The Quark Gluon Plasma

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1. Introduction: different regimes of QCD matter
2. The first thing about hot perturbation theory: what are the quasiparticles in the plasma?
3. Test perturbation theory for hard modes ($|\mathbf{k}| \sim \mathbf{T}$): evaluate the equation of state
4. Check the computation of the equation of state using quark number susceptibilities
5. Compute the photon production rate: perturbation theory guides the analysis of lattice data
6. List of main results

Three temperature ranges

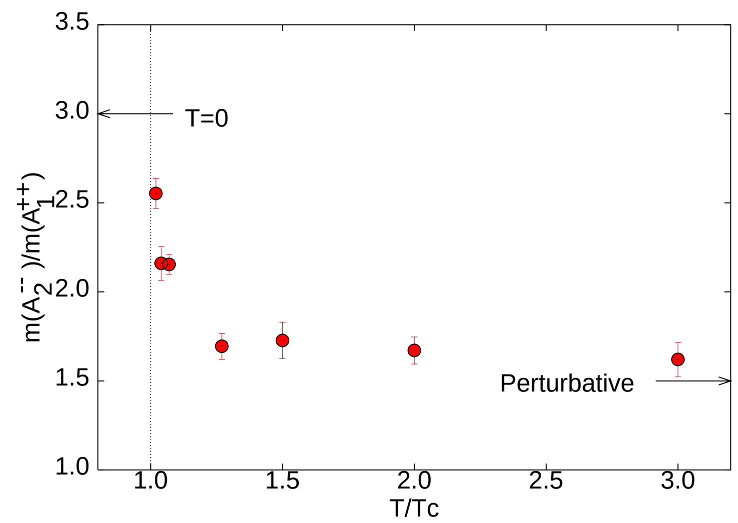
$$T_c/\Lambda_{\overline{MS}} \simeq 0.5$$

- QCD matter at $T \ll T_c$ is hard to deal with— use effective field theories such as chiral perturbation theory. Interesting predictions for lukewarm pion gas, phases of cold and dense QCD *etc*.

- QCD matter at $T \sim T_c$ can only be studied on the lattice— very costly because QCD transition is near a 2nd order transition, *i.e.*, has very large correlation length, and therefore needs very large lattices.

- QCD matter for $T \gg T_c$ can probably be handled by a judicious mixture of perturbation theory guided by lattice computations. Topic of this talk.

Quasiparticles in the plasma



S. Datta and S. Gupta, hep-lat/0208001

- A_1^{++} is Re L, needs two electric gluon exchange at lowest order
- A_2^{--} is Im L, needs three electric gluon exchange at lowest order

The equation of state

Preliminary evidence for energy equilibration from the SPS heavy-ion program; strengthened by RHIC data reported in QM 2001 and 2002. RHIC also saw some evidence for hydrodynamic flow. All predictions of flow need to take into account the equation of state of the matter that flows.

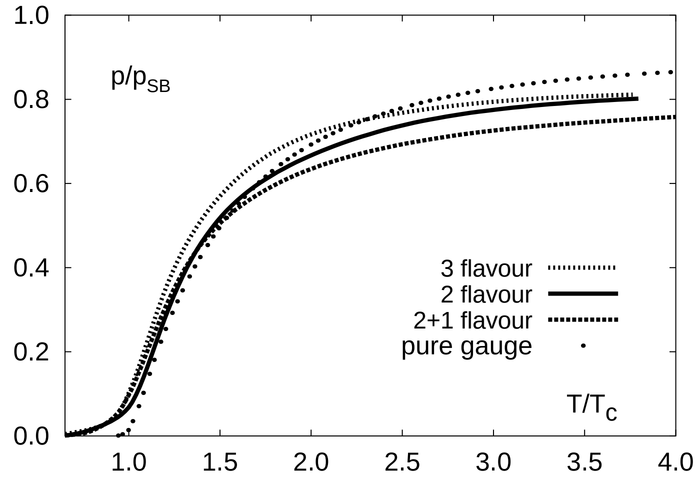
1. The lattice data

2. Is it perturbative?

3. HTL and DR

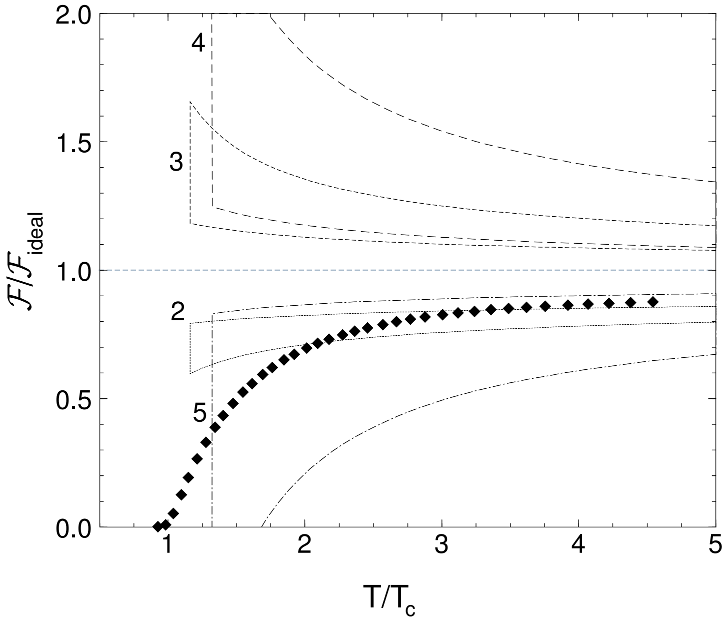
4. Skeleton graph resummation

The lattice data



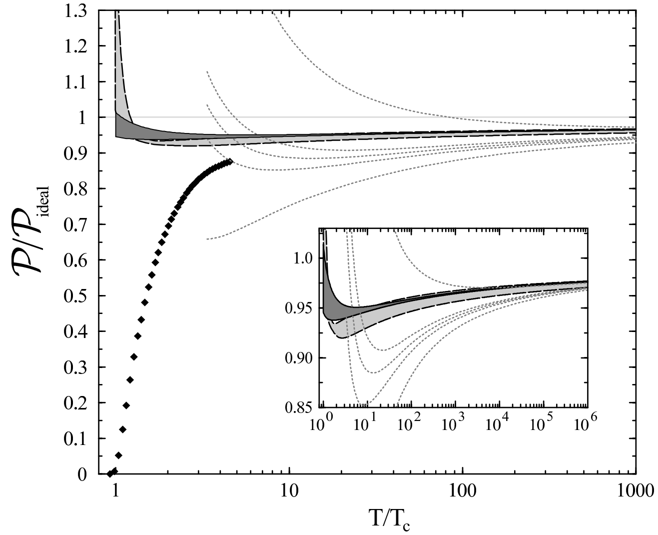
For detailed reviews see F. Karsch, Nucl.Phys.A698:199c,2002, and K. Kanaya, hep-ph/0209116

Is it perturbative?



J. O. Andersen, E. Braaten and M. Strikland, Phys.Rev.Lett.83:2139-2142,1999

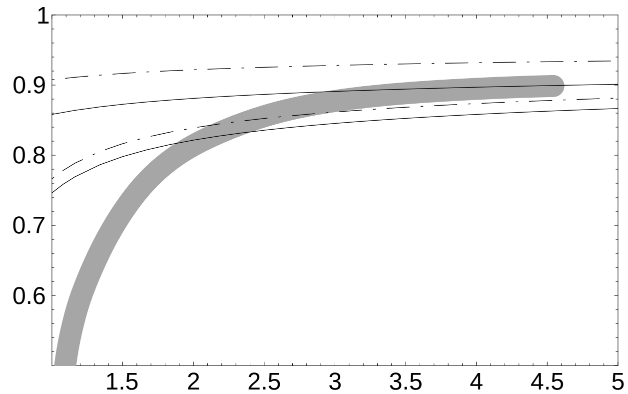
HTL and DR



J. O. Andersen, E. Braaten and M. Strikland, Phys.Rev.D66:085016,2002

K. Kajantie et al, Phys.Rev.Lett.86:10-13,2001

Skeleton graph resummation



J-P. Blaizot, E. Iancu and A. Rebhan, Phys.Rev.D63:065003,2001

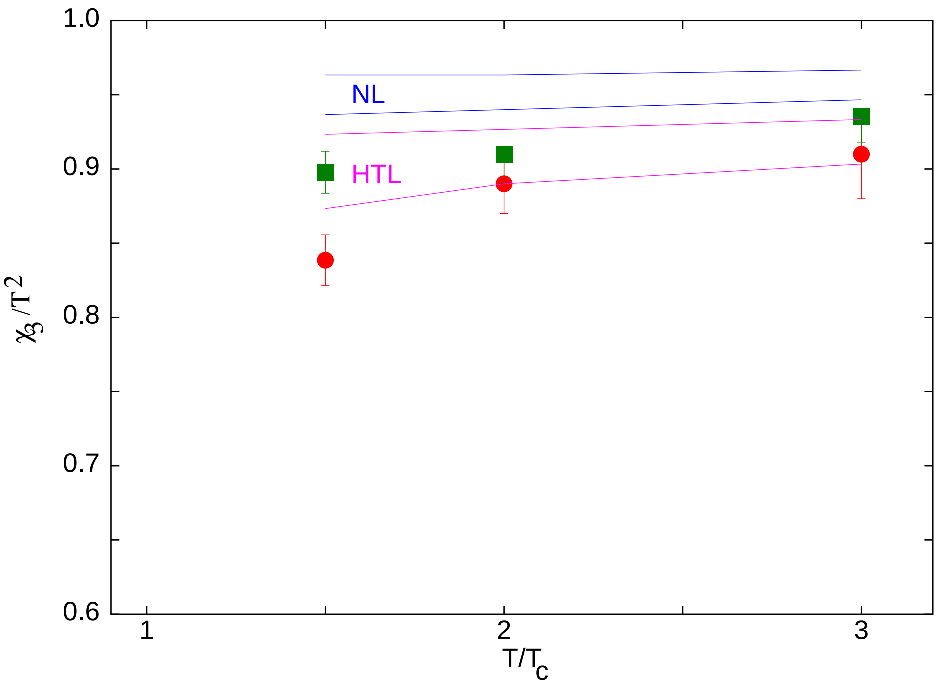
Quark number susceptibilities

$$\begin{aligned}\Omega(T,\mu_u,\mu_d,\mu_s) &= T\log Z(T,\mu_u,\mu_d,\mu_s) = PV\\ \chi_{ij} &= \left(\frac{1}{V}\right)\frac{\partial^2\Omega}{\partial\mu_i\partial\mu_j}\bigg|_{\mu_u=\mu_d=\mu_s=0}\end{aligned}$$

1. Check computations of Ω or P by asking it to reproduce lattice computations of χ.

2. χ is a response function, and hence turns out to be central to many phenomena— charge, baryon number and strangeness fluctuations in equilibrium, strangeness production, and Euclidean correlators.

Lattice vs perturbation theory



R.V. Gavai and S. Gupta, hep-lat/0211015

More on this— wait for Gavai's talk.

Event to event fluctuations

Each heavy-ion collision event, followed by the hadronisation, is one realisation of the whole ensemble of possible thermodynamic systems. Within a given rapidity region, the total amount of any conserved charge fluctuates from one event to another. The variance is determined by the response function of QCD matter in equilibrium.

Charge fluctuations suggested by M. Asakawa et al, Phys.Rev.Lett.85:2072-2075,2000 and S. Jeon et al, Phys.Rev.Lett.85:2076-2079,2000,

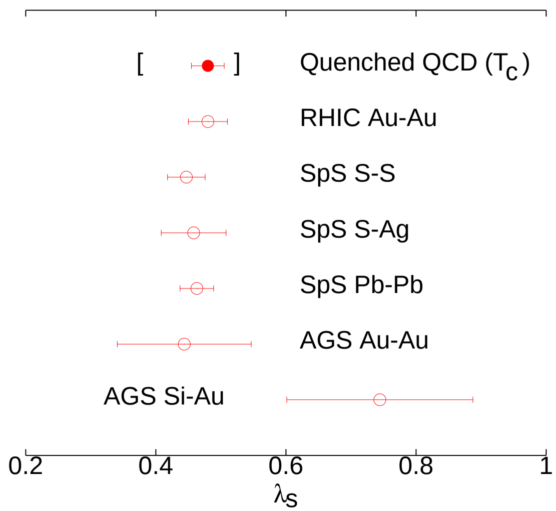
Baryon fluctuations considered by D. Bower and S. Gavin, Phys.Rev.C64:051902,2001

From lattice computations it is seen that

$$\begin{array}{ll} \chi_B < \chi_Q < \chi_s & (T > T_c) \\ \chi_B > \chi_Q > \chi_s & (T < T_c) \end{array}$$

R.V. Gavai, S. Gupta, P. Majumdar, Phys.Rev.D65:054506,2002

Strangeness: Wroblewski Parameter



$$\lambda_s \simeq \frac{2\chi_{ss}}{\chi_{uu}+\chi_{dd}} = \frac{\chi_{ss}}{\chi_{uu}}$$

R.V. Gavai and S. Gupta, Phys.Rev.D65:094515,2002

Correlators and susceptibilities

$$G(t,\mathbf{x}) = \left\langle \sum_{\mathbf{y}} O(t,\mathbf{x}+\mathbf{y})O^\dagger(\mathbf{y}) \right\rangle$$

$$G(\omega,\mathbf{k}) = \left(\frac{T}{V}\right) \sum_{t,\mathbf{x}} \mathrm{e}^{i\omega t,\mathbf{k}\cdot\mathbf{x}} G(t,\mathbf{x})$$

Quark number susceptibility

$$\chi = G(0,\mathbf{0}), \qquad \text{where} \qquad O = \overline{\psi}\gamma_0\psi$$

Limits $\omega \to 0$ and $\mathbf{k} \to \mathbf{0}$ can be taken in either order, since the lattice correlators are regulated objects.

Photon rates from the plasma

$$\omega \frac{dN}{dt d^3V d^3\mathbf{k}} = \frac{1}{(2\pi)^3} B(\omega) \mathrm{Im}\Pi^\mu_\mu(\omega, \mathbf{k}) \propto \frac{1}{(2\pi)^3} B(\omega) \rho(\omega, \mathbf{k})$$

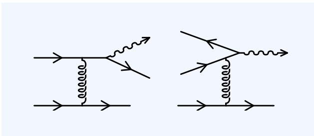
L. MacLerran and T. Toimela, Phys.Rev.D31:545,1985,

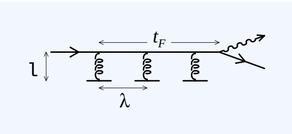
See F. Gelis, hep-ph/0209072 for a recent review.

1. Problems with perturbation theory
2. The first lattice computation
3. Further perturbative analysis
4. First results from a new lattice computation

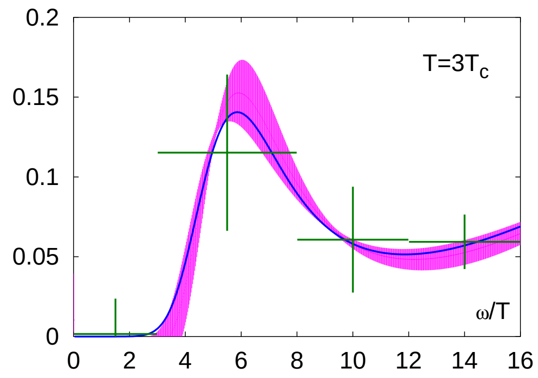
Perturbation theory for $\mathrm{Im}\Pi$

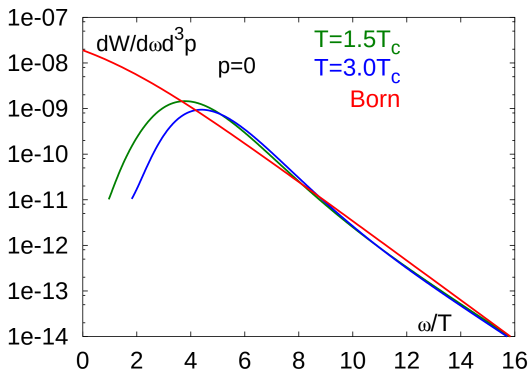
The main technicality is the treatment of internal quark lines which are nearly on-shell. Perturbation theory (after HTL resummation) at $\mathcal{O}(\alpha_s)$ seems to be in good shape when ω and the virtuality is large enough. However, there remain two related problems—

1. Collinear singularities from higher order diagrams contribute at lower order when an internal quark line has small virutality. 

2. Multiple scattering (LPM) of a hard quark gives a collisional width of order $\alpha_s T \log(1/\alpha_s)$ and hence needs all order resummations. 

The first lattice computation





F. Karsch et al, Phys.Lett.B530:147,2002

The spectral density is extracted from the Euclidean correlators by a Bayesian fit using the maximum entropy principle from the formula

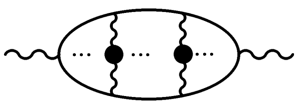
$$G(\tau) = \int_0^\infty d\omega \rho(\omega) K(\tau, \omega)$$

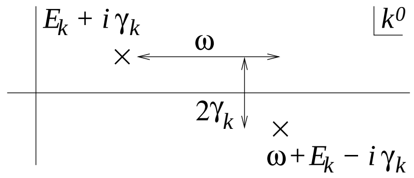
Full agreement with Born for $\omega/T \geq 4$

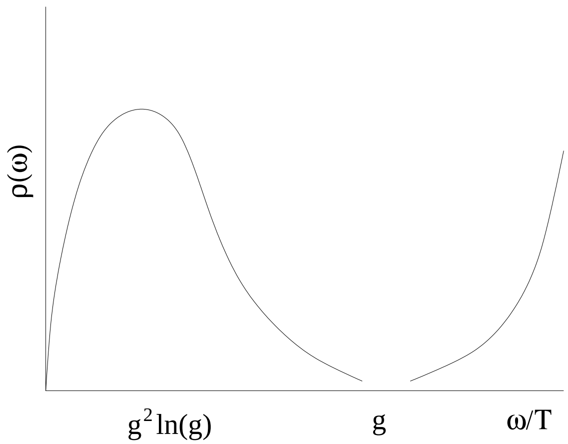
Transport and pinch

$$\sigma = \frac{1}{6} \frac{\partial}{\partial \omega} \rho(\omega, \mathbf{0}) \Big|_{\omega=0}, \qquad \text{where} \qquad \mathbf{j}_{EM} = \sigma \mathbf{E}.$$

There are pinch singularities at small external energy, ω, from ladder diagrams.



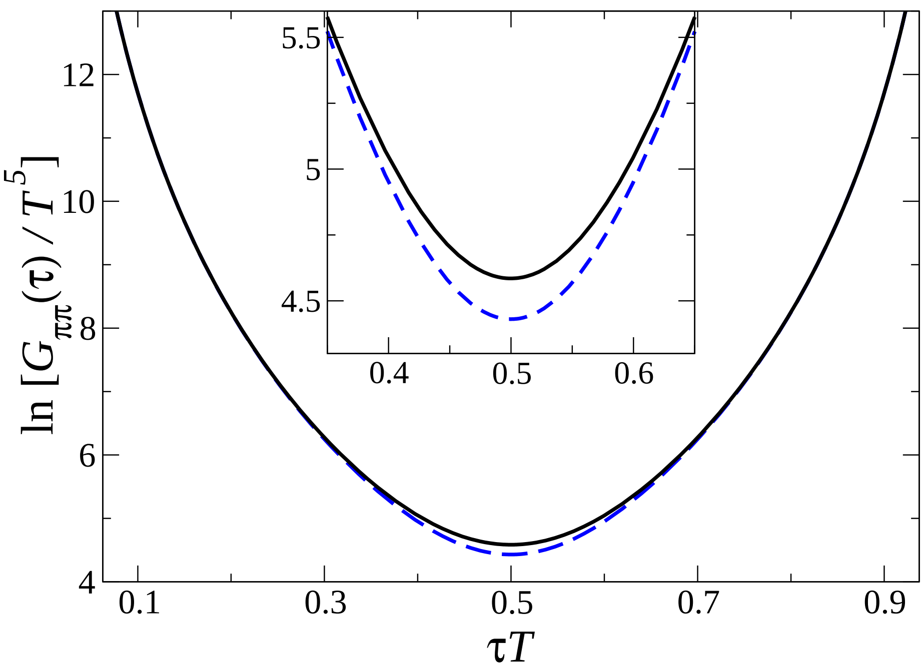




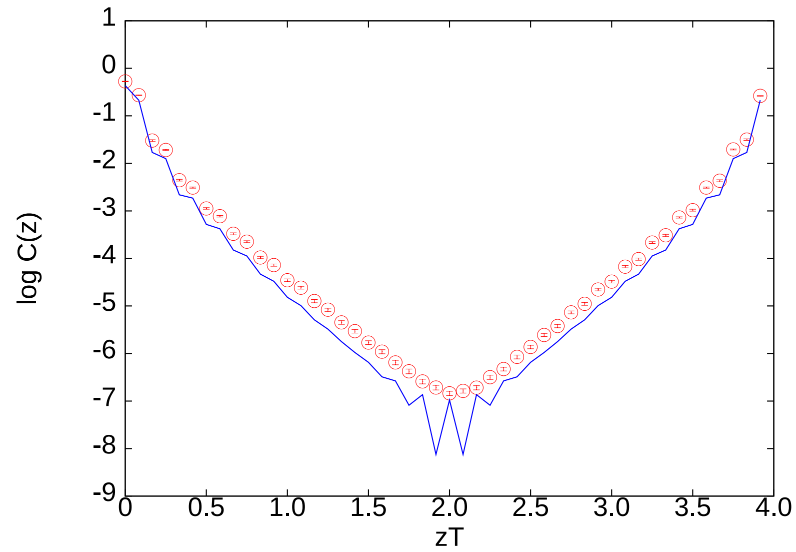
G. Aarts and J.M.M. Resco JHEP 0204:053,2002, hep-lat/0209033

Analysis of Euclidean correlators

$$\rho(\omega) = \frac{b\omega}{1 + c\omega^2} + \rho_H(\omega)$$



The electrical conductivity of the plasma



$$\frac{\chi}{T^2} = \frac{b}{2T} + \frac{\chi_H}{T^2}, \qquad \frac{\sigma}{T} = \frac{b}{6T} = \frac{\chi - \chi_H}{3T^2}$$

$$\frac{\sigma}{T} \simeq 2.4 \pm 0.4 \qquad (\text{at } T = 2T_c)$$

(not the) Conclusion

- First guides to the phenomenology of the QCD plasma from the lattice were computations of T_c and the order of the transition (included in Gavai's talk).

- Second generation of results are of direct use to phenomenology— ordering of fluctuations, the Wroblewski parameter in strangeness yields, virtual photon cross sections, and the first computations of transport coefficients. More results are in the pipeline (*e.g.*, direct computation of charmonium).

- Piles of data from RHIC need interpretation in terms of basic underlying QCD, in order to guide observations at the LHC. Need to supplement models by QCD computations.