Exploring Matter under Extreme Conditions with Numerical Simulations

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Introduction

There is the limiting temperature beyond which hadrons (the observed strongly interacting particles) can no longer exist [1]. This temperature can be estimated to be about $170MeV$ ($\simeq 10^{12}K$). On the basis of asymptotic freedom one would expect that dominant degrees of freedom at very high temperature and/or densities are quarks and gluons which are no longer subject to confinement [2]. Such qualitatively different behavior of usual hadronic matter with confinement and chiral symmetry breaking and this new state of matter (usually called Quark Gluon Plasma or QGP in short) would suggest a phase transition at some temperature. Using the lattice formulation of the theory of strong interactions, Quantum Chromodynamics (or QCD in short) we can study the phase diagram and properties of strongly interacting matter at very high temperatures and/or baryon densities. The current knowledge of the QCD phase diagram is summarized in Fig. 1

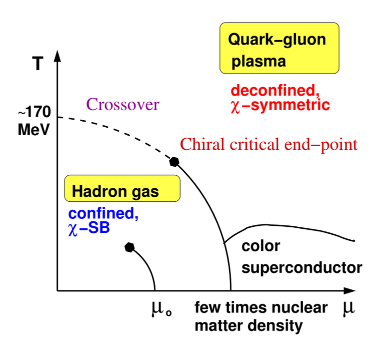

Fig. 1 *Phase digram of QCD at finite temperature and baryon density*

Numerical results on the transition temperature

Current lattice calculations with Wilson and staggered formulations indicate that the transition to the new state of matter at finite temperature and zero baryon density is not a real phase transition but a crossover, i.e. no thermodynamic singularities are associated with this transition [3,4,5,6,7,8]. The most recent results for the transition temperature [3,4,5,6,7,8] are summarized in Fig. 2. As the critical energy density $\epsilon_c \sim T_c^4$, the uncertainty in T_c converts into large uncertainty in ϵ_c, $\epsilon_c = (0.3-1.3)GeV/fm^3$.

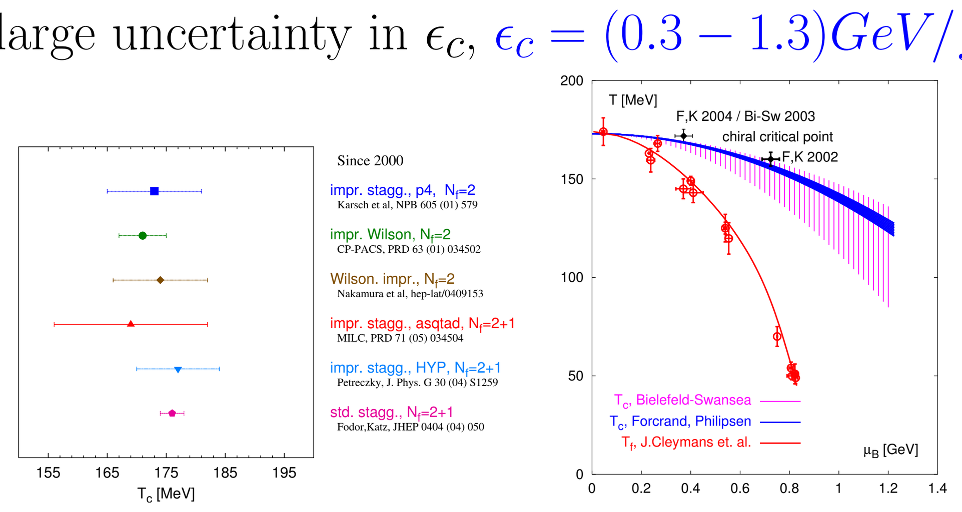

Fig. 2 : *The transition temperature for zero and finite* μ_B

At certain a value of baryon density corresponding to chiral critical point the transition turn from crossover to a 1^{st} order phase transition. It is very difficult to locate the chiral critical end-point because for finite baryon density the Boltzmann weight become complex. The preliminary results for the phase boundary at finite baryon density are also shown in Fig. 2

Bulk Thermodynamic observables

The pressure and energy density as function of the temperature has been calculated on the lattice [9] and is shown in Fig. 3. Both quantity show a very rapid rise at T_c. The pressure approaches the ideal gas limit much slower than the energy density. As the consequence the speed of sound for temperatures relevant for RHIC is smaller than the ideal gas value.

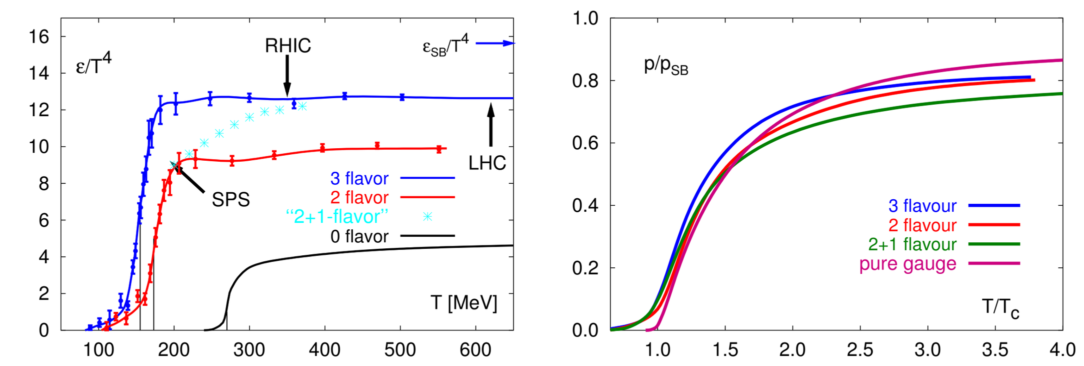

Fig. 3 : *The pressure and energy denisty of strongly interacting matter*

One can also calculate the the second derivative of the pressure with respect to the baryon chemical potential. This quantity is known as quark number susceptibility and describes fluctuations of the baryon number at finite temperature. Therefore it can be relevant for studying event-by-event fluctuations at RHIC. Recent results for this quantity [6] are shown in Fig. 4

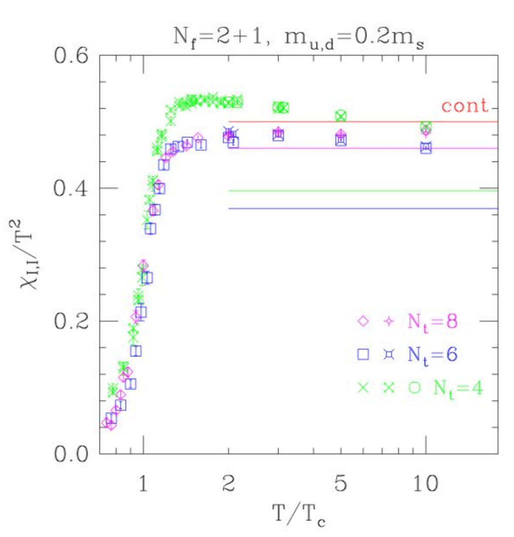

Fig. 4 : *The quark number susceptibility of strongly interacting matter*

Heavy quarks at finite temperature

Heavy quarks are interesting probes of the high temperature QCD phase both from the theoretical and the experimental point of view. From the theoretical point of view one can use them to address the question of in-medium modification of inter-quark forces (color electric screening). It has been argued long ago that dissolutions of bound state of heavy quark and ant-quark (heavy quarkonia) can be use as signature of QGP formation in heavy ion collisions [11]. The easiest way to study the problem of in-medium modification of inter-quark forces is to consider the free energy of static (infinitely heavy) quark anti-quark pair. Recent lattice results on this quantity are shown in Fig. 5 [12].

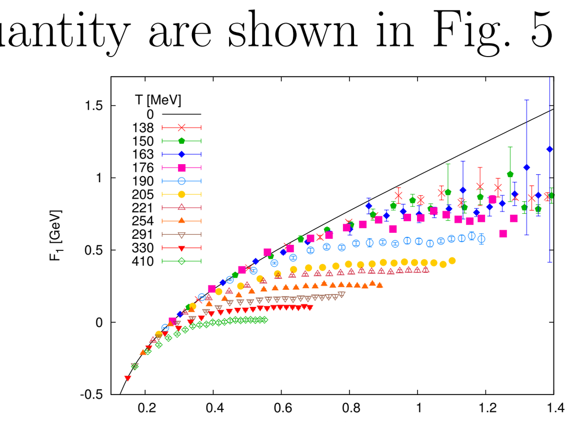

Fig. 5 : *The free energy of static quark anti-quark pair* .

To study the properties of heavy quarkonia at finite temperature and to determine at which temperature they dissolve temporal meson correlation functions have to be calculated [13,14,15]. These correlation functions are related to the so-called spectral functions (also known as dynamic structure functions) by the integral representation. To reconstruct the spectral function from the meson correlation function the *Maximum Entropy Method* has been used [15].

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

The results on the spectral functions for 1S state charmonia, J/ψ (bound state of charm and anti-charm quark) are shown in Fig. 6. As one can see from the figure this state exist in the plasma up to temperatures as high as $1.5T_c$. Contrary the first orbital excitation of the charmonia, the 1P χ_c state is dissolved at $1.1T_c$ as shown in Fig. 7.

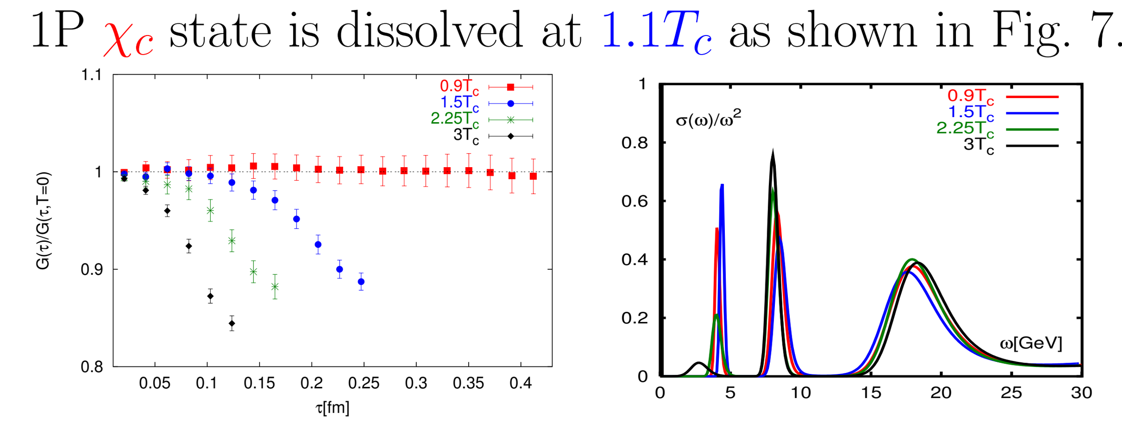

Fig. 6 : *The meson correlator and spectral function for* J/ψ.

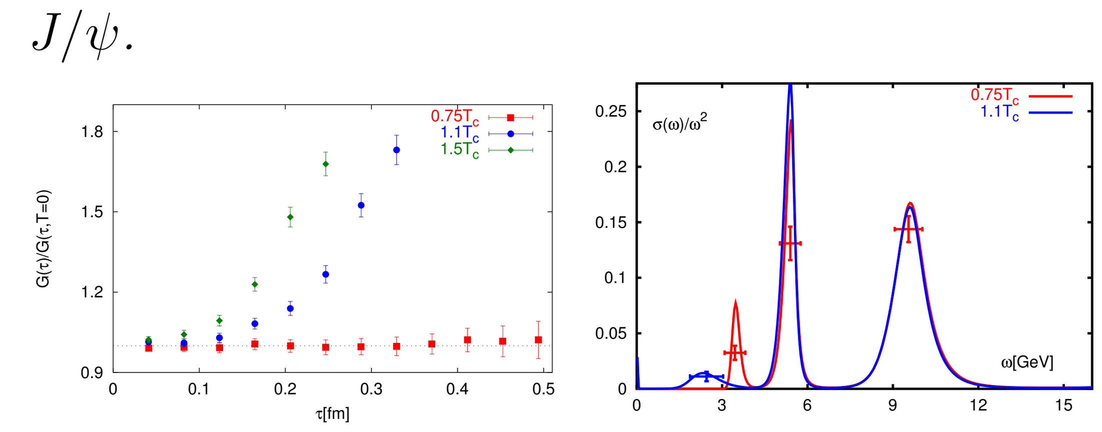

Fig. 7 : *The meson correlator and spectral function for* χ_c.

Calculations of the quarkonia with the heavier b-quark are also being done [16] and the preliminary results are shown in Fig. 8

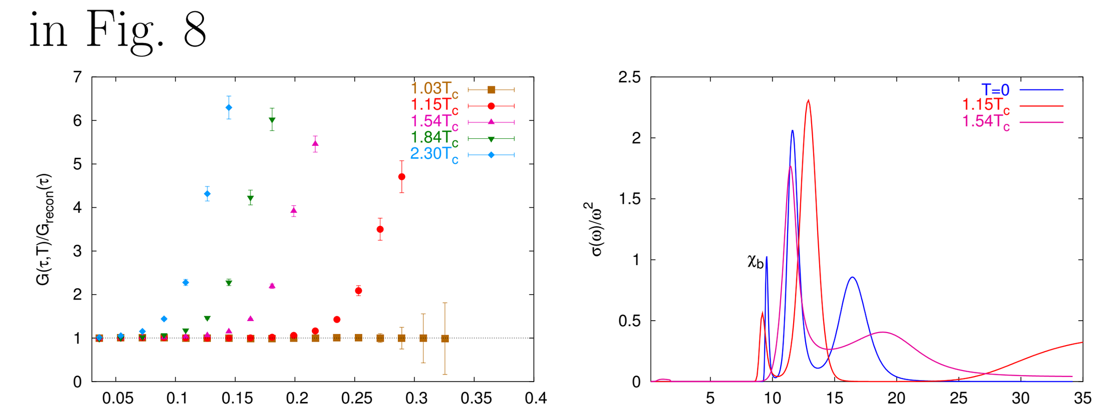

Fig. 8 : *The meson correlator and spectral function for* χ_b.

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