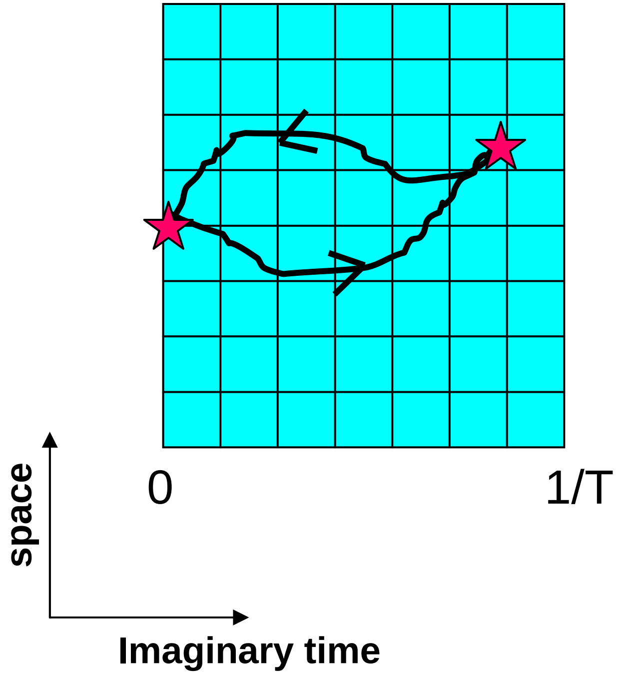
Dilute gas	Percolation transition	Closely packed
$T \sim 0$	$T \sim T_c$	$T \sim T_c^*$



Volume fraction: $\frac{N_\pi(T_c)\cdot v_\pi}{V} \simeq 0.35$ $\quad \frac{N_\pi(T_c^*)\cdot v_\pi}{V} \simeq 1$

$$T_c^* \simeq \left(\frac{1}{0.35}\right)^{1/3} T_c = 1.4 T_c$$

Spectral functions from lattice QCD



How to extract spectral structures at finite T ?

Spectral function from lattice QCD

$$D(\tau,\vec{p}) = \int \left\langle J^{+}(\tau,\vec{x}) J(0,0) \right\rangle e^{i\vec{p}\vec{x}} d^3x$$

$$= \int K(\tau,\omega) A(\omega,\vec{p})\, d\omega$$

Lattice data

"Laplace" kernel

$K(\tau,\omega)$

$= e^{-\omega\tau} / (1 \mp e^{-\omega/T})$

Spectral Function using Maximum Entropy Method (MEM)

P[A|D] ~ P[D|A] P[A]

1. No parametrization on A
2. Unique solution
3. Error analysis possible

Asakawa, Nakahara & T.H, Phys. Rev. D60 ('99) 091503

Asakawa, Nakahara & T.H., Prog. Part. Nucl. Phys. 46 ('01) 459

Spectral function from lattice QCD

$$D(\tau,\vec{p}) = \int \left\langle J^{+}(\tau,\vec{x})J(0,0)\right\rangle e^{i\vec{p}\vec{x}} d^3x$$

$$= \int K(\tau,\omega)\, A(\omega,\vec{p})\, d\omega$$

Lattice data

"Laplace" kernel

$$K(\tau,\omega)$$

$$= e^{-\omega\tau}/(1 \mp e^{-\omega/T})$$

Sasaki, Sasaki + TH, ('04)

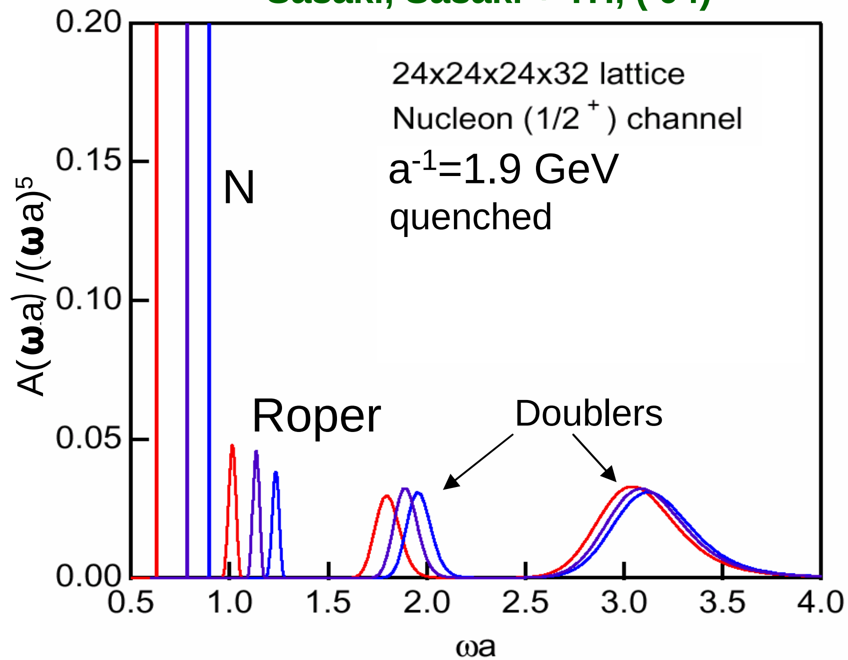
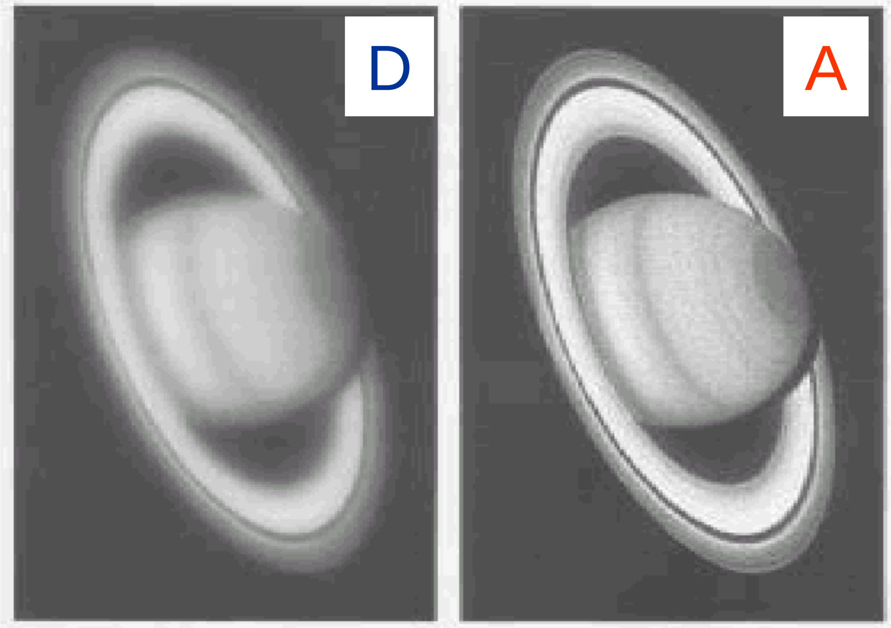


Image reconstruction by MEM

$$D = K \times A$$

The girl's portrait

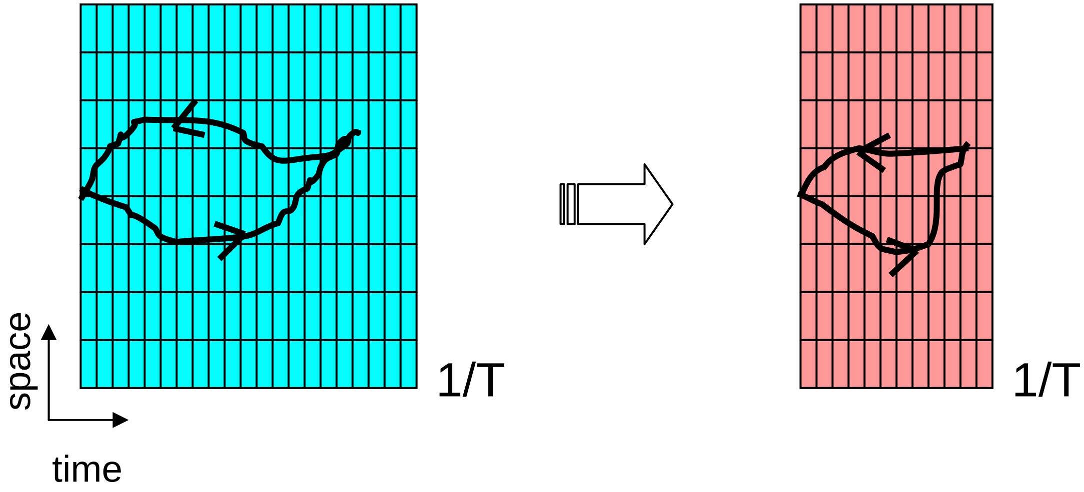
The Image of Saturn



From N. Wu, "The Maximum Entropy Method" (1997)

Hadrons above Tc
from lattice QCD

Asakawa + T.H., Phys. Rev. Lett. 92 ('04) 012001
J. Phys.G30 ('04) S1337

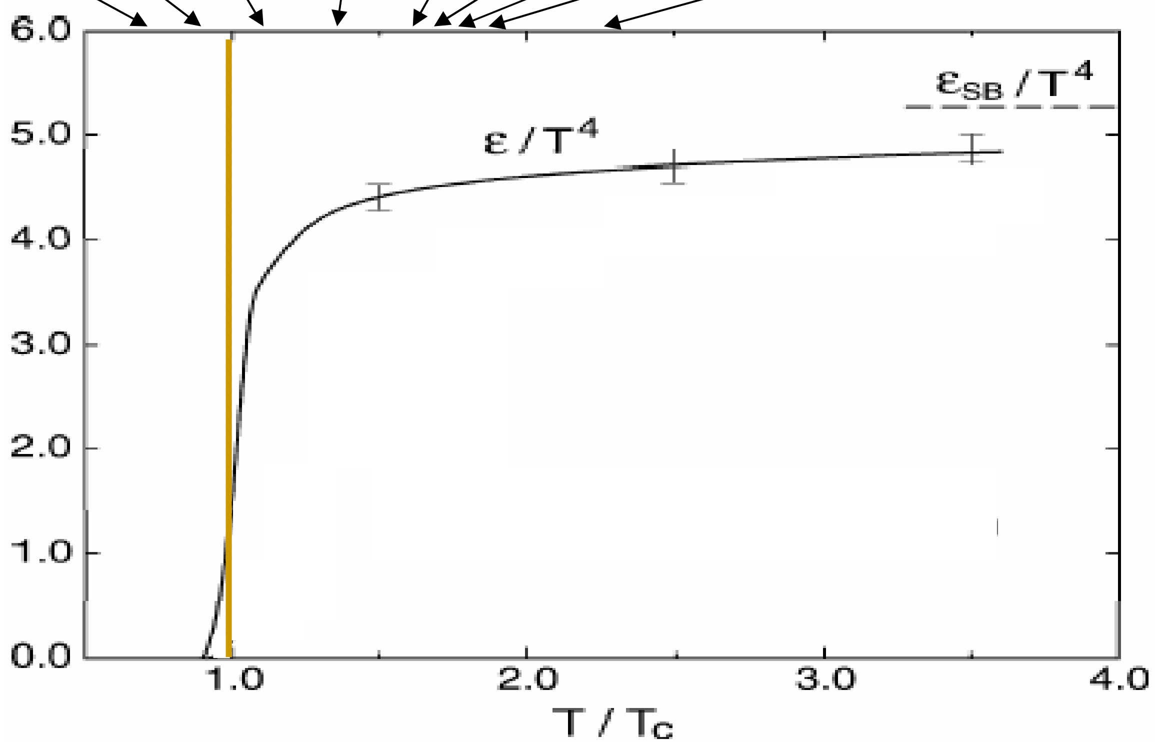


a_s = 0.04 fm & a_τ = 0.01 fm

32^3 x 96 (T/T$_c$=0.8) ⇨ 32^3 x 32 (T/T$_c$=2.3)

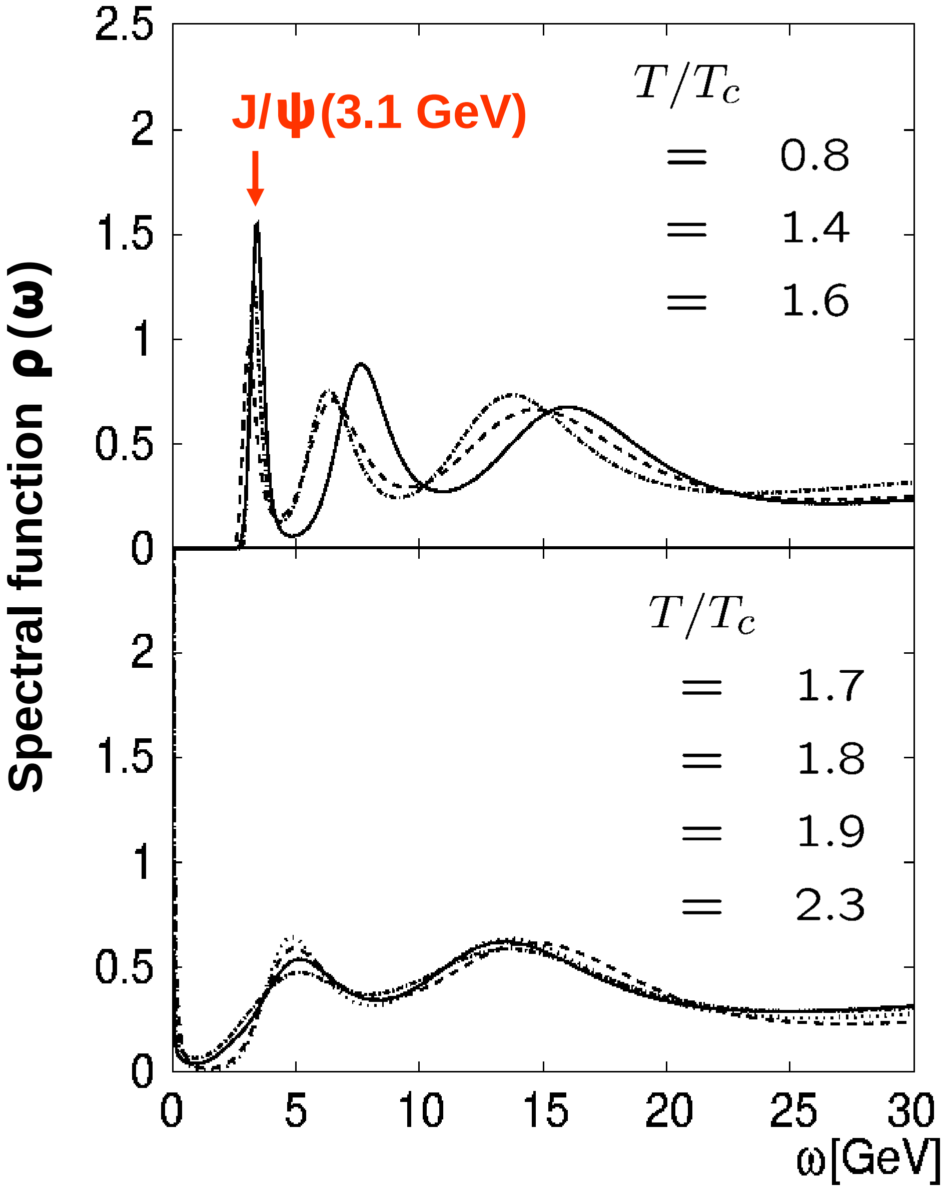
Range of temperature covered

N_τ	96	80	72	54	46	44	42	40	32
T / T_c	0.78	0.93	1.04	1.38	1.62	1.70	1.78	1.87	2.33
# of Config.	194	110	150	150	182	180	180	181	141



- quenched
- Wilson fermion
- no improved action

J/ψ and η_c *above T_c* *(quenched simulation)*



1. J/ψ survives up to 1.6 Tc

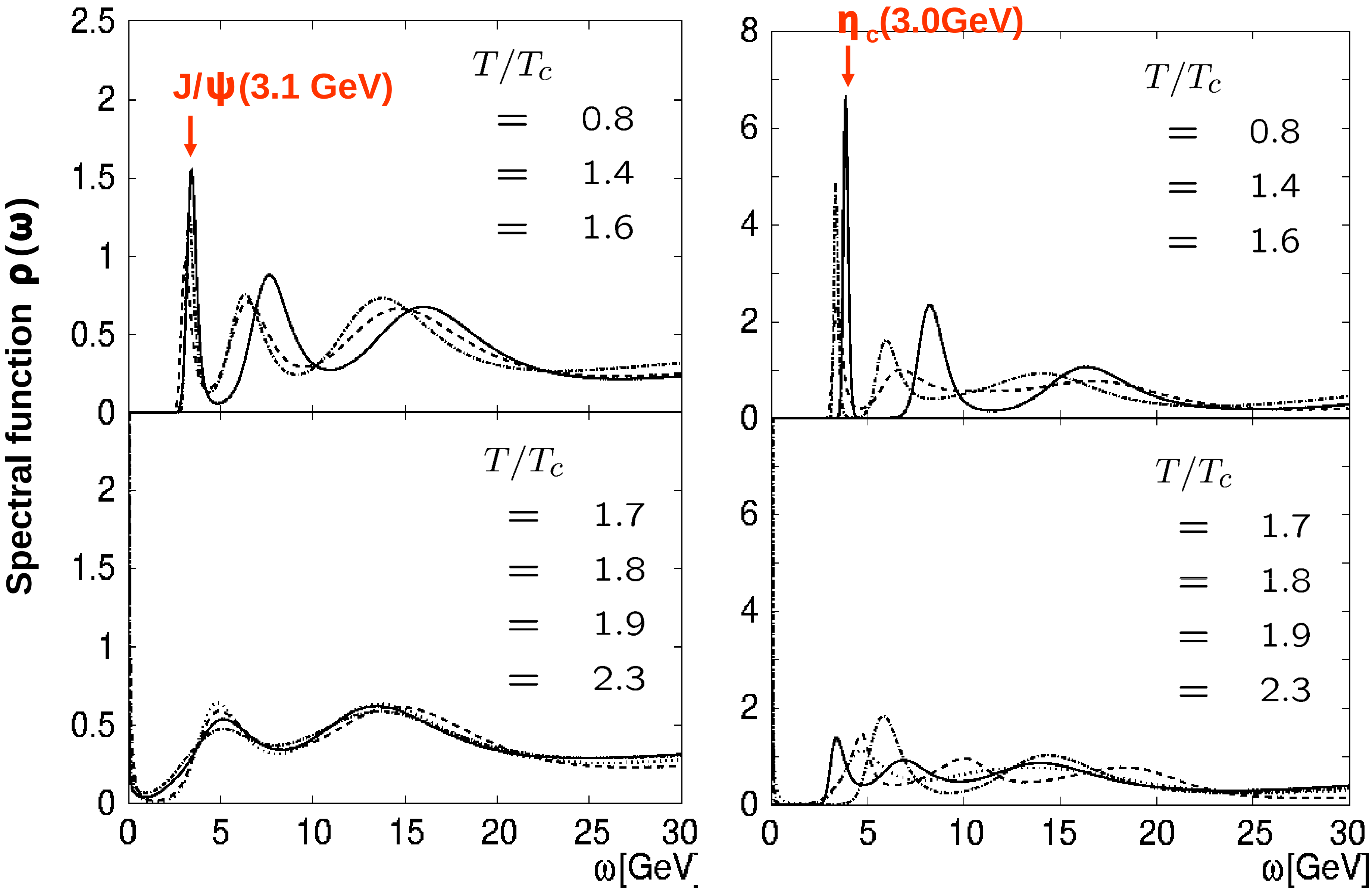
2. J/ψ disappears in 1.6 Tc < T < 1.7 Tc

Asakawa & Hatsuda, PRL 92 ('04) 012001

⇕

Umeda et al, hep-lat/0401010
Datta et al., PRD 69 ('04) 094507

J/ψ and η_c *above T_c* *(quenched simulation)*



1

Frequently asked questions

Q. What are the 2^{nd} and 3^{rd} peaks ?

A. Likely to be bound states of Wilson doublers ($\boldsymbol{\omega}$~1/a)

Q. Thermal width ?

A. Integrated strength at the peak ⇔ pole residue (decay const.)

Q. What will happen in full QCD ?

A. We do not know, but

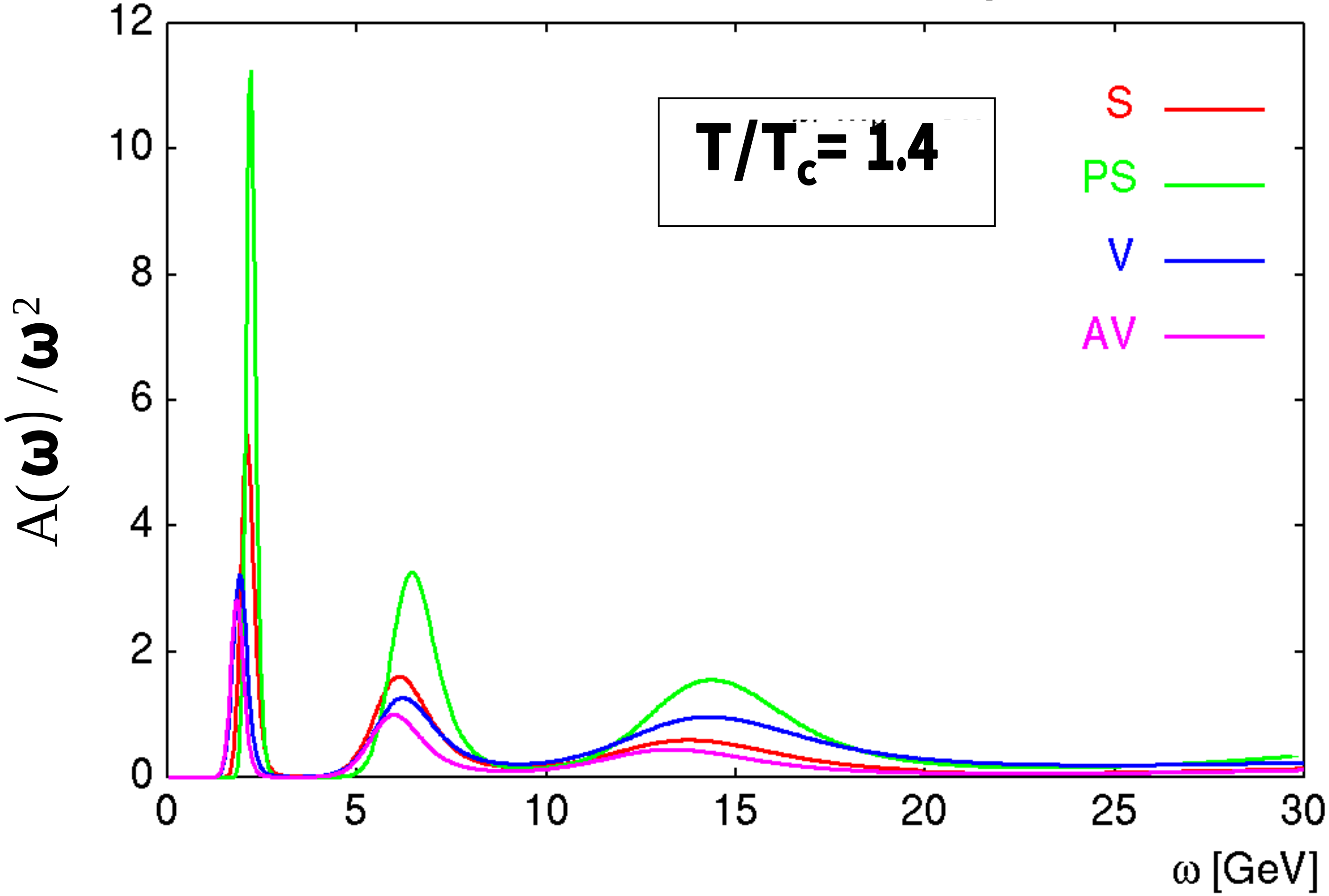
$$n_{quench} \propto 16 \times T_c^3 = 16 \times (270 \text{ MeV})^3$$
$$n_{full} \propto (16+21) \times T_c^3 = 37 \times (175 \text{ MeV})^3 = 0.62\, n_{quench}$$

Q. What about light mesons such as $\boldsymbol{\rho}$, $\boldsymbol{\omega}$, $\boldsymbol{\phi}$ ….. ?

A. Next slide

Hot $s\bar{s}$

$M_\phi(T=0)=1.03$ GeV



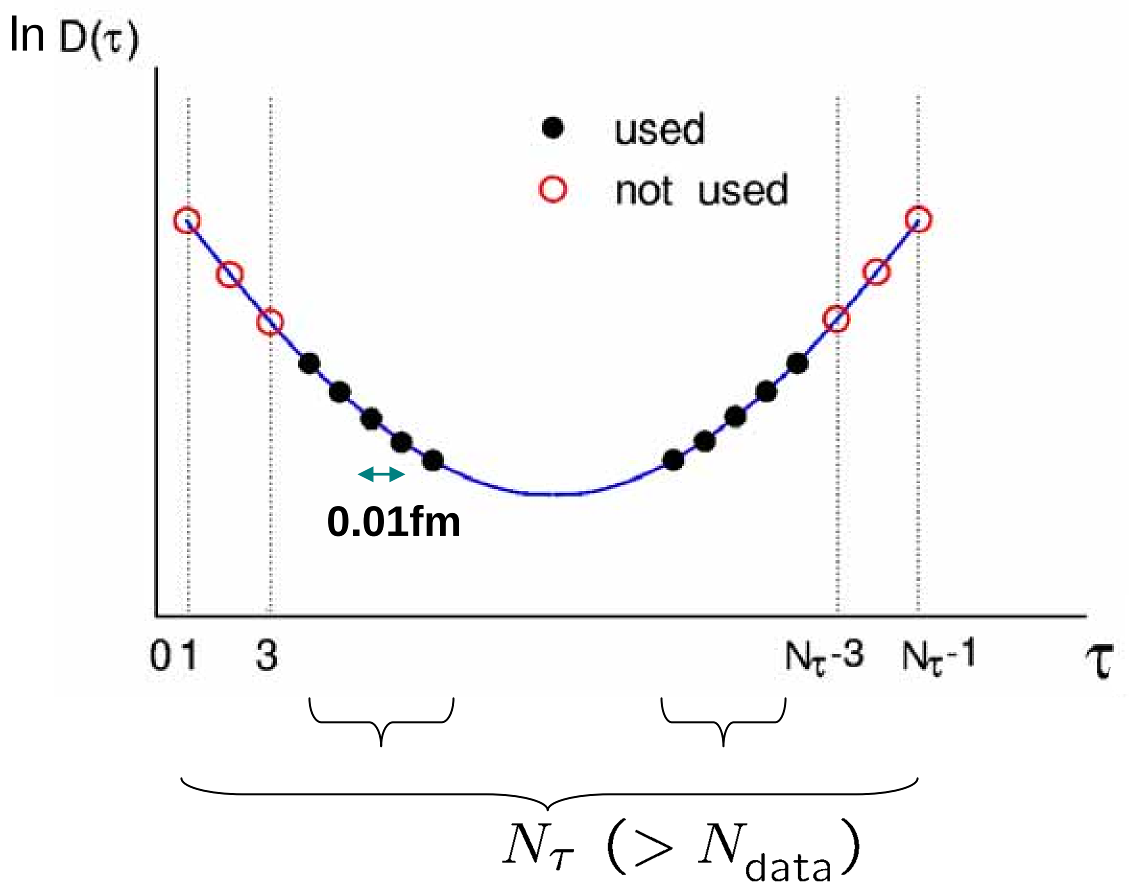
Asakawa & T.H.,
Prog. Theor. Phys. Suppl. 149 ('03)

MEM analysis : two crucial steps

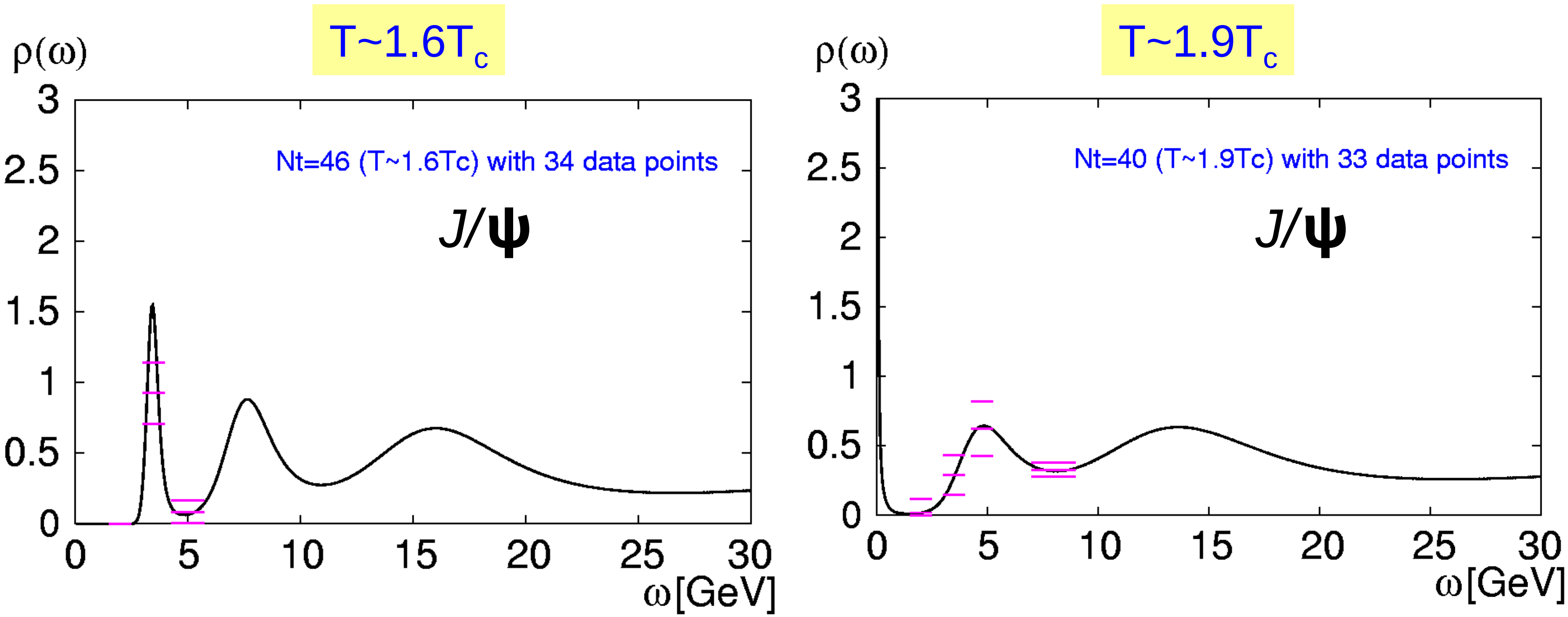
I. Put MEM error to the spectral func.
II. Check N_{data}-dependence of spectral func.

To avoid fake peaks

to avoid fake smearing of peaks

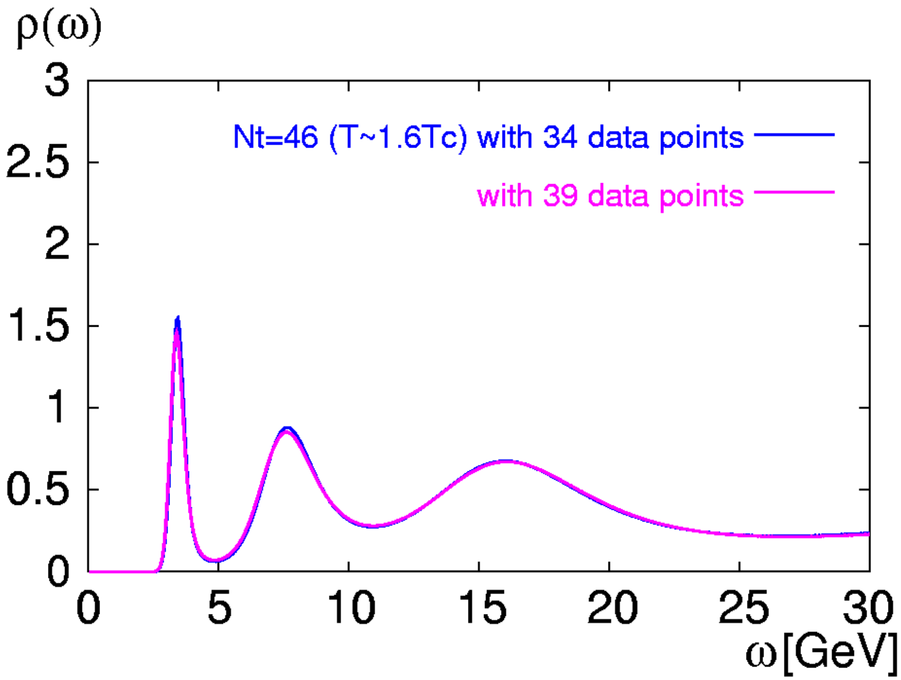


J/ψ above T_c (MEM error bars)

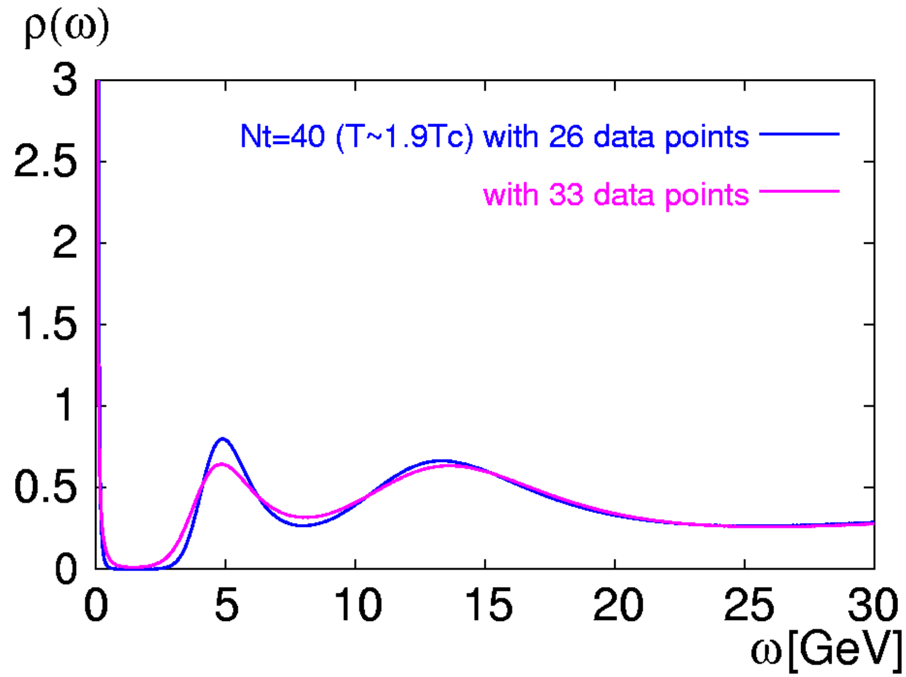


J/ψ above T_c (N_τ dependence)

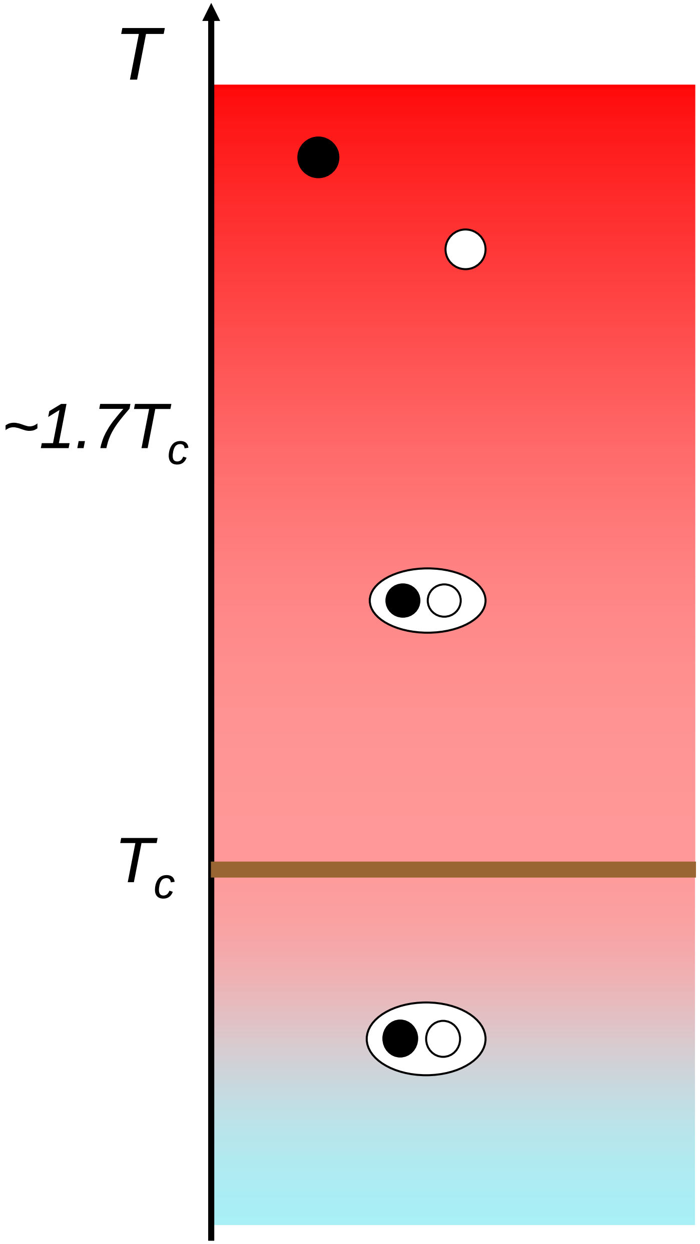
J/ψ at $T/T_c = 1.6$



J/ψ at $T/T_c = 1.9$



Lessons from quenched QCD

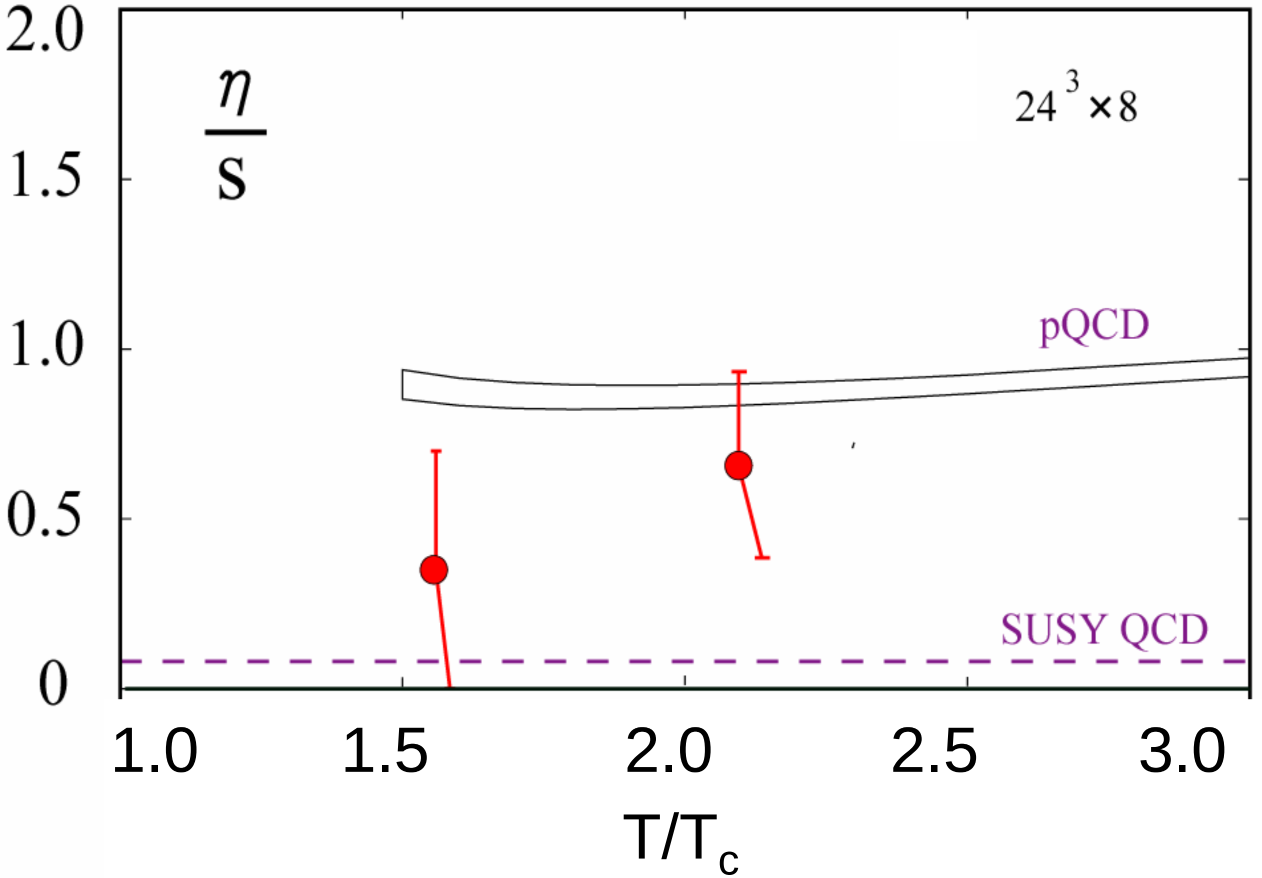


Weakly interacting matter
→ viscous fluid ?

Strongly interactiing matter
→ perfect fluid ?

Shear viscosity *(quenched QCD simuation)*

Nakamura and Sakai, hep-lat/0406009

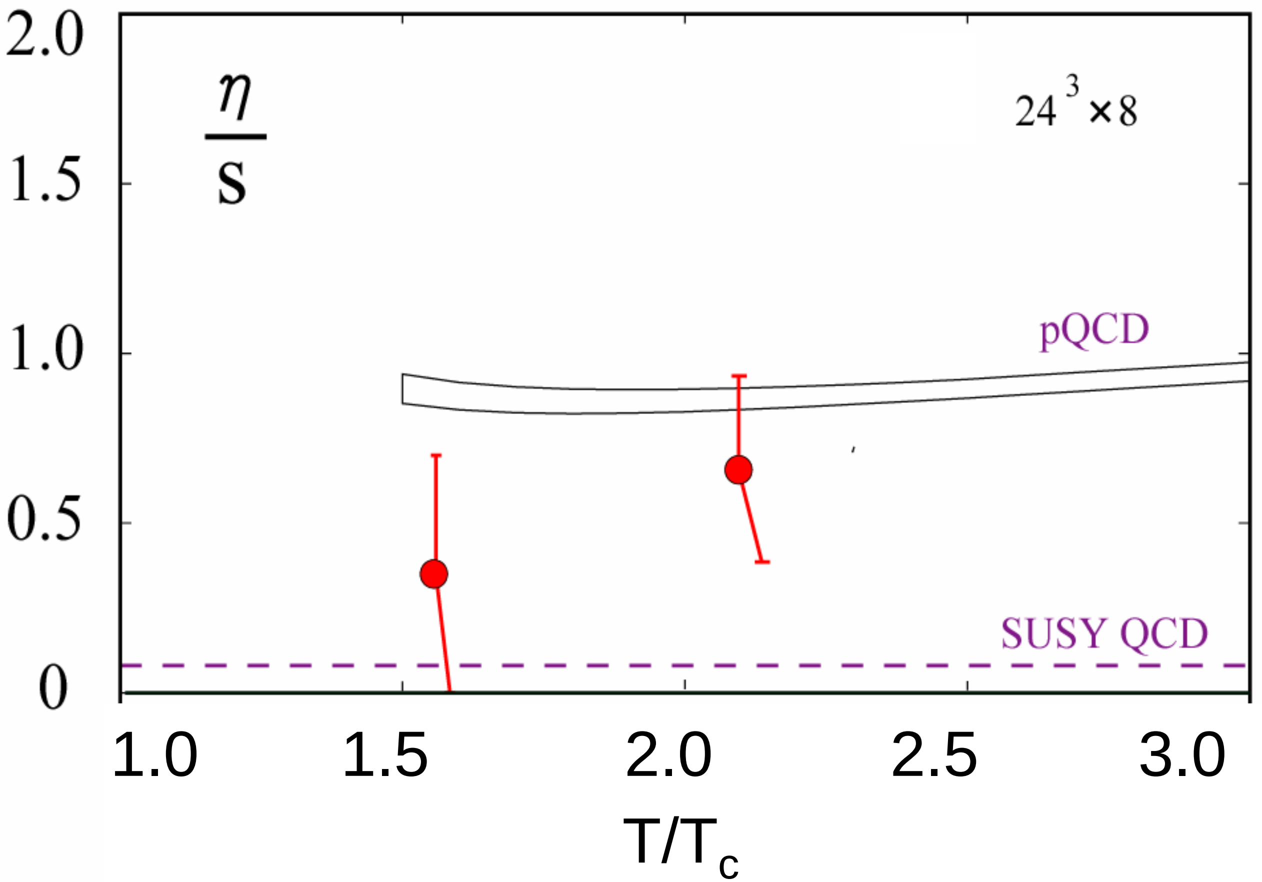


Baym, Monien, Pethick & Ravenhall ('90)
Arnold, Moore & Yaffe, ('03)

Kovtun, Son & Starinets ('04)

Shear viscosity *(quenched QCD simuation)*

Nakamura and Sakai, hep-lat/0406009



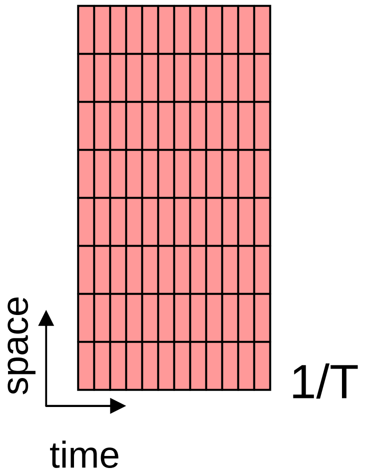
Viscous fluid
R << 1

Perfect fluid
R >> 1

"Reynolds number"

$$R = \left(\frac{\frac{4}{3}\eta + \zeta}{s} \cdot \frac{1}{T\tau} \right)^{-1}$$

Summay and outlook



1. Spectral Functions from lattice QCD + MEM

quenched simulation on an anisotropic lattice

T/T_c = 0.8, 1.4, 1.6, 1.7, 1.8, 1.9, 2.3 (0.93, 1.04)

2. J/ψ and η_c survive up to T=1.6-1.7 T_c in quenched QCD

Why ? ⇔ comparison to models **Digal et al., Shuryak-Zahed, Brown et al.**

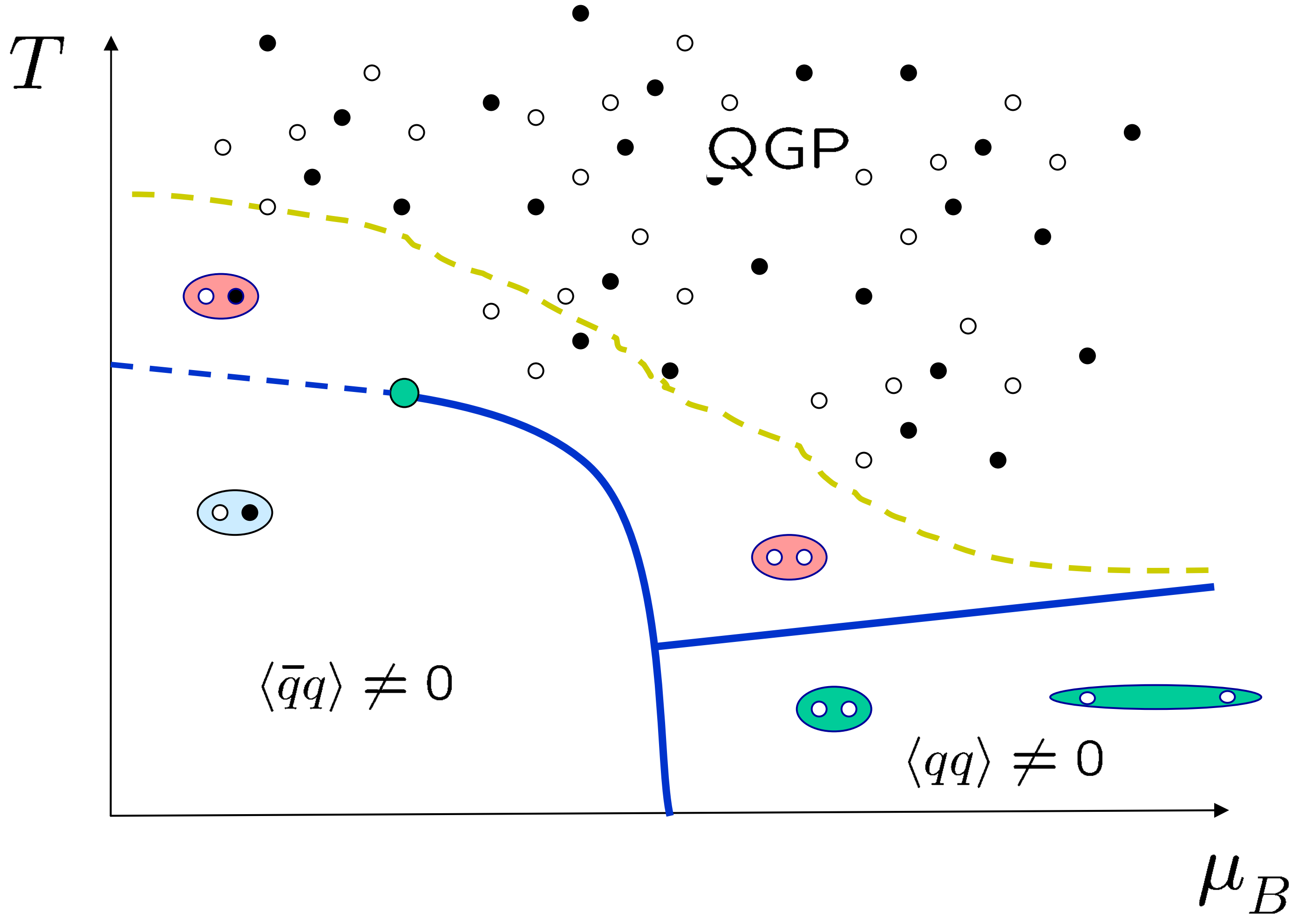
⇔ comparison to spatial wave function **QCD-TARO Coll.**

What about χ_c ? What about finite p ? **Datta et al.**

What about light hadrons ?

3. Full QCD : very important

QCD phase structure



BCS-BEC crossover

Leggett ,
Lec. Notes in Phys. ('82)

Abuki, Itakura & T.H.
Phys. Rev. D ('02)

QCD phase structure