QCD phase transition and the properties of the deconfined phase at T>0

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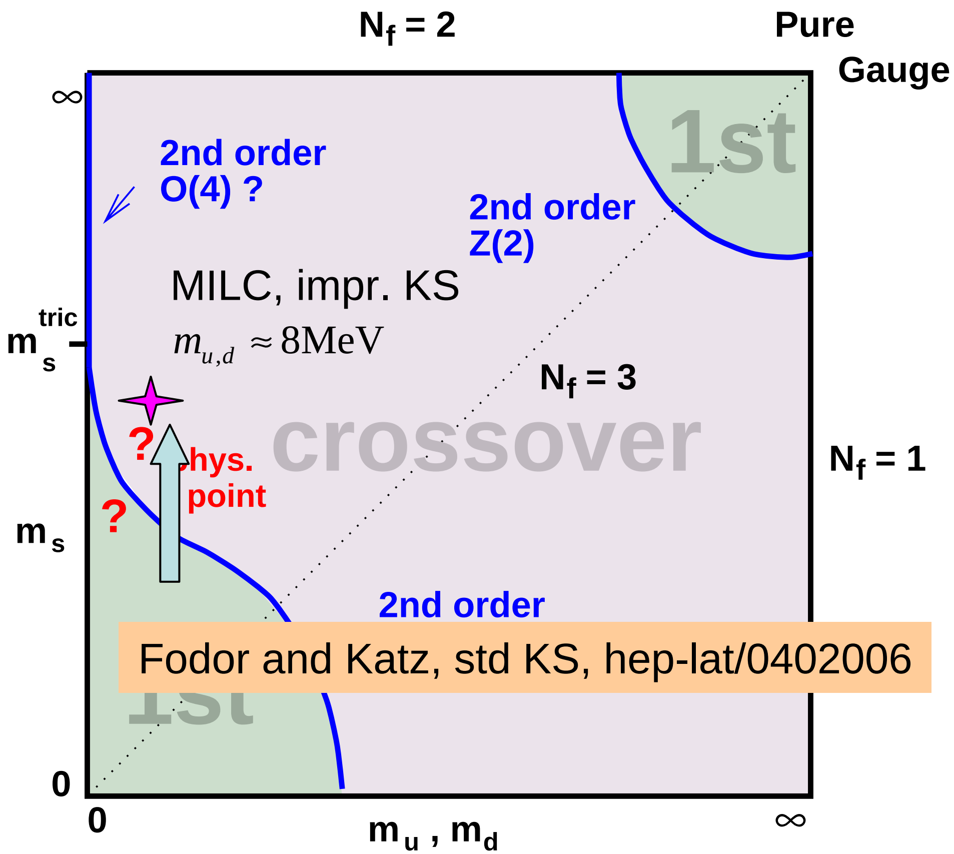
- Deconfinement/chiral transition in QCD
- Exploring the properties of hot matter with $Q\bar{Q}$ pair
(potential, spectral functions etc. in the deconfined phase)

QCD phase diagram at T>0

Lattice calculations of QCD for physical value of the quark (pion) masses is extremely difficult:



Physical point: (MILC Coll.) hep-lat/0405022

$$m_{u,d}(\mu^{\overline{MS}} = 2GeV) = 2.8MeV$$

$$m_s(\mu^{\overline{MS}} = 2GeV) = 76MeV$$

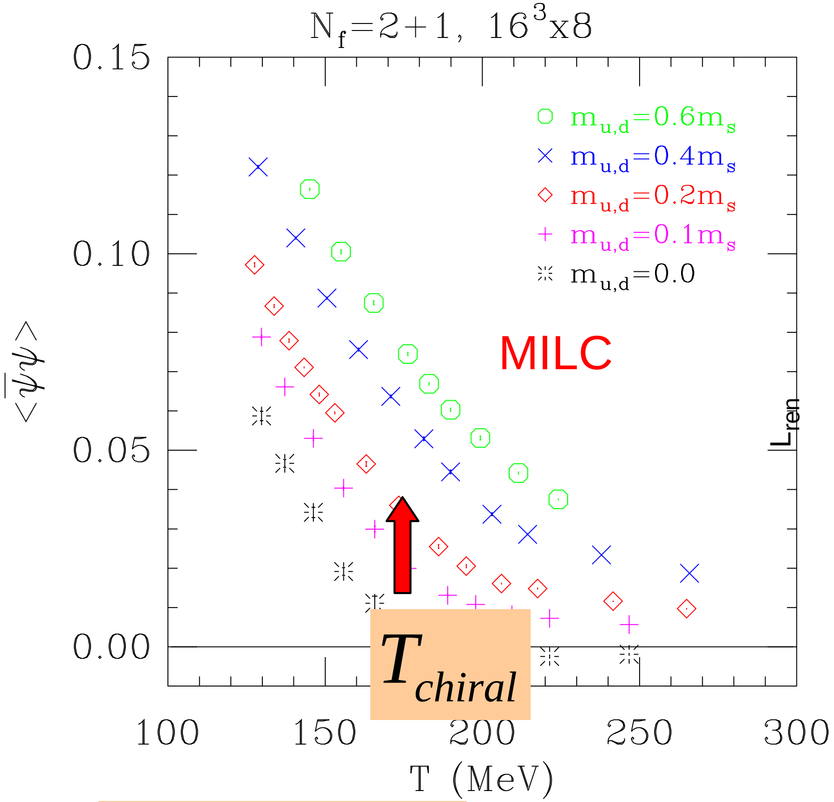
Transition in "real" QCD is most likely a rapid crossover

Bielefeld, Coulombia, MILC

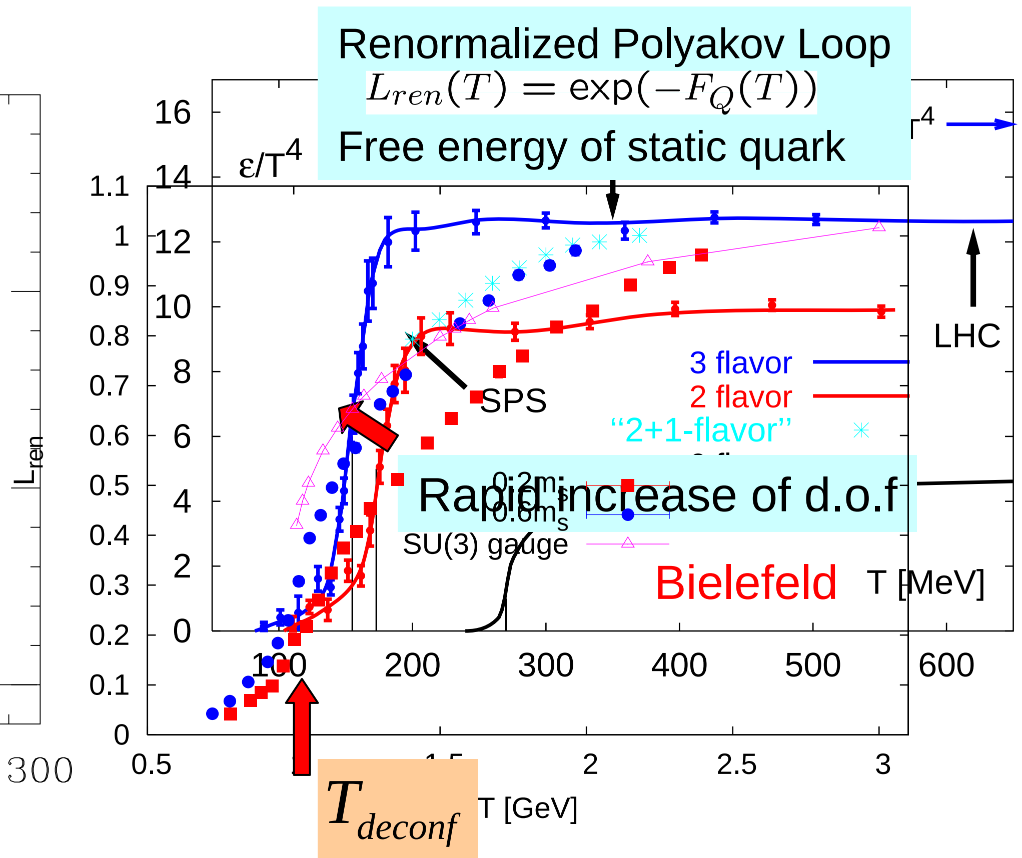
Staggered fermions violate flavor symmetry, $\to U(1) \otimes U(1)$ $\in SU_A(3)$

Chiral and deconfinement aspects of the QCD transition

Chiral transition



Deconfinement transition



$T_{chiral} \approx T_{deconf}$

Why ??

Recent meanfield considerations:

Mocsy, Sannino, Touminen, hep-ph/0401149

Testing hot matter with static quark anti-quark pair

All started with

McLerran and Svetitsky, PRD 24 (1981) 450

Matsui and Satz, PLB 178 (1986) 416

- Static quark anti-quark pair → heavy quark potentials

Time scales: $1/T < t < \infty$

Heavy quarkonia and open charm physics at T>0

- Heavy quark anti-quark pair → heavy quarkonia spectral functions

Time scales: $1/m < t < 1/mv$

Heavy quarkonia physics at T>0

- Light quark anti-quark pair → light meson spectral functions

Time scales: $t \sim 1/T$

Thermal dilepton and photons, ρ, ω, ϕ mesons

Static quark anti-quark pair in T>0 QCD

QCD partition function in the presence of static $Q\bar{Q}$ pair

McLerran, Svetitsky, PRD 24 (1981) 450

$$\frac{Z_{Q\bar{Q}}(r,T)}{Z(T)} = \int \mathcal{D}A_\mu \mathcal{D}\psi \mathcal{D}\bar{\psi} W(\vec{r}) W^\dagger(0) e^{-\int_0^{1/T} d\tau d^3x L_{QCD}}$$

$$Z(T) = \int \mathcal{D}A_\mu \mathcal{D}\psi \mathcal{D}\bar{\psi} e^{-\int_0^{1/T} d\tau d^3x L_{QCD}}$$

temporal Wilson line: $W(\vec{x}) = \mathcal{P} e^{ig\int_0^{1/T} d\tau A_0(\tau,\vec{x})} = \prod_{\tau=0}^{N_\tau - 1} U_0(\tau,\vec{x})$

Polyakov loop: $L(\vec{x}) = \mathrm{Tr}\, W(\vec{x})$

$$3 \otimes \bar{3} = 1 \oplus 8$$

⇨ Separate singlet and octet contributions using projection operators

P_1 and P_8 Nadkarni, PRD 34 (1986) 3904

Color singlet free energy:

$$\exp(-F_1(r,T)/T) = \frac{1}{Z(T)}\frac{\mathrm{Tr}P_1 Z_{Q\bar{Q}}}{\mathrm{Tr}P_1} = \frac{1}{3}\mathrm{Tr}\langle W(\vec{r})W^{\dagger}(0)\rangle$$

Color octet free energy:

$$\exp(-F_8(r,T)/T) = \frac{1}{Z(T)}\frac{\mathrm{Tr}P_8 Z_{Q\bar{Q}}}{\mathrm{Tr}P_8} =$$

$$\frac{1}{8}\langle \mathrm{Tr}W(\vec{r})\mathrm{Tr}W^{\dagger}(0)\rangle - \frac{1}{24}\mathrm{Tr}\langle W(\vec{r})W^{\dagger}(0)\rangle$$

Fix the Coulomb gauge transfer matrix can be defined

equivalent

Dressed gauge invariant Wilson line Philipsen, PLB 535 (2002) 138

$$W(\vec{x}) \rightarrow \tilde{W}(\vec{x}) = \Omega^{\dagger}W(\vec{x})\Omega(\vec{x})$$

$$\Omega = f_{\alpha}^{n},\ D_{\mu}^{2}f_{\alpha}^{(n)} = \lambda_n f_{\alpha}^{(n)},\ \tau = 0$$

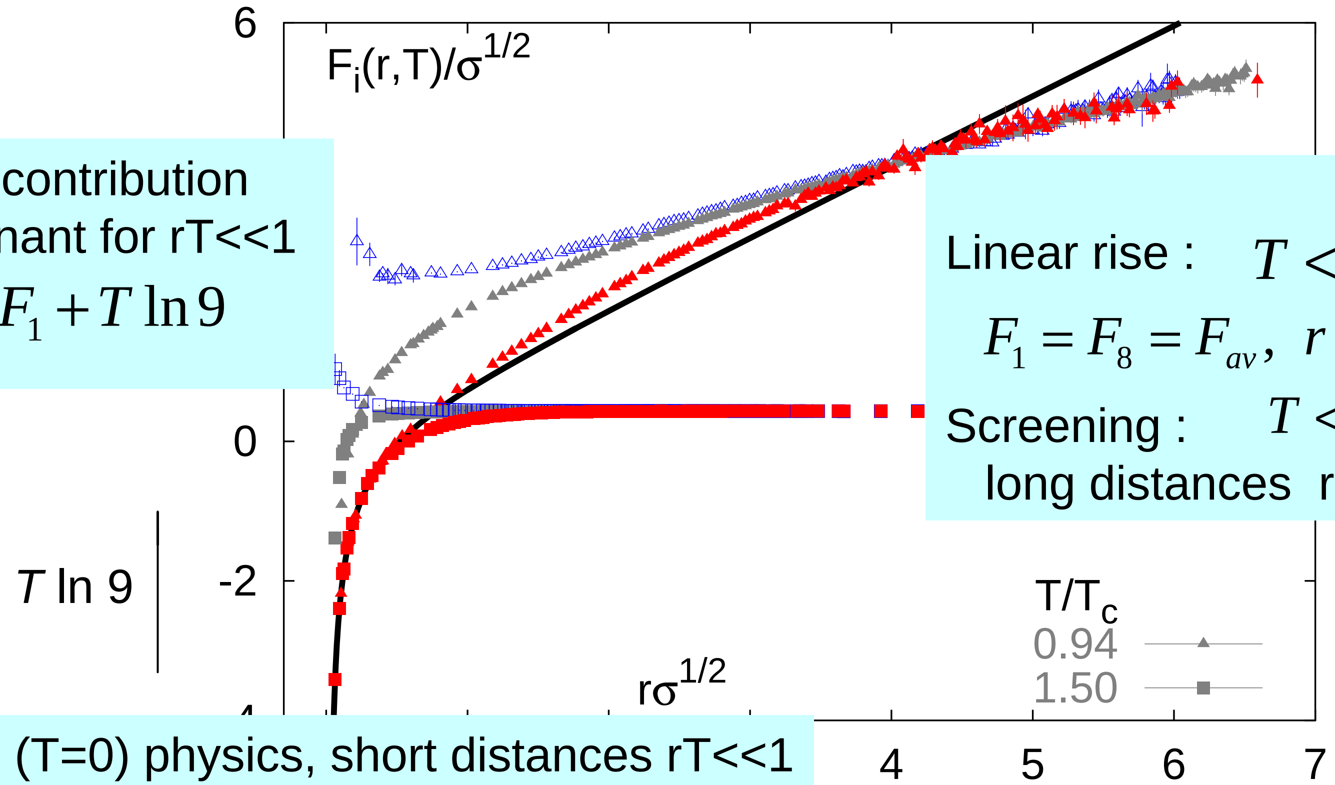
At T=0 equivalent to definition through Wilson loop, Philipsen, PLB 535 (2002) 138

Color averaged free energy:

$$\exp(-F_{av}(r,T)/T) = \frac{1}{Z(T)} \frac{\mathrm{Tr}(P_1+P_8)Z_{Q\bar{Q}}}{\mathrm{Tr}(P_1+P_8)} = \frac{1}{9}\langle \mathrm{Tr}W(\vec{r})\mathrm{Tr}W^{\dagger}(0)\rangle$$

$$= \frac{1}{9}\exp(-F_1(r,T)/T) + \frac{8}{9}\exp(-F_8(r,T)/T)$$

Kaczmarek, Karsch, P.P., Zantow, hep-lat/0309121



Singlet contribution is dominant for rT<<1

$F_{av} \approx F_1 + T \ln 9$

Linear rise : $T < T_c$

$F_1 = F_8 = F_{av},\ r \to \infty$

Screening : $T < T_c$

long distances rT>>1

Vacuum (T=0) physics, short distances rT<<1

Short vs. long distance physics in singlet free energy

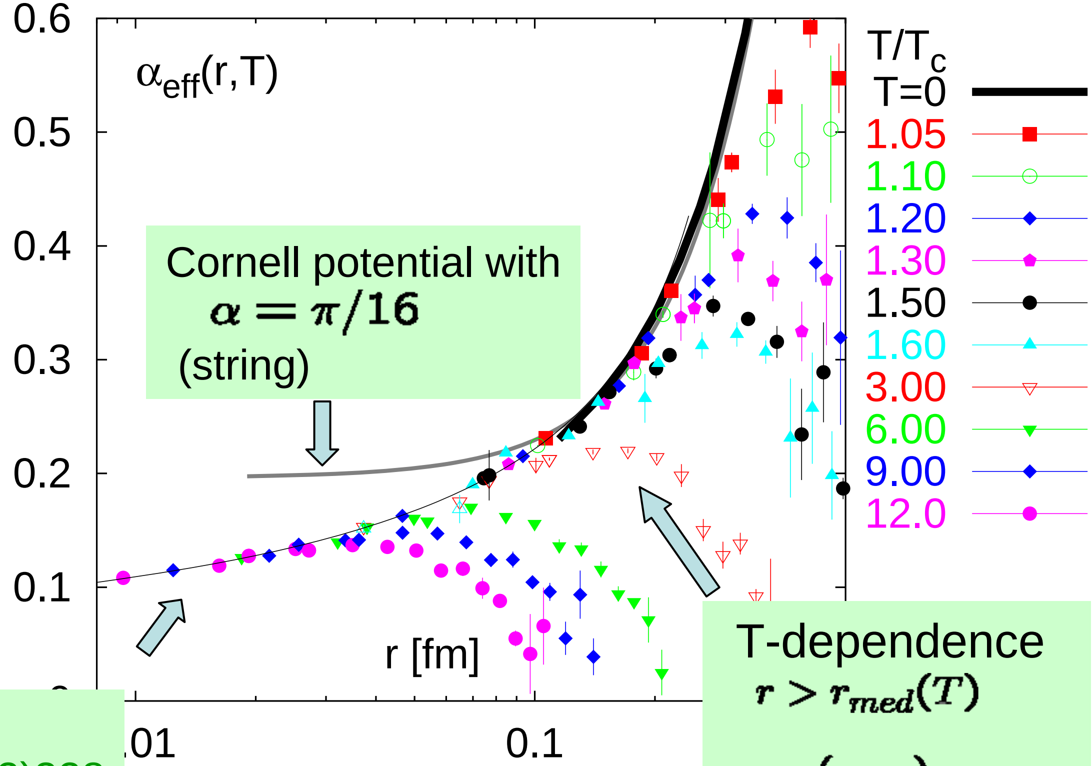
Effective running coupling constant at short distances :

$$\alpha_{eff}(r,T) = \frac{3r^2}{4}\frac{dF_1(r,T)}{dr}$$

Perturbation theory:

$$rT \ll 1, \quad F_1(r,T) = -\frac{4}{3}\frac{\alpha_s(r)}{r}$$

Kaczmarek, Karsch, P.P., Zantow, work in progress



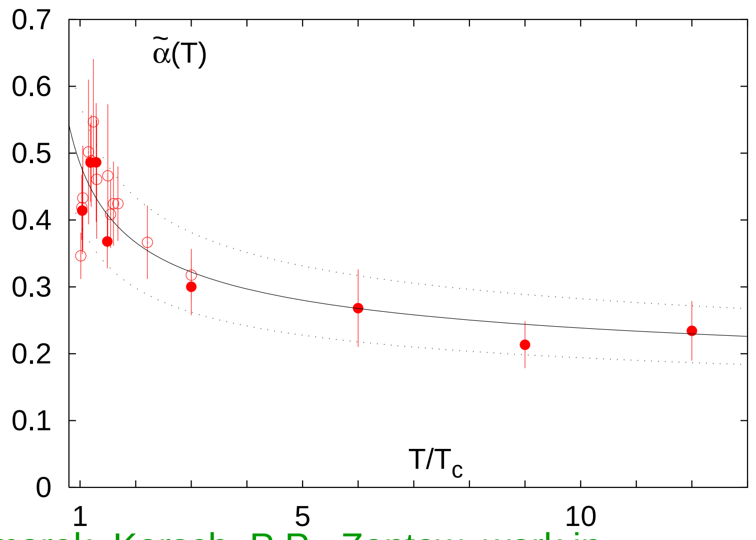
3-loop running coupling
Necco, Sommer, NPB 622 (02)328

T-dependence $r > r_{med}(T)$

$\alpha_{eff}(r_{med}) = \alpha_{max}$

Screening at large distances:

$$F_1(r,T) = -\frac{4}{3}\frac{\alpha(T)}{r}\exp(-\sqrt{4\pi\tilde{\alpha}_s(T)}r)$$



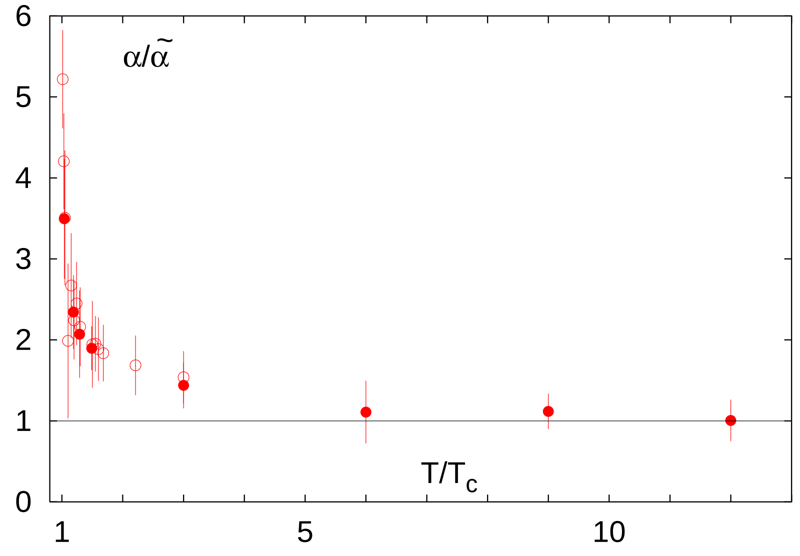
Kaczmarek, Karsch, P.P., Zantow, work in progress

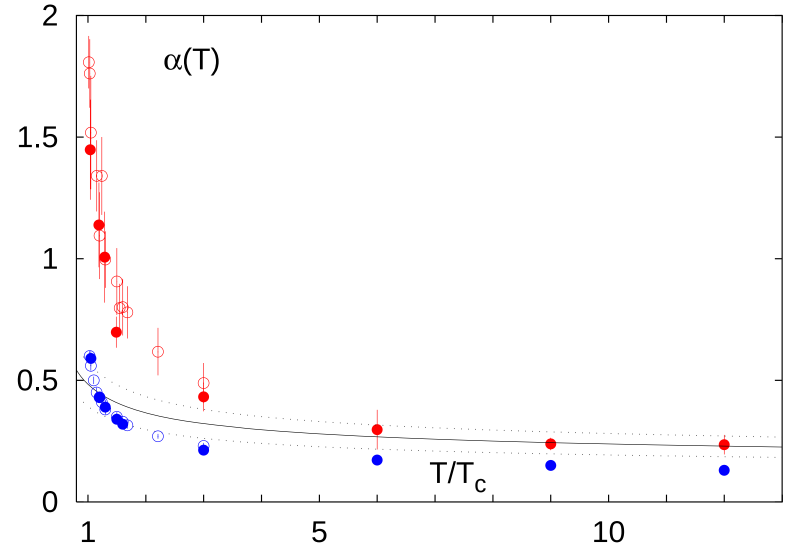
High temperature perturbation theory:

$$F_1(r,T) = -\frac{4}{3}\frac{\alpha_s}{r}\exp(-\sqrt{4\pi\alpha_s}r)$$

$$T \geq 6T_c, \quad \tilde{\alpha}(T) = \alpha(T) = 2.17(7)\alpha_{\overline{MS}}(2\pi T)$$

The only non-perturbative information

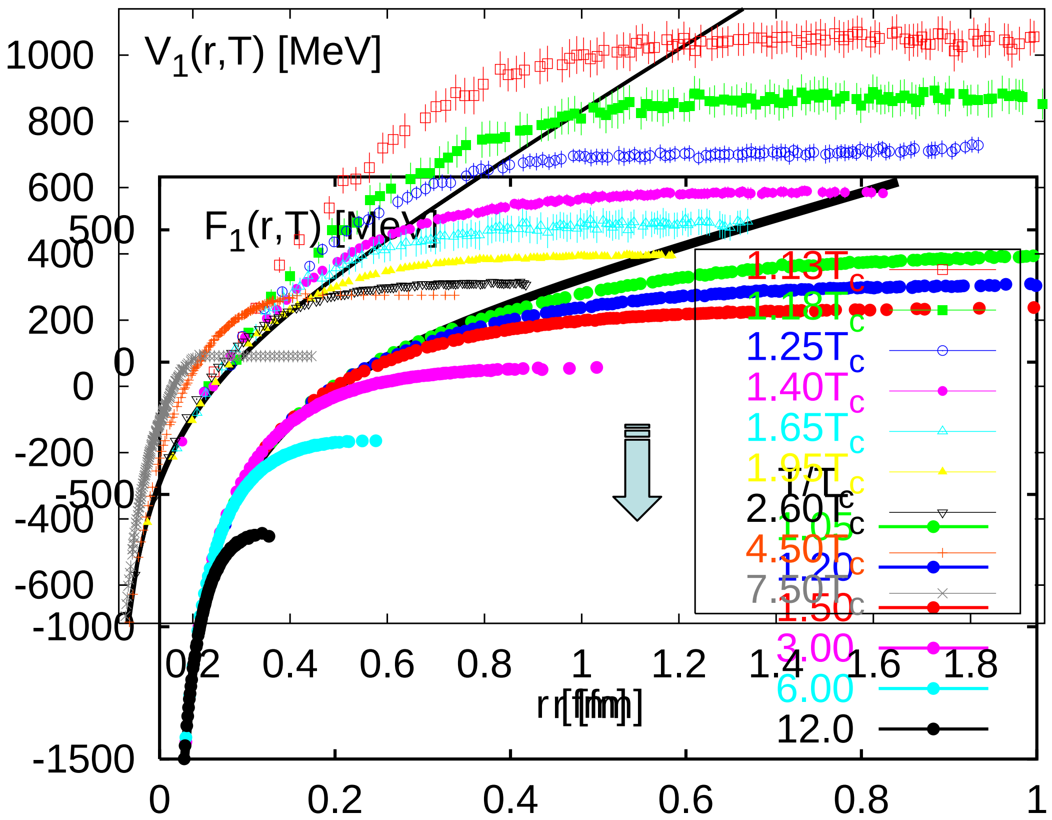




The entropy contribution and the internal energy

$$S_1(r,T) = \frac{\partial}{\partial T} \ln \left(T \frac{Z^1_{Q\bar{Q}}(r,T)}{Z(T)} \right)$$

$$\begin{aligned} V_1(r,T) &= T^2 \frac{\partial}{\partial T} \ln \left(\frac{Z^1_{Q\bar{Q}}(r,T)}{Z(T)} \right) \\ &= F_1(r,T) - T S_1(r,T) \end{aligned}$$



Numerically:

$$F_1(r=\infty, 1.4T_c) = 200 MeV$$

$$V_1(r=\infty, 1.4T_c) = 600 MeV$$

$$-\frac{\partial F_1}{\partial T} > 0$$

Negative entropy contribution

Kaczmarek, Karsch, P.P., Zantow, hep-lat/0309121

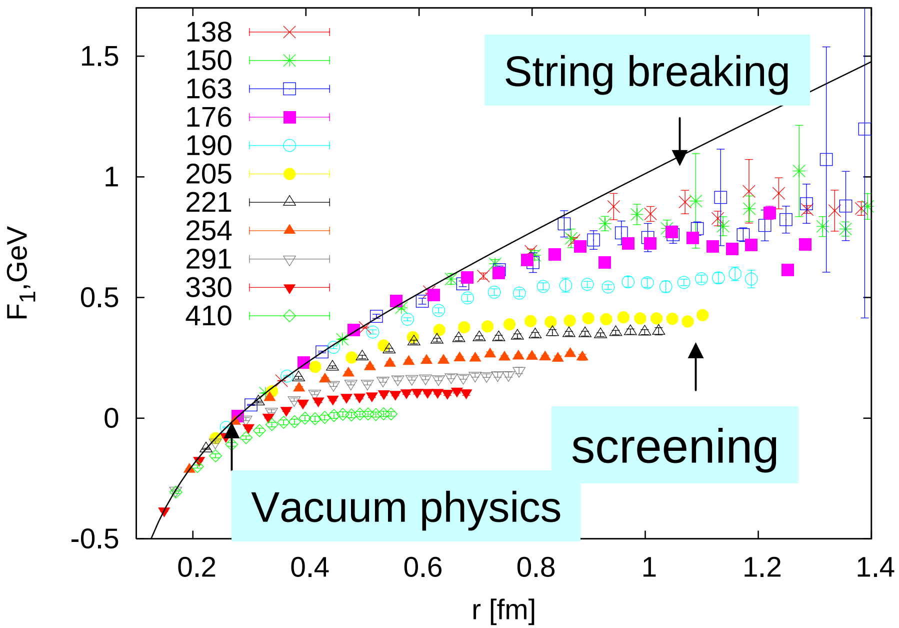
Static free energy in 3 flavor QCD

Asqtad action, $8^3 \times 4,\ 12^3 \times 4,\ 12^3 \times 6$ lattices

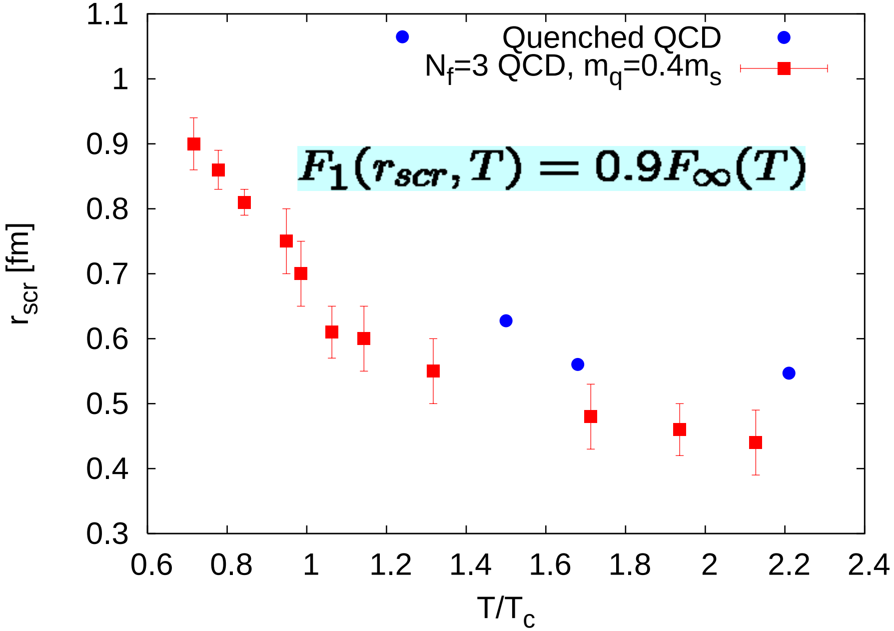
Quark masses: $0.2 m_s,\ 0.4 m_s,\ 0.6 m_s$

K. Petrov, P.P, hep-lat/0405009

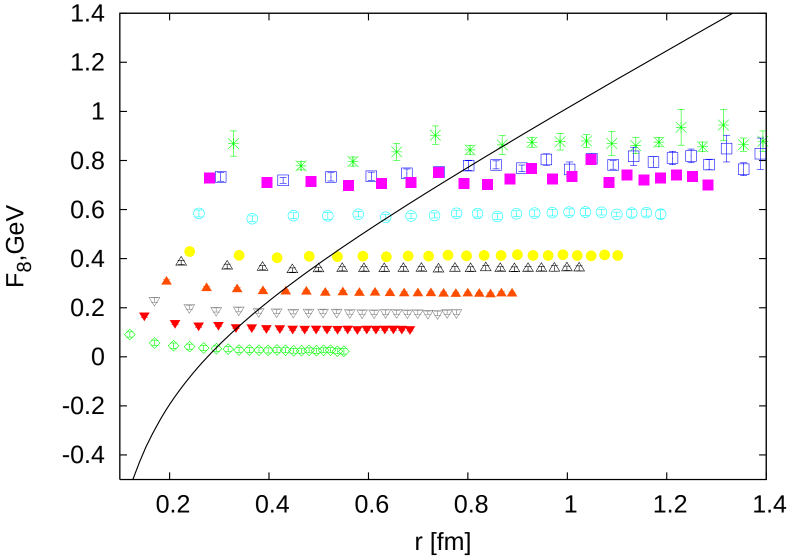
$F_\infty(T) = \lim_{r \to \infty} F_1(r,T) \neq 0$ for any T



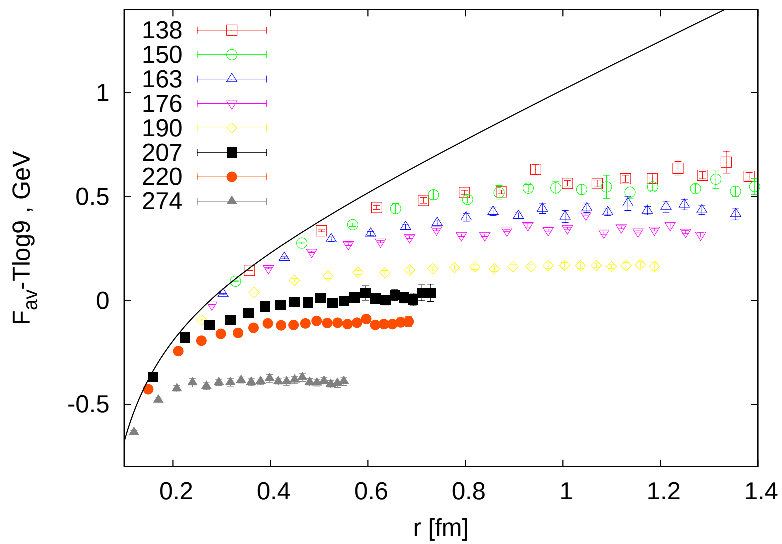
Effective screening radius r_{scr}



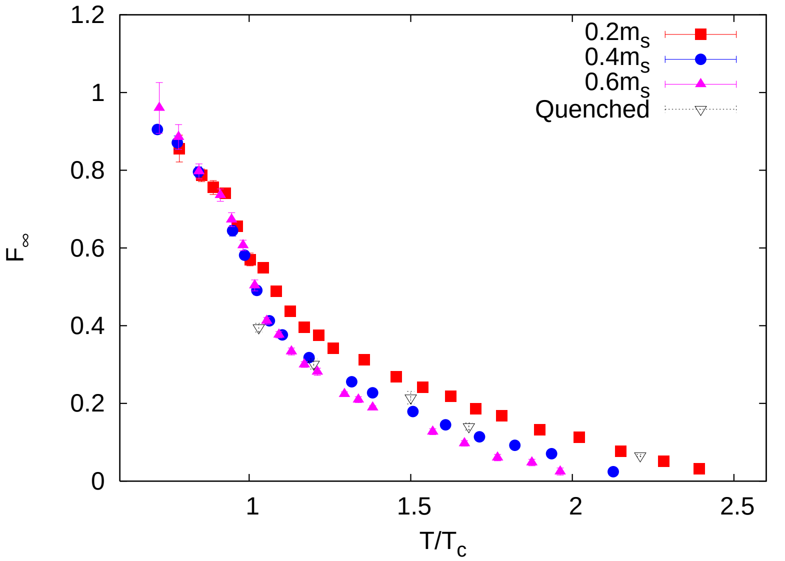
Color octet free energy

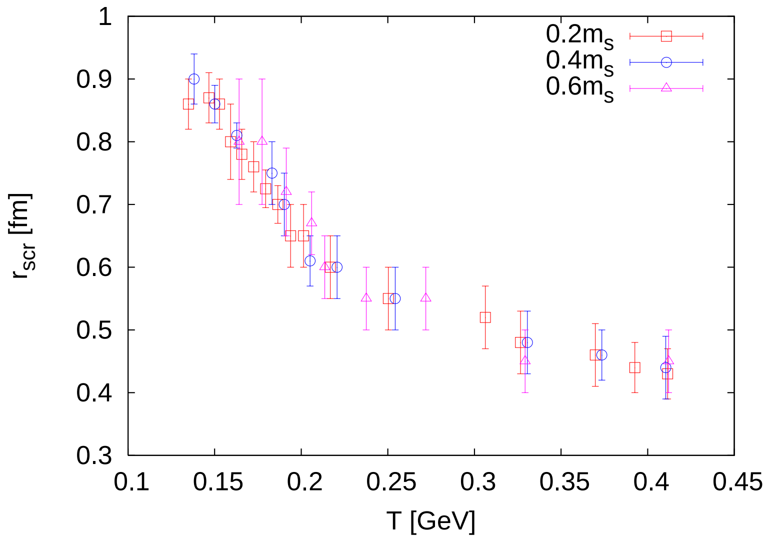


Color averaged free energy



Mass dependence:



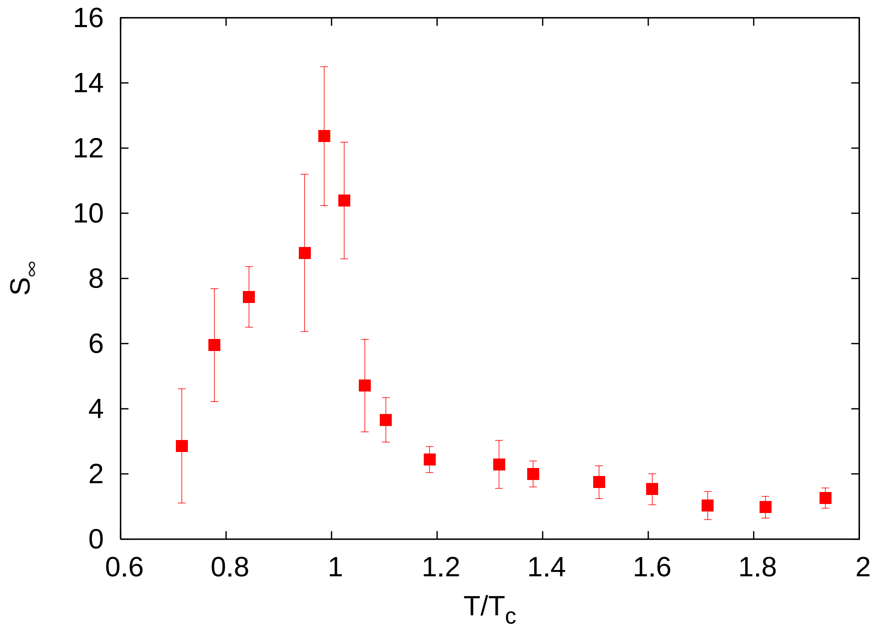


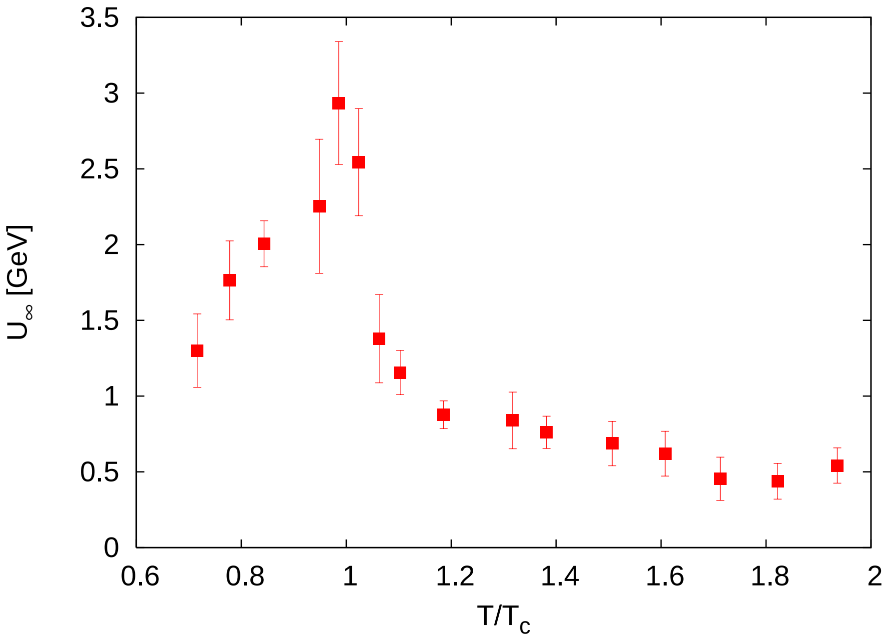
D,B -meson masses:

Digal, P.P. , Satz, PLB 514 (2001) 57

$$2M_{D,B} = 2m_{c,b} + F_\infty, \quad T \ll T_c$$

$F_\infty(T)$ decreases, do D,B meson masses decrease ?? ⇨ Entropy contribution





Large increase in the entropy and internal energy !

Meson spectral functions

$$G_T(\tau,\vec{p}) = \int d^3x\, e^{i\vec{p}\cdot\vec{x}} \left\langle J_H(\tau,\vec{x})\, J_H^{\,+}(0,0) \right\rangle, \quad J_H(\tau,\vec{x}) = q(\tau,\vec{x})\Gamma_H q(\tau,\vec{x})$$

$$\Gamma_H = 1,\ \gamma_5,\ \gamma_\mu,\ \gamma_5\cdot\gamma_\mu$$

LGT

$$G_T(\tau) = D^>(-i\tau)$$

⇧ Imaginary time ⇧ Real time

Experiment

$$\frac{\mathrm{d}W}{\mathrm{d}\omega\mathrm{d}^3p} = \frac{5\alpha^2}{27\pi^2}\frac{1}{\omega^2(\mathrm{e}^{\omega/T}-1)}\sigma_V(\omega,\vec{p},T)$$

$$\frac{D^>(\omega) - D^<(\omega)}{2\pi} = \frac{1}{\pi}\mathrm{Im}\, D_R(\omega) = \sigma(\omega)$$

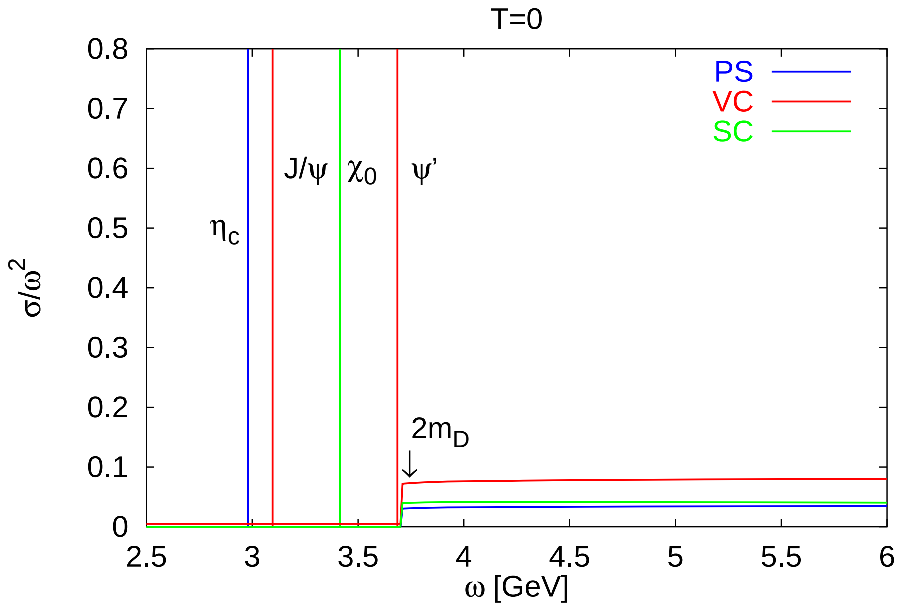
➡ Quasi-particle masses and width

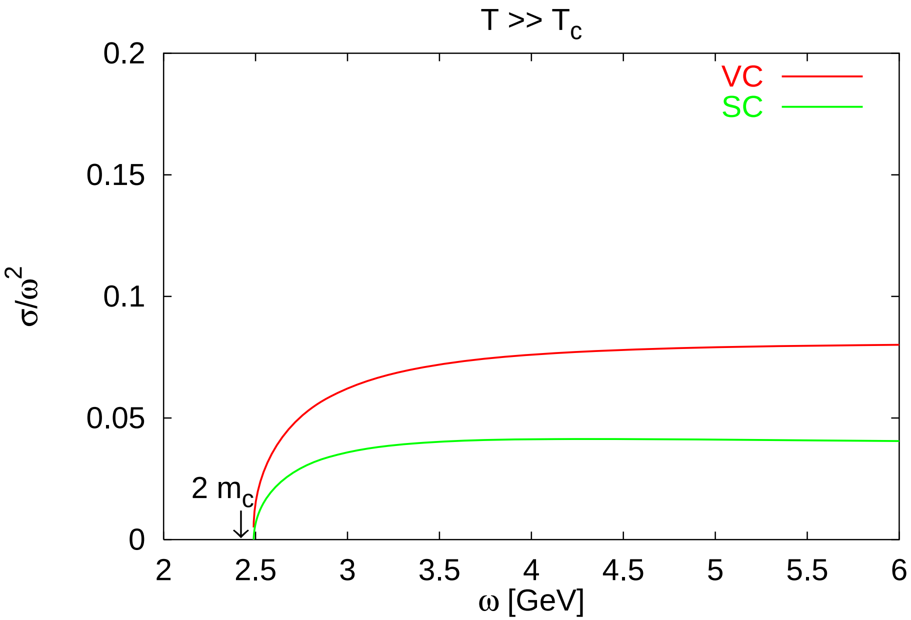
$$G_T(\tau) = \int_0^\infty d\omega\,\sigma(\omega)\frac{\cosh(\omega(\tau - 1/(2T)))}{\sinh(\omega/(2T))}$$

$G_T(\tau,\vec{p})$ ➡ MEM ➡ $\sigma(\omega,\vec{p})$

Heavy quarkonia spectral functions (I)

What do we expect ?





Ground states (1S):

Pseudo-scalar (PS) $\rightarrow \eta_c, \quad \eta_b$

Vector (VC) $\rightarrow J/\psi, \Upsilon$

Excited states (1P) :

Scalar (SC) $\rightarrow \chi_{c0}, \chi_{b0}$

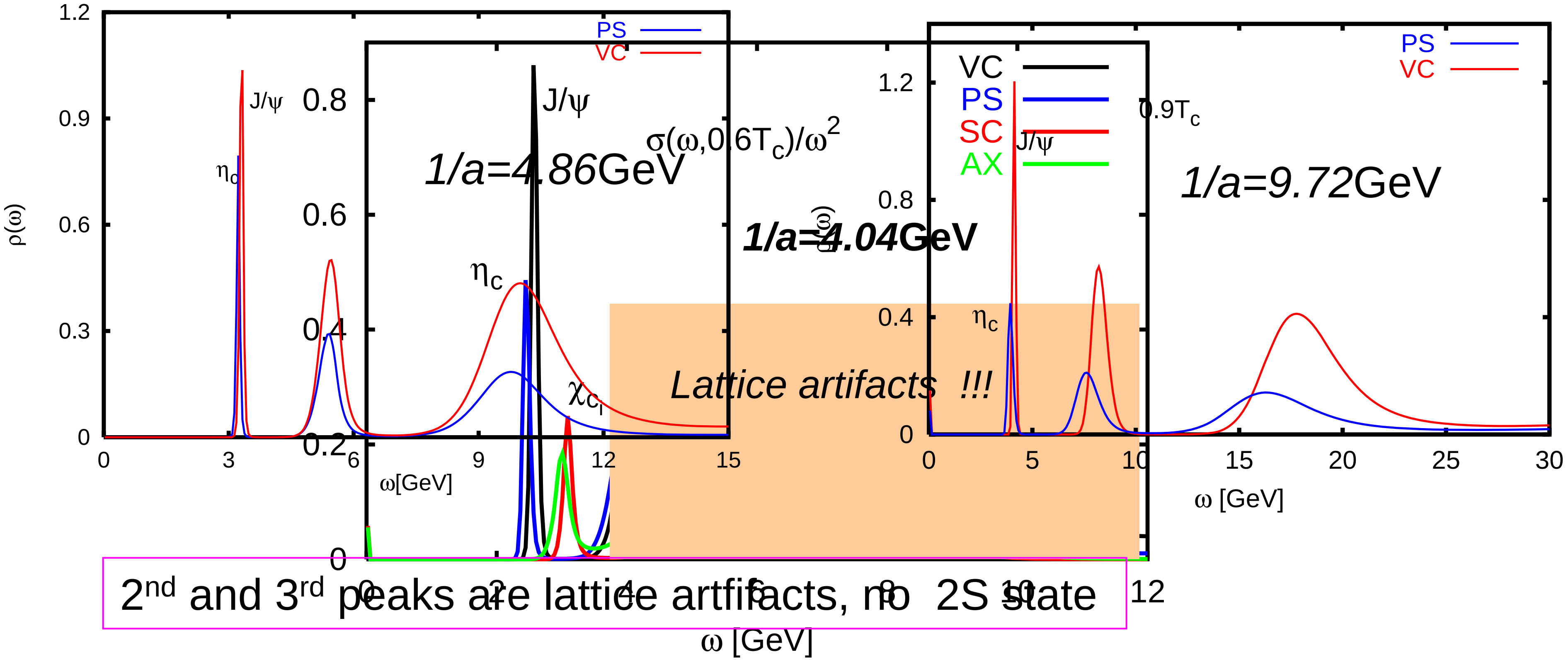
Axial-vecor (AX) $\rightarrow \chi_{c1}, \chi_{b1}$

Heavy quarkonia spectral functions (II)

What do we get at low temperature from lattice calculations ?

Calculations performed on isotropic lattices for *1/a=4.04*GeV, *4.86*GeV, *9.72*GeV

Datta, Karsch, P.P, Wetzorke, hep-lat/0312037



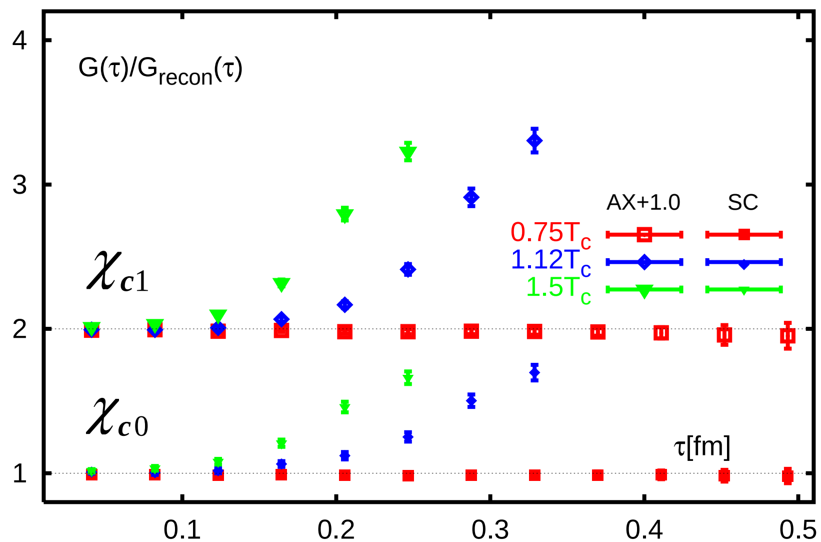
2nd and 3rd peaks are lattice artifacts, no 2S state

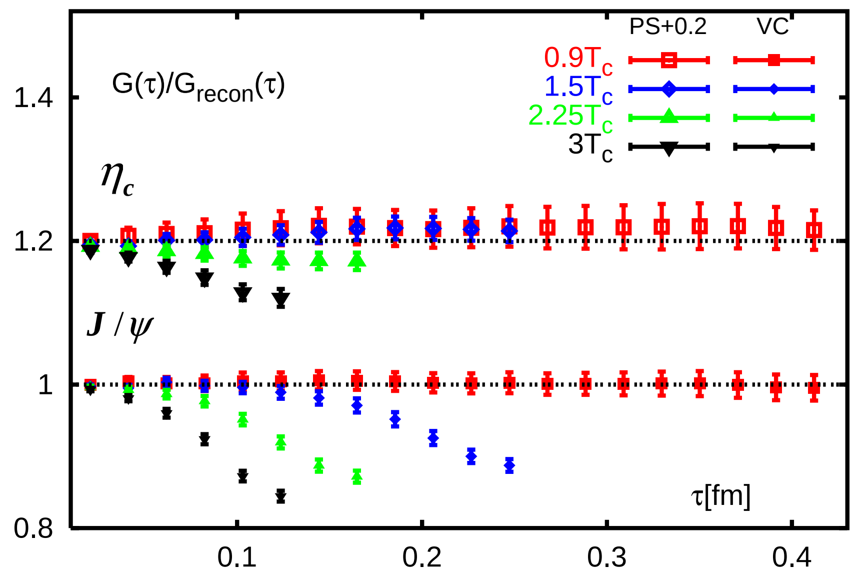
Heavy quarkonia spectral functions (III)

The temperature dependence of the correlators

$$G(\tau,T) = \int_0^\infty d\omega \sigma(\omega,T) \frac{\cosh(\omega\cdot(\tau - 1/(2T))}{\sinh(\omega/(2T))}$$

If there is no T-dependence in the spectral function, $G(\tau,T)/G_{recon}(\tau,T) = 1$

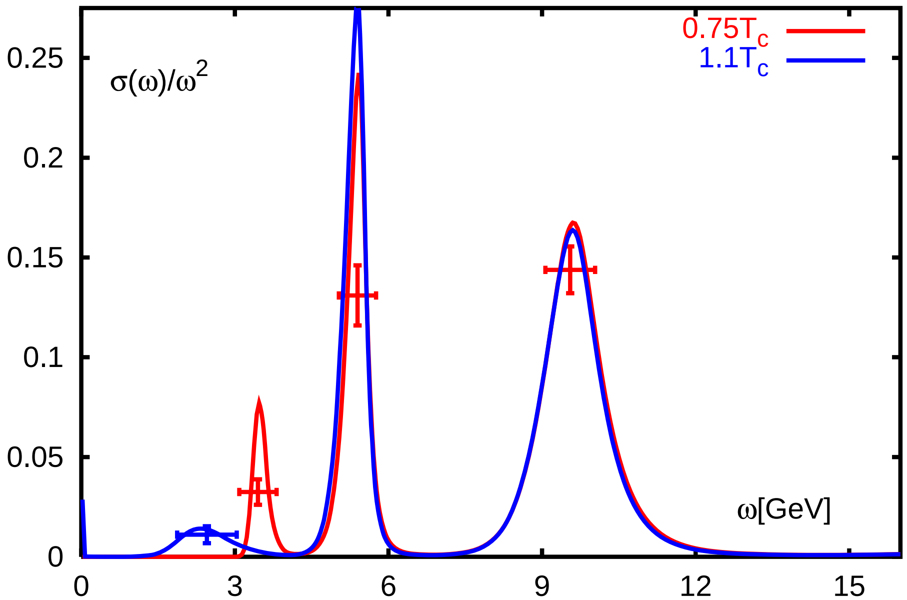


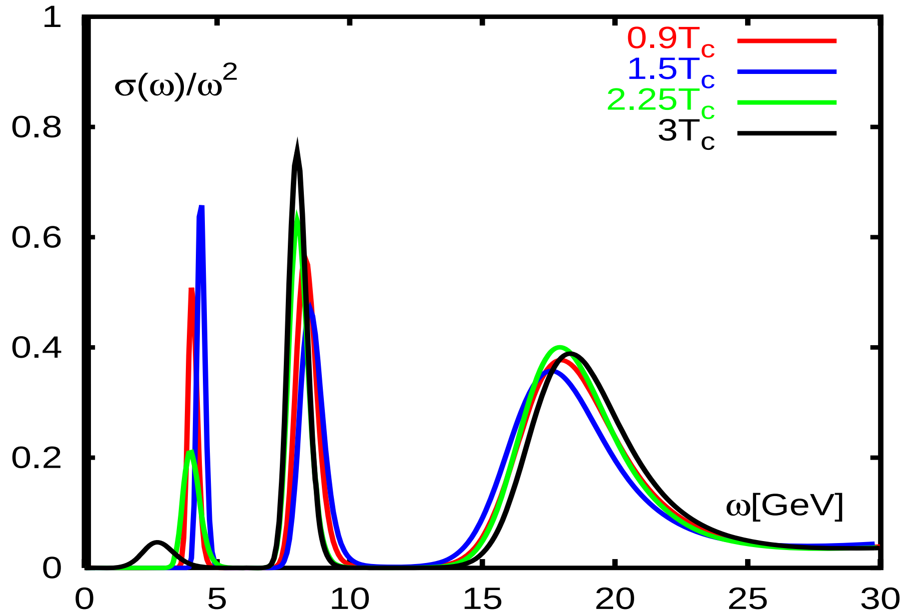


Datta, Karsch, P.P., Wetzorke, hep-lat/0312037

Heavy quarkonia spectral functions (IV)

Spectral functions from MEM:





η_c Is dissolved at $1.1T_c$

J/ψ is dissolved at $3T_c$

Datta, Karsch, P.P., Wetzorke, hep-lat/0312037

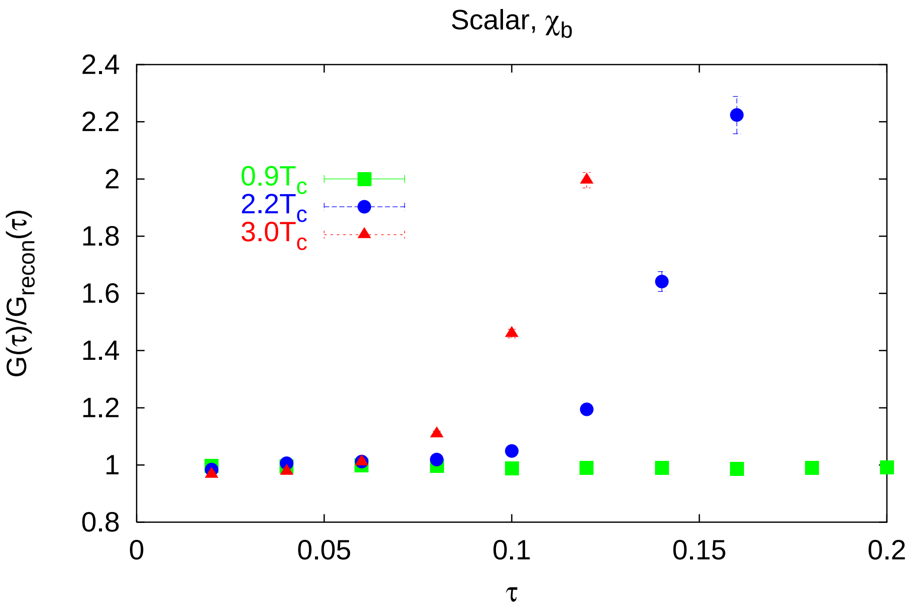
Gradual dissolution of J/ψ

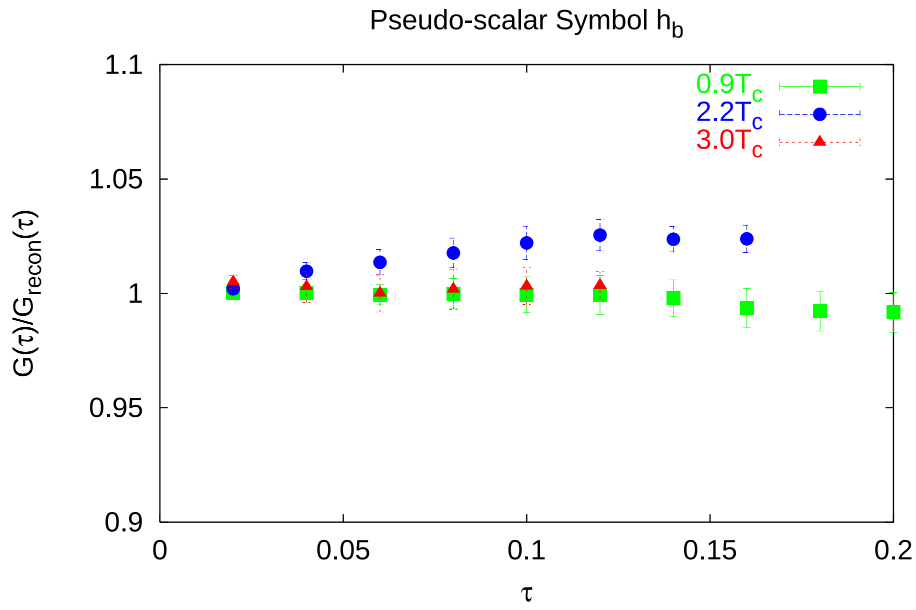
50% reduction in the dilepton rate

Heavy quarkonia spectral functions (V)

Bottomonia correlators:

Datta, Karsch, P.P., Wetzorke, work in progress

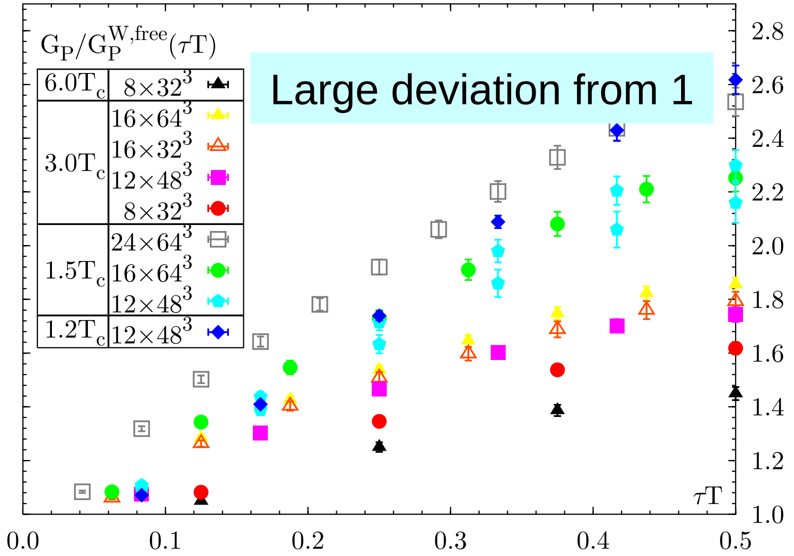




χ_b dissolves at $2.2T_c$

η_b, Υ survive till $3T_c$

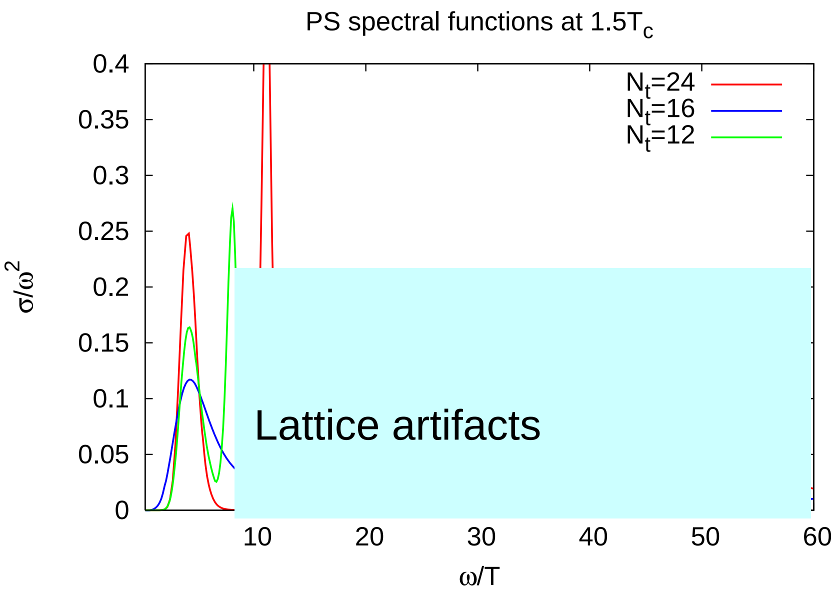
Light meson spectral functions

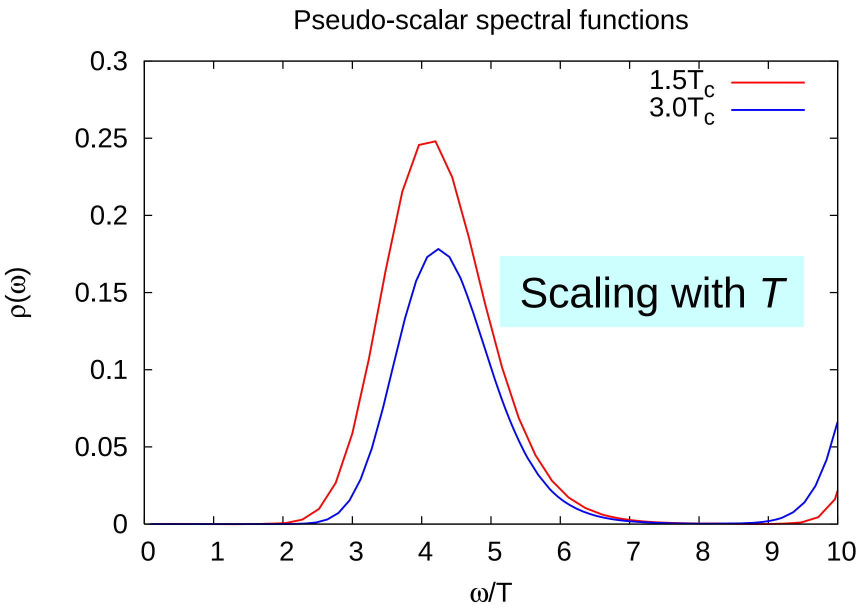


We expect no mesons
but free quark propagation
at $T >> T_c$:

$$G(\tau,T)/G_{free}(\tau,T) \approx 1$$

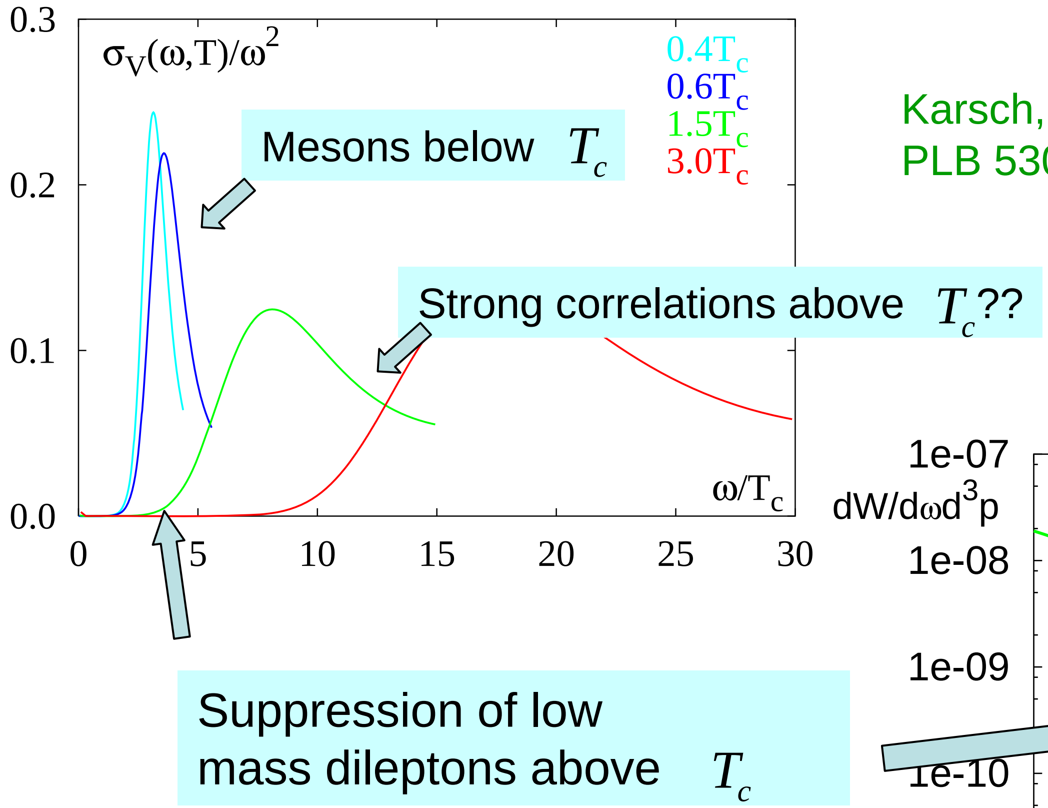
Karsch, Laermann, P.P.,Stickan, Wetzorke,
work in progress

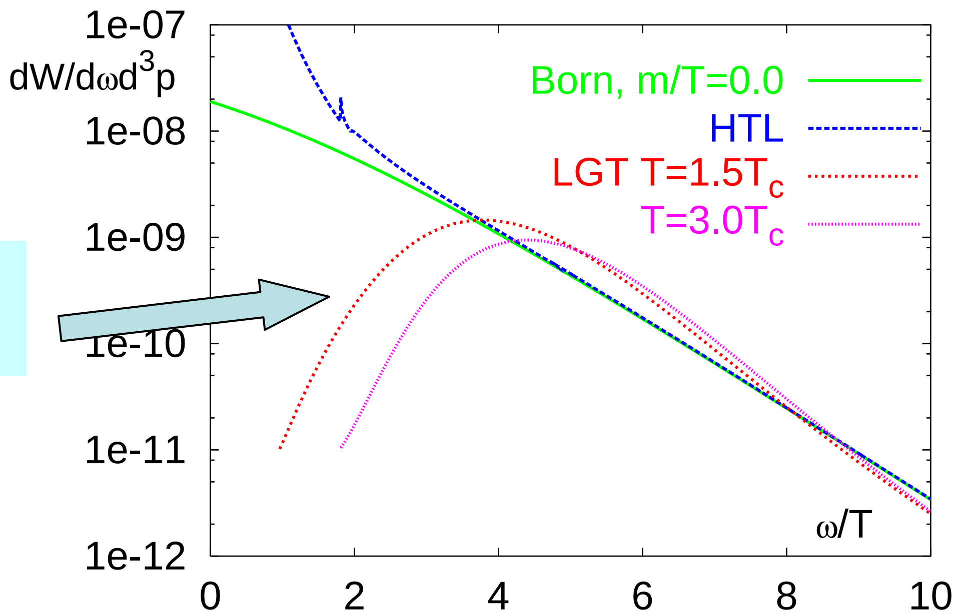




Vector spectral functions and thermal dilepton rate:

Karsch, Laermann, P.P.,Stickan, Wetzorke,
PLB 530 (2002) 147, work in progress





Summary

• There is most likely no phase transition but rapid crossover in full QCD

• Strong interaction between quarks in the deconfined phase:

non-perturbative behavior of the static quark anti-quark free energy

survival of the ground state charmonia

suppression of low mass dileptons

this is sQGP as seen on lattice !!!

• For future progress improvements in algorithm and increase in computer power are necessary for more precise quantitative statements