Probing the sQGP in A-A collisions

by measuring energetic low-mass dileptons

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Analysis of measurements at RHIC: elliptic flow, viscosity, jet quenching,.. indicate a strongly interacting plasma different from QGP at high T

Top physics story of 2005 is the RHIC discovery of the strongly interacting quark-gluon plasma (called sQGP), which behaves almost like a perfect fluid, with very low viscosity

[T. D. Lee]

How to get reasonably direct information about the properties of the thermal quanta of the plasma?

[A. H. Mueller]

point of view in this talk

how to measure effects/phenomena due to quasiparticles and cuts (weak coupling) versus quasinormal black hole/brane modes (strong coupling)?

quasinormal modes have complex frequencies - there is a discrete infinity of them
in gravity: characteristic excited classical oscillations of (AdS-) black holes and black branes responding to generic perturbations - approach to thermal equilibrium

[review by Berti, Cardoso and Starinets (2009)]

illustrative example:
electromagnetic processes - retarded (R-) current-current correlators/Green's functions at high temperature

However, so far it is difficult to calculate the time dependent properties of thermal QCD in the strong coupling limit, i.e.

QCD-NONEQUILIBRIUM DYNAMICS

attractive alternative: **gauge-gravity duality**

canonical model: $\mathcal{N} = 4\ SU(N)$ SYM field theory in the large 't Hooft coupling limit

$$\lambda = g^2 N \to \infty, \text{ fixed } g << 1$$

holographically dual to AdS_5 classical black hole gravity

[Maldacena; Gubser et al.; Witten (1998)]

electromagnetic processes / $R-$current correlators

- heavy dileptons at rest: mass $Q >> T$

$$\frac{d\Gamma}{d^4q}|_{SYM} \simeq \frac{\alpha^2 N^2}{32\pi^4} n_B(Q/T)$$

independent on the coupling λ: pairs escape with a thermal spectrum essentially independent of the type of plasma!

[Huot et al. (2006)]

- energetic low-mass dileptons: $q^0 >> Q,\ Q < T$

$$R_{pQCD} = \frac{\Gamma^{(1)}}{\Gamma^{(0)}} \simeq \frac{4\pi\alpha_s}{3}\frac{T^2}{Q^2}\ln\frac{const}{\alpha_s}$$

$\Gamma^{(1)} \equiv$ Hard Thermal Loop real photon rate: dynamical screening of quark exchange by Landau damping

[Altherr and Ruuskanen (1992)]

low mass pairs $q^0 = \omega >> T$, cont.

strong coupling limit $\lambda \to \infty$:

$$q^0 \frac{d\Gamma_{ll}}{dM^2 d^3q}|_{SYM} \simeq \frac{\alpha^2}{4\pi^2 Q^2} \underbrace{\frac{N^2 T^2}{\Gamma^2(1/3)} (\frac{\omega}{6\pi T})^{2/3}} n_B(q^0)$$

[Huot et al. (2006)]

to note that this rate is related to the thermal (space-like) structure function $F_1(x = \frac{-Q^2}{2\omega T} \leq x_s \sim \frac{T}{\sqrt{-Q^2}}, Q^2 < 0)$

[Hatta, Iancu and Mueller (2007)]

remark: calculation based on Kroll-Wada formula (1955)

$$\frac{1}{2}\frac{d\Gamma_{ll}}{d^4q} = q^0 \frac{d\Gamma_{ll}}{dM^2 d^3q} \simeq \frac{\alpha}{3\pi Q^2} q^0 \frac{d\Gamma_\gamma}{d^3q}\,, m_l = 0,\ M = Q$$

low mass pairs $q^0 = \omega >> T$, cont.

Equivalently consider the ratio:

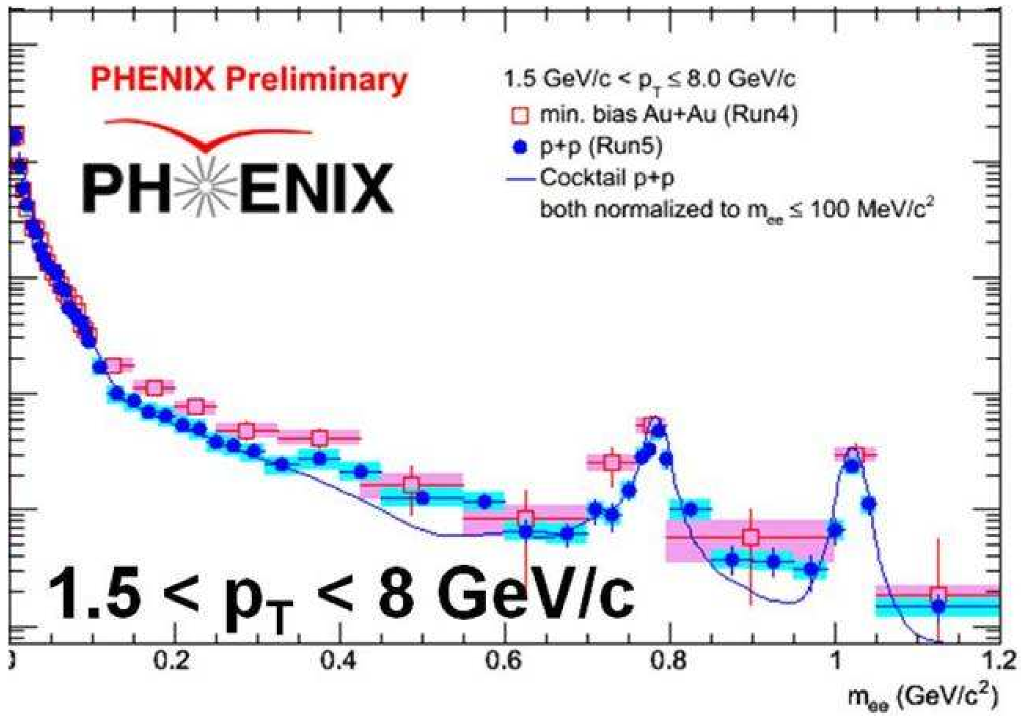
$$R(\lambda)|_{SYM} = \frac{\Gamma(\lambda \to \infty)}{\Gamma(\lambda \to 0)} \simeq \frac{12\pi^2}{\Gamma^2(1/3)} \frac{1}{\lambda \ln(1/\lambda)} \; (\frac{\omega}{6\pi T})^{2/3}$$

could indeed be large for $\omega >> T$,

showing a characteristic energy dependence in the strong coupling limit -
effectively due to quasinormal modes

cf.: RHIC data by PHENIX Collab.

mass distribution of e^+e^- pairs



$Au - Au$ data show a large enhancement at low mass, large p_T versus the pp cocktail

[Y. Akiba for PHENIX Collab. (2009)]

quasinormal modes

photon rates are proportional to the imaginary part of the retarded Green function $G_R(q^0 = \omega, \vec{q}),\ Q^2 = \omega^2 - q^2$

for discussion explicit analytical results are obtained in AdS_3, e.g. in $D = 1 + 1$ dimensions in the strong coupling limit of SYM (only ingoing waves near the horizon):

$$G_R(\hat{q}_+ = \frac{\omega + q}{2\pi T}, \hat{q}_- = \frac{\omega - q}{2\pi T}) \simeq \frac{Q^2}{T^2} \sum_{n=1}^{\infty} (\frac{\hat{q}_+}{\hat{q}_+ + 2in} + \frac{\hat{q}_-}{\hat{q}_- + 2in})$$

showing explicitly the quasinormal, even highly damped modes,

$$\omega = \pm q - 4\pi i T n\ ,\ \ overtone\ number\ n = 1, 2, ...,$$

i.e. discrete set of complex ω, independent of the coupling

[Birmingham (2001); Son and Starinets (2002)] with a smooth imaginary part:

$$\Im m G_R \simeq \frac{Q^2}{T^2}[\coth(\hat{q}_+/2) + \coth(\hat{q}_-/2)]$$

for fixed Q^2 and $\omega >> Q$:

$$\Im m G_R \simeq \frac{\omega}{T}$$

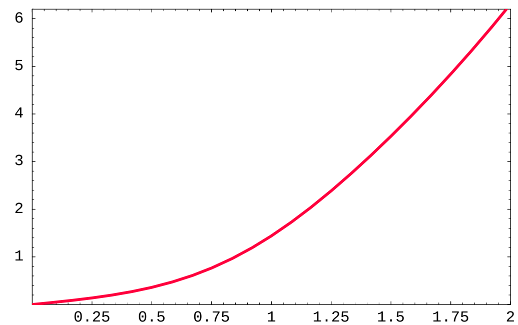
whereas for $q = 0$

$$\Im m G_R(x = \frac{\omega}{4\pi T}, q = 0) \simeq x^2 \coth\ x$$

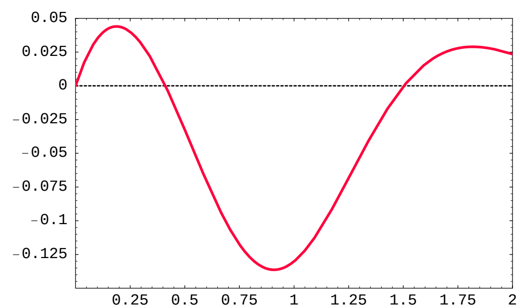
showing no quasiparticle peaks, as in the case for AdS_5

AdS_5

quasinormal poles at $\omega = 2\pi T(\pm n - in),\ n = 1, 2, ...$
$\Im m G_R(\omega, \vec{q} = 0)$ in AdS_5 plotted versus $\omega/2\pi T$:



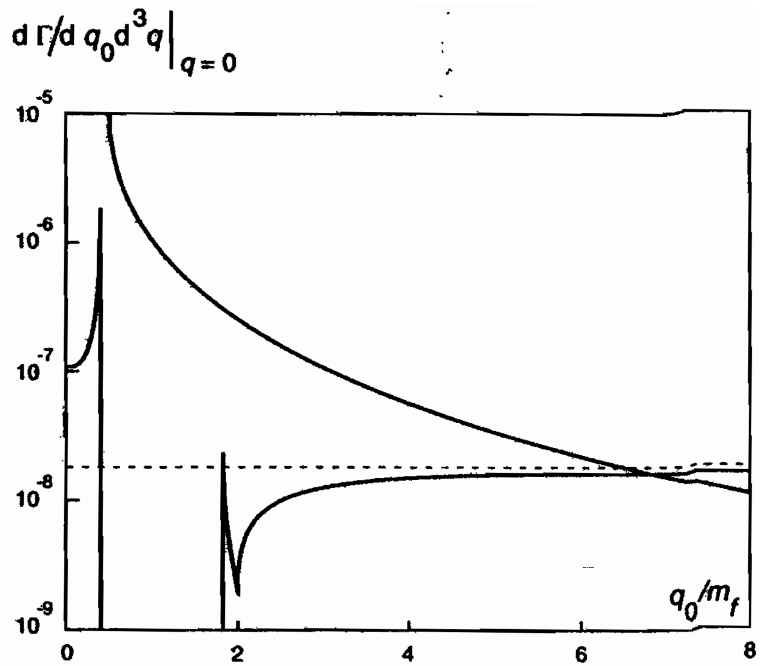
$T = 0$ contribution subtracted, oscillation around the $T = 0$ result:



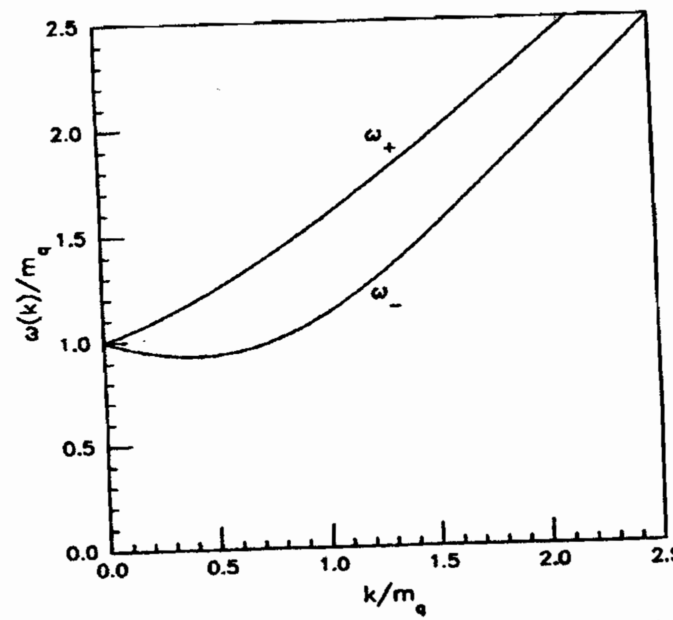
$\Im m G_R - \Im m G_R|_{T=0} \sim N^2 \omega^2 \exp(-\omega/2T) \cos \frac{\omega}{2T},\ \omega > T$

[Myers et al. (2006)]

HTL-soft dileptons



Dilepton production (adapted from Braaten, Pisarski and Yuan (1990)).

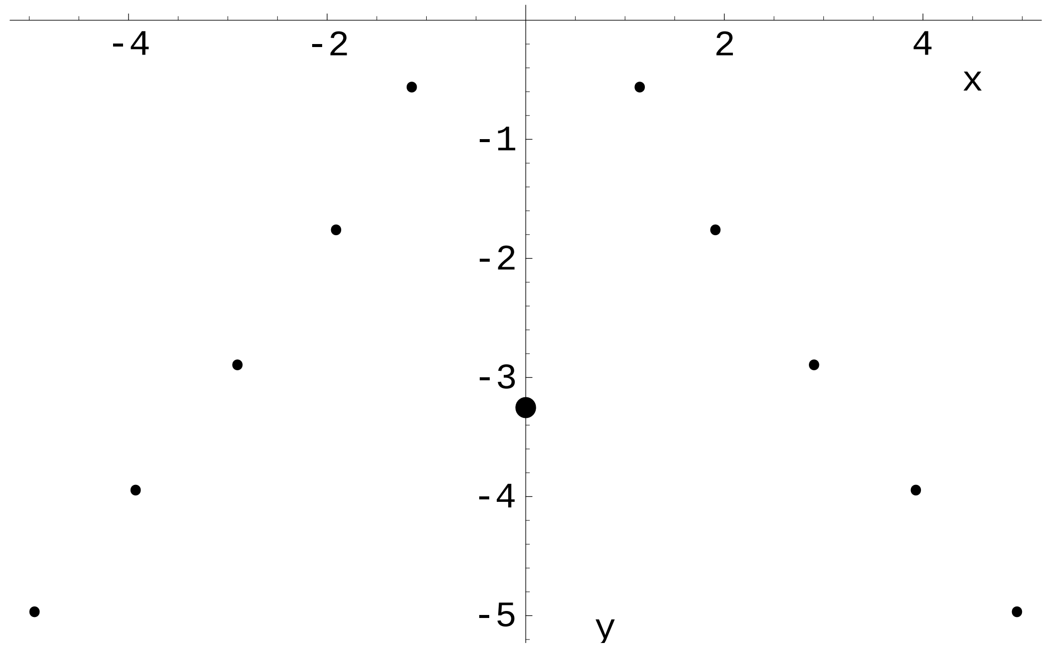


The quark dispersion relations $\omega_+(k)$ and $\omega_-(k)$.

remarkable structure of the dilepton rate (at rest) in the QCD-HTL approximation due to quasiparticle transitions (pole-pole contributions) and due collision processes involving hard quarks and gluons (cuts in the HTL quark propagator)

longitudinal field fluctuations

- AdS_5 -



quasinormal spectrum in the plane of complex $\omega/2\pi T$ and spatial momentum $q/2\pi T = 1$. The pole marked with a **large dot** is purely imaginary and is a manifestation of the diffusive relaxation of the R-charge density fluctuations $(\omega, q << T)$:

$$\omega = -iD_R q^2 + O(q^4),\ D_R = \frac{1}{2\pi T}$$

[Núñez and Starinets (2003)]

interpretation

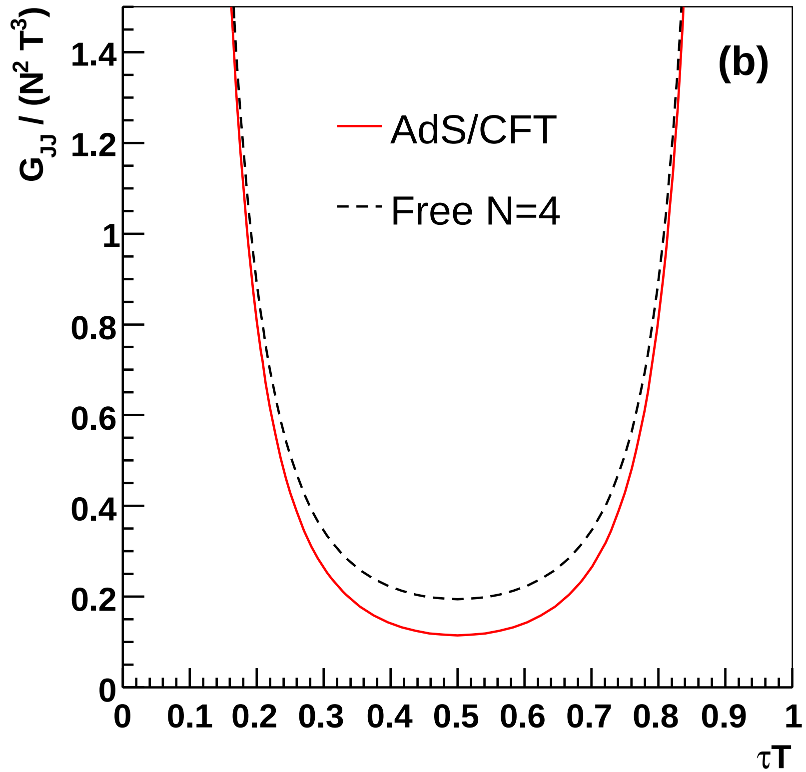
the interpretation of the non-diffusive and non-hydrodynamic quasinormal modes is obscured by the fact that still very little is known about thermal correlation functions at strong coupling. Poles associated with the quasinormal sequence, e.g.

$$\omega = 2\pi T(\pm n - in), \; n = 1, 2, ...$$

cannot be interpreted as quasiparticles of $\mathcal{N} = 4$ SYM, since their imaginary part is large!

at weak coupling the singularities of thermal correlators appear to be cuts - Landau damping - rather than poles with large imaginary frequencies

euclidean current-current correlator



the difference between the free ($\lambda = 0$) and interacting ($\lambda \to \infty$) $G_{JJ}(\tau, \vec{q} = 0),\ 0 \leq \tau \leq \beta = 1/T,$ is at most $20\ \%$ - how to differentiate strong versus weak coupling?

[Teaney (2006)]

sum rules

current-current correlator $\mathcal{N} = 4$ SYM spectral densities $\rho_{JJ} = -\Im m G_R/\pi$ at vanishing three momentum ($\vec{q} = 0$):

[taken from Teaney (2006) and Myers et al. (2006), resp.]

$$\delta\rho(\omega) \equiv \rho_{JJ}(\omega) - \rho_{JJ}(\omega)|_{T=0}$$

- strong coupling case ($\lambda \to \infty$):

$$\int_0^\infty \frac{d\omega}{\omega} \delta\rho(\omega) = 0$$

(c.f. sum rule for hydrodynamic mode [Romatschke and Son (2009)])

- free - one loop case ($\lambda = 0$):

$$\int_0^\infty \frac{d\omega}{\omega} \delta\rho(\omega) = \frac{N^2 T^2}{12}$$

with contributions only from the quasiparticles

questions

- at finite temperature the analytic structure of the frequency space propagator in perturbative field theory is qualitatively different to the strong coupling results obtained from perturbations about AdS black brane spacetimes:

quasiparticle poles and branch cuts (due to Landau damping) rather than towers of quasinormal poles

- is there a critical ’t Hooft coupling? [Hartnoll and Kumar (2005)]
- how to measure more directly these different structures?

- identify generic qualitative differences between weak and strong coupling $\rightarrow$ better signatures for novel plasma states?

Happy Birthday, Al !

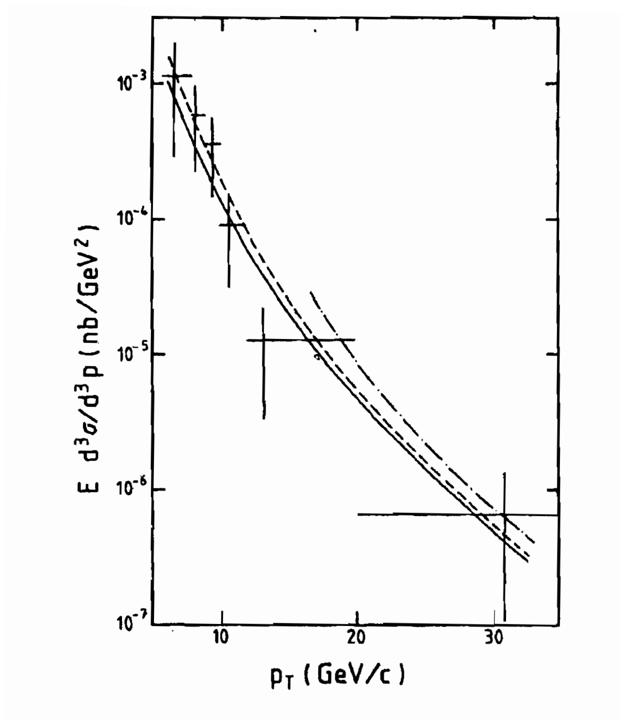
I am very grateful to your deep kindness during our collaboration, which started in 1995, together with different coworkers and friends during these couple of years

still I hope that we may find further possibilities and interesting problems to continue our common discussions

EXTRAS

$$pp \to \mu^+\mu^- X$$

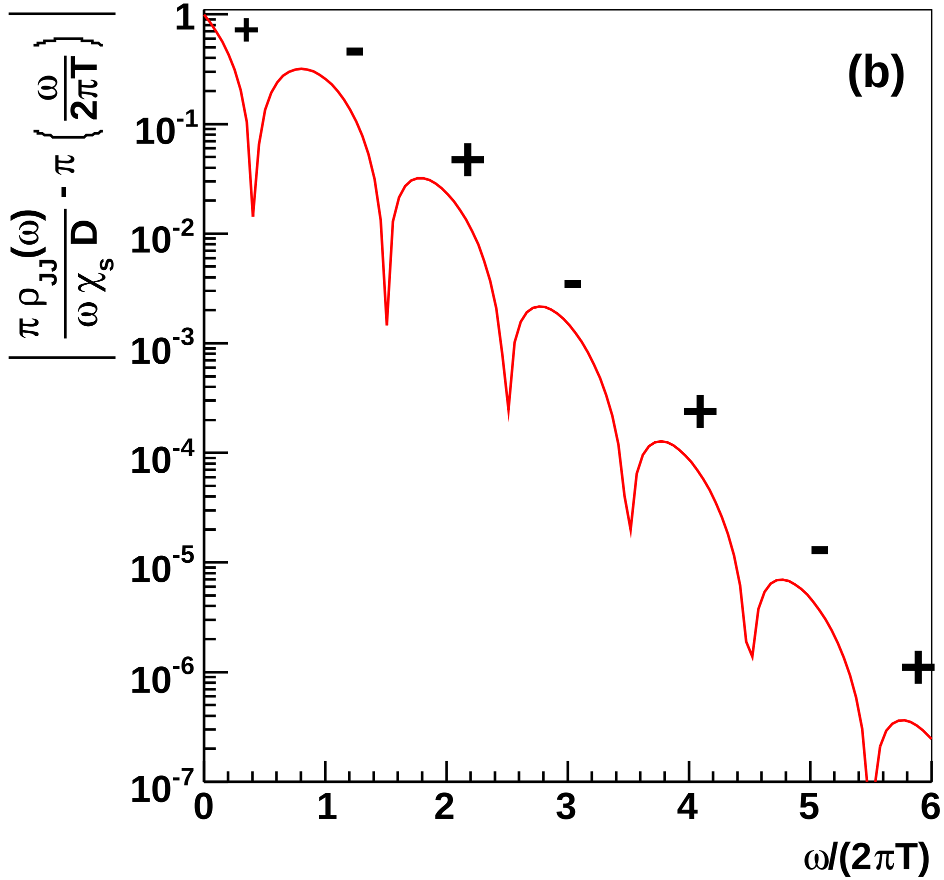
low-mass pairs at large p_T - using Kroll-Wada formula



UA1 data at $\sqrt{s} = 630\ GeV$, $M(\mu^+\mu^-) \leq 2.5\ GeV, y = 0$ successfully compared with prompt (isolated) large p_T photon calculations (curves)

[Aurenche, Baier and Fontannaz (1988)]
[also: Kang, Qiu and Vogelsang (2009)]

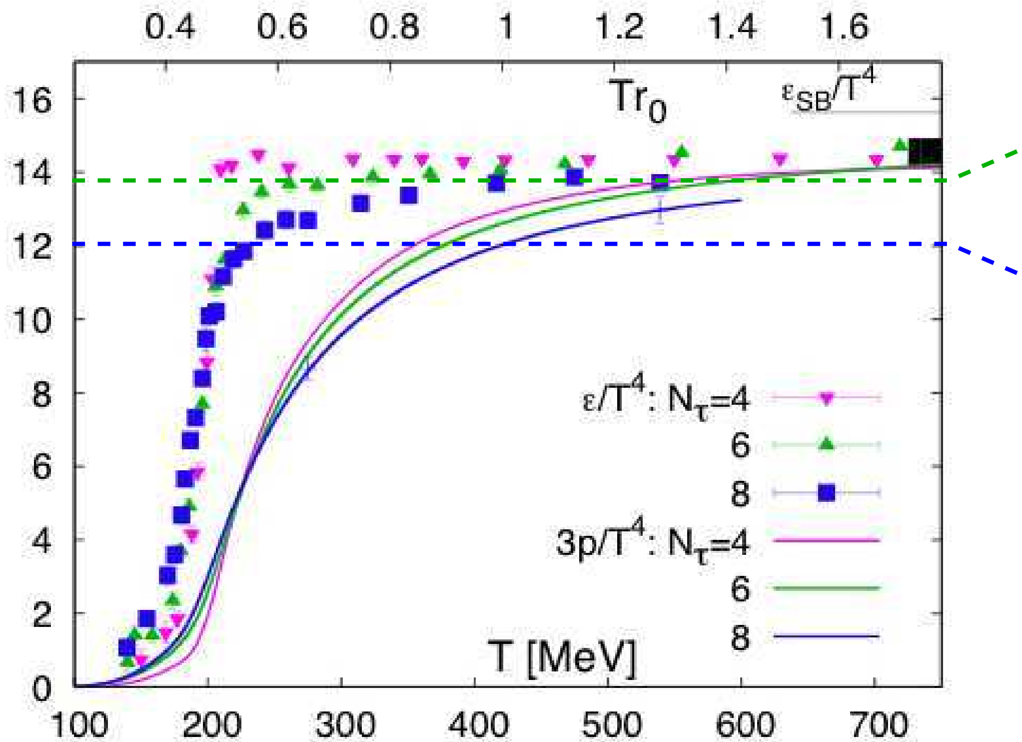
current-current correlator



finite temperature spectral density (zero temperature result subtracted)

[Teaney (2006)]

equation of state of QCD - $n_f = 0$ massless flavours

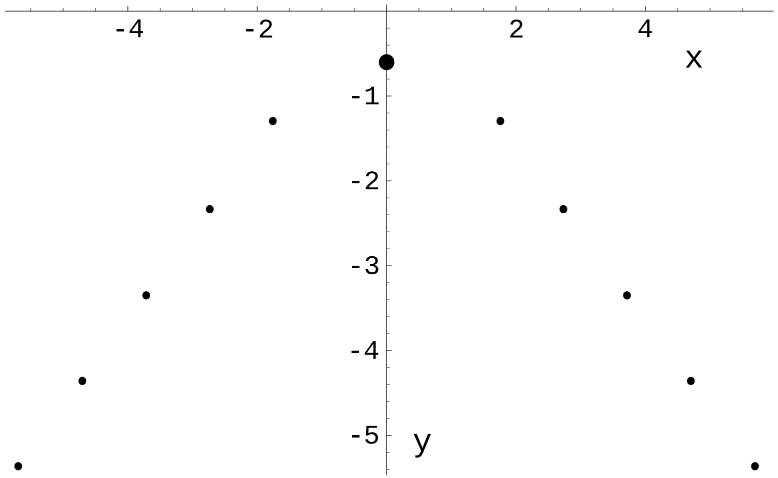


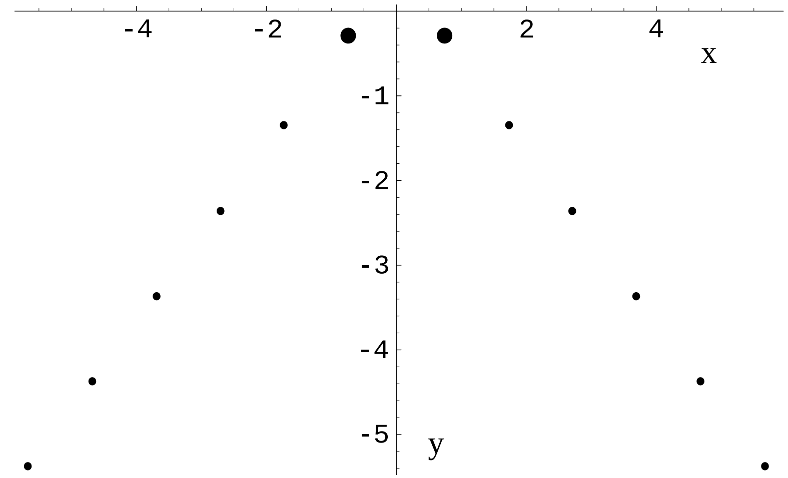
"a perilous comparison" with $\mathcal{N} = 4$ SYM:

$\frac{\epsilon}{\epsilon_{free}} = 0.88,\ \lambda = 5.5$ (dashed green); $\frac{\epsilon}{\epsilon_{free}} = 0.77,\ \lambda = 6\pi$ (dashed blue)

[A. Bazavov et al. (2009); Gubser (2009)]

hydrodynamic modes





quasinormal spectrum of black brane gravitational fluctuations in the shear and sound channels at fixed spatial momentum as a function of complex frequency

[Kovtun and Starinets (2005)]

hydrodynamic modes are marked by full dots, e.g.

$$\omega = -i\frac{\eta}{Ts}q^2 + O(q^3) = -i\frac{1}{4\pi T}q^2 + O(q^3)$$

[Kovtun, Son and Starinets (2005)]

momentum sum rules

for hydrodynamic excitations -
e.g. sum rule for the momentum correlator at $\vec{q} = 0$:

- interacting case ($\lambda \to \infty$):

$$\int_0^\infty \frac{d\omega}{\omega} \delta\rho^{yxyx}(\omega) = \frac{3\pi^2}{40} \, N^2 T^4 = \frac{\epsilon}{5}$$

[Romatschke and Son (2009)]

- free - one loop case ($\lambda = 0$):

$$\int_0^\infty \frac{d\omega}{\omega} \delta\rho^{yxyx}(\omega) = \frac{17\pi^2}{120} \, N^2 T^4 = \frac{17\epsilon_{free}}{60}$$