Emerging Theory of Strongly Coupled Quark-Gluon Plasma

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RHIC data have shown robust collective flows, including recent spectacular “conical flow” from quenched jets: that confirms that QGP above the critical line is in a strongly coupled regime. One way to study Non-Abelian classical strongly coupled plasmas is via molecular dynamics, which was recently extended to plasmas with electric and magnetic charges. First results on its transport (diffusion and viscosity) are reported. AdS/CFT correspondence is another actively pursuit approach to strong coupling regime: we review new results for heavy quark motion and even complete picture of conical flow, obtained from linearized gravity dual. Recent developments in (non-linearized) gravity aims at reproduction of the whole time-dependent picture of the explosion. We finally compare transport properties obtained from RHIC data to those obtained in MD and AdS/CFT.

§1. Why strongly coupled?

A realization\textsuperscript{1–3)} that QGP at RHIC is not a weakly coupled gas but rather a strongly coupled liquid has lead to a paradigm shift in the field. It was extensively debated at the “discovery” BNL workshop in 2004 and multiple other meetings since. The experimental situation was then summarized by “white papers” of four RHIC experiments, who basically confirmed this picture. In the last 4 years strong efforts has been made to understand why QGP (at least) at $T = (1 - 2)T_c$ is strongly coupled, and what exactly it means. Another formidable “old” problem is that of confinement/deconfinement, which got new attention lately. We have learned a lot from other branches of physics which had experience with strongly coupled systems: atomic gases in strongly coupled regime, classical plasmas and AdS/CFT. Those provided important clues: but we are somewhere in the middle of the process, just starting to see how it all makes a common picture.

The list of arguments explaining why we think QGP is strongly coupled at $T > T_c$ is long and constantly growing:

1. \textbf{Phenomenology}: Collective flows observed at RHIC lead hydro practitioners to a conclusion that QGP as a “near perfect liquid”, with unexpectedly small viscosity-to-entropy ratio $\eta/s = .1 - .2 \ll 1$ in striking contrast to pQCD predictions. Charmed and possibly even b quarks are strongly quenched: their diffusion constant $D_c$ (deduced from the data on single electron quenching and elliptic flow) is much lower than pQCD expectations.

2. \textbf{Lattice/spectroscopy}: Lattice data suggest rather heavy quasiparticles and strong interparticle potentials, combining the two one finds a lot of quasiparticle bound states.\textsuperscript{2)} That is why $\eta, J/\psi$ remain bound at $T = (1 - 2)T_c$, as found on the lattice\textsuperscript{5)} (and also at RHIC). Heavy-light resonances help to explain charm

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Near-zero bound states (Feshbach-type resonances) are known to turn dilute ultracold trapped atoms into a strongly coupled liquid with small viscosity.\(^2\),\(^6\)

3. **Classical plasmas**: The interaction parameter \(\Gamma \sim \frac{<\text{pot.\,energy}>}{<\text{kin.\,energy}>}\), is not small in sQGP. Classical electromagnetic plasmas at comparable coupling \(\Gamma \sim 1 - 10\) are also good liquids. This is also true for non-Abelian plasmas,\(^8\) as well as plasmas containing magnetic monopoles.\(^9\)

4. **AdS/CFT** correspondence between conformal field theory (CFT) \(\mathcal{N}=4\) supersymmetric YM at strong coupling and string theory in Anti-de-Sitter space (AdS) in weak coupling is the basis for many intriguing results on the CFT plasma properties. Those are generally close to what is observed for sQGP: both are good liquids with record low viscosity, which strongly quench heavy quarks, generate conical flow and have rapid onset of hydro regime.

5. **Electric–Magnetic duality** is perhaps the key to confinement. In the “Seiberg-Witten” theory \(\mathcal{N}=2\) SUSY YM confinement is induced by monopole condensation. In QGP, as \(T\) decreases toward \(T_c\), one finds rapid activation of magnetic monopoles. U(1) beta function demands they are weakly coupled in IR. Then, due to Dirac condition, electric coupling is forced to be strongly coupled. Uncondensed monopoles\(^9\) seem to be an important player in the sQGP close to \(T_c\).

§2. **Collective Flows in Heavy Ion Collisions**

Collective radial and elliptic flows, related with explosive behavior of hot matter, observed at SPS and RHIC, are quite accurately reproduced by the ideal hydrodynamics. The so-called *conical flow*\(^10\) is a hydrodynamical phenomenon induced by jets quenched in sQGP. Fig.\(\Pi\)(a) explains a view of the process, in a plane transverse to the beam. Two oppositely moving jets originate from the hard collision point B. Due to strong quenching, the survival of the trigger jet biases it to be produced close to the surface and to move outward. This forces its companion to move inward through matter and to be maximally quenched. The energy deposition starts at point B, thus a spherical sound wave appears (the dashed circle in Fig.\(\Pi\)). Further energy deposition is along the jet line, and is propagating with a speed of light, till the leading parton is found at point A at the moment of the snapshot. The main prediction is that associated secondaries fly preferentially to a very large angle \(\approx 70\) degrees relative to jet, which is consistent with the Mach angle for (a time-averaged) speed of sound. As shown in Fig.\(\Pi\)(b), this seems to be what indeed is observed. Its studies at RHIC has been extended to 3-particle correlations, which confirmed conical structure of the effect. The 2-particle signal for conical flow has been reported at SPS by CERES collaboration (see proc. of QM06). These observation further proves that viscosity of the produced matter is small enough, allowing these waves too survive till freezeout time and be observed in spectra.

Antinori and myself\(^11\) suggested that b-quark jets, which can be tagged experimentally, will further test that the angle depend on velocity, not momentum, of the jets: the cone should then shrink to zero angle at \(v = c_s = 1/\sqrt{3}\). Casalderrey and myself\(^12\) have shown, using conservation of adiabatic invariants, that fireball expansion should in fact greatly enhance the sonic boom (like tsunami going onshore).
Fig. 1. (a) A schematic picture of flow created by a jet going through the fireball. The trigger jet is going to the right from the origination point B. The companion quenched jet is moving to the left, heating the matter (in shadowed area) and producing a shock cone with a flow normal to it, at the Mach angle \( \cos \theta_M = v/c_s \), where \( v, c_s \) are jet and sound velocities. (b) The background subtracted correlation functions from STAR and PHENIX experiments, a distribution in azimuthal angle \( \Delta \phi \) between the trigger jet and associated particle. Unlike in pp and \( dAu \) collisions where the decay of the companion jet create a peak at \( \Delta \phi = \pi \) (STAR plot), central \( AuAu \) collisions show a minimum at that angle and a maximum corresponding to the Mach angle (downward arrows).

§3. QGP with magnetic quasiparticles

We have already mentioned that electric-magnetic duality and Dirac quantization condition may provide a clue to why QGP is so strongly coupled. This part of the story is relatively new, in spite of many studies of magnetic excitations on the lattice, especially in Japan. We start with the overall picture we proposed, returning to brief discussion of its motivation later.

The picture proposed is different from the traditional approach, which puts confinement phenomenon at the center of the discussion, dividing the phase diagram into (i) confined/hadronic phase and (ii) deconfined or QGP phase. We however focus on the competition of electric and magnetic quasiparticles, and divide the phase diagram into (i) “magnetically dominated” region at lower \( T, \mu \) and (ii) “electrically dominated” one at large \( T, \mu \), separated by “E-M equilibrium” line at which the couplings of both interactions are equal:

\[
g_e^2/4\pi \hbar c = g_m^2/4\pi \hbar c = 1 \tag{3.1}\]

The last equality follows from the celebrated Dirac quantization condition

\[
g_e g_m/4\pi \hbar c = n/2 \tag{3.2}\]

\(^*\) We use field theory notations, in which \( g_e, g_m \) are electric and magnetic couplings, e/m duality transformation is \( \tau \rightarrow -1/\tau \) where \( \tau = \theta/2\pi + i4\pi/g_e^2 \). \( g_e = g \) and \( \hbar = c = 1 \) elsewhere.
with \( n \) being an integer, put to 2 because of adjoint color charge of relevant monopoles.

The “magnetic-dominated” low-\( T \) (and low-\( \mu \)) region (i) can in turn be subdivided into the *confining* part (i-a) in which electric field is confined into quantized flux tubes by magnetic condensate,\(^{14}\) and a new “postconfinement” region (i-b) at \( T_c < T < T_{E=M} \) in which electric sector is still strongly coupled and sub-dominant. We believe this picture better corresponds to a situation in which string-related physics is by no means terminated at \( T = T_c \); rather it is at its maximum there. Then if leaving this “magnetic-dominated” region and passing through the equilibrium region by increase of \( T \) and/or \( \mu \), we enter either the high-\( T \) “electric-dominated” QGP or a (color)electric superconductor at high-\( \mu \) replacing magnetic superconductor. (Electric diquark condensate obviously confine monopoles.) A phase diagram explaining this pictorially is shown in Fig.2(a).

Besides equal couplings, the equilibrium region is also presumably characterized by comparable densities as well as masses of both electric and magnetic quasiparticles. In QCD the issue is complicated by the fact that E-M duality is far from perfect, with different spins of electric (gluons and quarks) and magnetic quasiparticles. However other theories – especially \( \mathcal{N}=4 \) supersymmetric YM – have perfect self-duality of electric and magnetic description: it is also conformal and has no confinement to complicate the picture, while E and M-dominated parameter regions do exist\(^*\) see some discussion of e/m duality in this theory in.\(^{16}\)

Now brief motivations of this picture. One is well known t’Hooft-Mandelstamm scenario, in which the confined phase is a “dual superconductor”. If so, there should be uncondensed magnetic objects above \( T_c \) as well. And indeed, lattice studies show that electrically charged particles – quarks and gluons – are getting heavier as we decrease \( T \) toward \( T_c \), while monopoles gets lighter and more numerous.

The magnetic screening mass, although absent perturbatively, is nonzero, and even exceeds the electric one close to \( T_c \) (as shown e.g. by Nakamura et al\(^{17}\)). These screening masses as well as estimates of the densities of electric and magnetic objects, leads to the location of \( E-M \) equilibrium\(^9\) at

\[
T_{E=M} \approx (1.2 - 1.5)T_c = 250 - 300 \text{ MeV}
\]  

Another lattice-based puzzle is related with static \( \bar{Q}Q \) potentials close to \( T_c \). At deconfinement \( T = T_c \) a static quark pair has vanishing string tension in the free energy \( \exp(-F(T,r)) = \langle W \rangle \). However if one calculates the energy or entropy separately (by \( F = E - TS \), \( S = -\partial F/\partial T \)) one finds\(^{35}\) that the tension more than twice that in the vacuum, till rather large distances. The total energy added to a pair is surprisingly large, reaching \( E(T = T_c, r \to \infty) = 3 - 4 \text{ GeV} \), while the entropy \( S(T = T_c, r \to \infty) \sim 20 \).

Where all this energy and entropy may come from in the plasma phase? Most likely it is due to QCD string, surviving above \( T_c \) in some form. Liao and myself\(^{34}\) suggested “electric” approach toward solving this puzzle, by “polymerization” of gluonic quasiparticles in sQGP. “Magnetic” effect is that monopoles further compress

\(^*\) Not in the phase diagram, as in this theory couplings are independent of \( T, \mu \).
the electric flux tube, as their dual – electrons in solar plasma – do for magnetic flux tubes.

Are there bound states of electric and magnetic quasiparticles? Yes, there are a lot of them. A surprise is that even finite-$T$ instantons can be viewed as “magnetic baryons” being made of $N_c$ self-dual dyons,\(^{15}\) attracted to each other pair-wise, both electrically and magnetically. Not only such baryons-made-of-dyons have the same moduli space as instantons, the solutions can be obtained via very interesting AdS/CFT brane construction.\(^ {36}\) Many more exotic bound states of those are surely waiting to be discovered.

Transport properties of strongly coupled plasmas is a non-trivial issue. Especially let us ask what is the role of magnetic quasiparticles, as they may not be strongly coupled?

These issues were recently addressed using molecular dynamics (MD) methods of classical strongly coupled plasmas. In $e/m$ context the term “strongly coupled” is expressed via parameter $\Gamma = (Ze)^2/(a_{WS} T)$ characterizing the strength of the interparticle interaction. $Ze,a_{WS},T$ are respectively the charge, the Wigner-Seitz radius $a_{WT} = (3/4\pi n)^{1/3}$ and the temperature. Extensive studies using both MD and analytical methods, have revealed the following regimes: i. a gas regime for $\Gamma < 1$; ii. a liquid regime for $\Gamma \approx 10$; iii. a glass regime for $\Gamma \approx 100$; iv. a solid

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Fig. 2. (color online) (a) A schematic phase diagram on a (“compactified”) plane of temperature and baryonic chemical potential $T - \mu$. The (blue) shaded region shows “magnetically dominated” region $g < e$, which includes the e-confined hadronic phase as well as “postconfined” part of the QGP domain. Light region includes “electrically dominated” part of QGP and also color superconductivity (CS) region, which has e-charged diquark condensates and therefore obviously m-confined. The dashed line called “$e=$g line” is the line of electric-magnetic equilibrium. The solid lines indicate true phase transitions, while the dash-dotted line is a deconfinement cross-over line. (b) Plots of Log[1/(η/s)] v.s. Log[1/(2πTD)] including results from our MD simulations, the Ads/CFT calculations, the weakly coupled CFT calculations, as compared with experimental values. M00,M25,M50 mean 0,25 and 50% of monopoles in plasma.
regime for $\Gamma > 300$.

Gelman, Zahed and myself\(^8\) proposed a model for the description of strongly interacting quarks and gluon quasiparticles as a classical and nonrelativistic Non–Abelian Coulomb gas. The sign and strength of the inter-particle interactions are fixed by the scalar product of their classical color vectors subject to Wong’s equations.

The model was studied using Molecular Dynamics (MD), which means solving numerically EoM for $n \sim 10^2 - 10^3$ particles. As the Coulomb coupling is increased, we found at parameters corresponding to sQGP liquid-like, with a diffusion constant $D \approx 0.1/T$ and a bulk viscosity to entropy density ratio $\eta/s \approx 1/3$. Unfortunately there is no place here to show how diffusion and viscosity depends on coupling: we will discuss their interrelation in the Summary.

**Plasma with magnetic charges** was studied in\(^9\) by molecular dynamics. Unlike earlier works, it does not use periodic box but (self-contained) drops of plasma. Although in this case the system is not homogeneous, it allows to consider much larger systems. Simulations included transport properties such as diffusion coefficients and viscosity. A number of collective modes have been discovered, and their oscillation frequencies and damping parameters calculated. The results we will show in the next section, together with those from AdS/CFT correspondence.

§4. *AdS/CFT correspondence and CFT plasma properties*

Let me omit well known results on thermodynamics, heavy-quark potentials and viscosity\(^\ast\). Let me just remind that the Debye radius at strong coupling is unusual: unlike in pQCD it has no coupling constant. Although potential depends on distance $r$ still as in the Coulomb law, $1/r$ (at $T = 0$ it is due to conformity), it is has a notorious square root of the coupling. Semenoff and Zarembo\(^{21}\) noticed that summing ladder diagrams one can explain $\sqrt{g^2 N_c}$, although not a numerical constant. Zahed and myself\(^3\) pointed out that both static charges are color correlated during a parametrically small time $\delta t \sim r/(g^2 N_c)^{1/4}$: this explains\(^{22}\) why a field of the dipole is $1/r^7$ at large distance,\(^{22}\) not $1/r^6$. Debye screening range can also be explained by resummation of thermal polarizations.\(^3\) In another paper Zahed and myself\(^{23}\) had also discussed the velocity-dependent forces, as well as spin-spin and spin-orbit ones, at strong coupling. Using ladder resummation for non-parallel Wilson lines with spin they concluded that all of them join into one common square root

$$V(T, r, g) \sim \sqrt{(g^2 N_c)[1 - \vec{v}_1 \cdot \vec{v}_2 + (\text{spin} - \text{spin}) + (\text{spin} - \text{orbit})]/r} \quad (4.1)$$

Here $\vec{v}_1, \vec{v}_2$ are velocities of the quarks: and the corresponding term is a strong coupling version of Ampere’s interaction between two currents\(^{**}\). No results on that are known from a gravity side.

\(^\ast\) See Son’s talk in the same proceedings.

\(^**\) Note that in a quarkonium their scalar product is negative, increasing attraction.
Bound states of fundamental particles should be present in any strongly coupled theory. Zahed and myself looked for heavy quarks bound states, using a Coulombic potential with Maldacena’s \( \sqrt{g^2 N_c} \) and Klein-Gordon/Dirac eqns. There is no problem with states at large orbital momentum \( J \gg \sqrt{g^2 N_c} \), but otherwise one has the famous “falling on a center” solutions: we argued that a significant density of bound states develops, at all energies, from zero to \( 2M_{HQ} \).

And yet, a study of the gravity side found that there is no falling. In more detail, the Coulombic states at large \( J \) are supplemented by two more families: Regge ones with the mass \( \sim M_{HQ}/(g^2 N_c)^{1/4} \) and the lowest s-wave states (one may call \( \eta_c, J/\psi \)) with even smaller masses \( \sim M_{HQ}/\sqrt{g^2 N_c} \). The issue of “falling” was further discussed by Klebanov, Maldacena and Thorn for a pair of static quarks: they calculated the spectral density of states via a semiclassical quantization of string vibrations. They argued that their corresponding density of states should appear at exactly the same critical coupling as the famous “falling” in the Klein-Gordon eqn..

AdS/CFT also has multi-body states similar to “polymeric chains” discussed for sQGP in. Hong, Yoon and Strassler have studied such states when the endpoints are static quarks, and the intermediate gluons are conveniently replaced by adjoint scalars, so that one can use their “flavor” to see how long the chain is.

Heavy quark transport in the CFT plasma was a subject of recent breakthroughs. Heavy quark diffusion constant has been calculated by Casalderrey-Solana and Teaney:

\[
D_{HQ} = \frac{2}{\pi T \sqrt{g^2 N_c}}
\]

which leads to stopping length much smaller than an expression for the momentum diffusion \( D_p = \eta/(\epsilon + p) \sim 1/4\pi T \). This work is methodically quite different from others: one has to use full Kruskal coordinates, including the inside of the black hole connecting two Universes (with opposite time directions) simultaneously, see Fig.3 Further important result is calculation of the mean transverse energy squared per unit length (1/2 of the popular parameter \( \hat{q} \) for a gluon) for a quark moving with gamma factor \( \gamma = 1/\sqrt{1 - v^2} \)

\[
k_t = \sqrt{\gamma \lambda \pi T^3}
\]

Jet quenching studies by many authors have resulted in the following expression for the drag force

\[
\frac{dP}{dt} = \frac{\pi T^2 \sqrt{g^2 N_c v}}{2\sqrt{1 - v^2}}
\]
Quite remarkably, the Einstein relation which relates the heavy quark diffusion constant (given above) to the drag force is actually fulfilled, in spite of quite different gravity settings. This result is valid in a stationary setting, in which a quark is dragged with constant velocity \( v \) by “an invisible hand”, see Fig.3b. Friess et al\(^{29}\) then solved linearized Einstein equations and found corrections to the metric \( h_{\mu\nu} \) induced by a falling string, obtaining the stress tensor of floating matter on the brane. Quite remarkably, when they analyzed harmonics of this stress at small momenta they have found the “conical flow”, disappearing at “subsonic” \( v < 1/\sqrt{3} \) and peaked at the Mach cone. Recent studies of near-zone flow\(^{46}\) found that picture changes at velocity a bit above the speed of sound, and a different angle of the maximum. This indeed should happen because finite amplitude shocks do propagate with a speed \textit{larger} than that of sound.

**“Gravity duals”** to complete hydrodynamical explosion is perhaps the ultimate AdS/CFT application: but unfortunately solving non-linearized Einstein equations with evolving black holes is a very challenging task, both conceptually and technically.

The need for \textit{dynamically generated} black hole (BH), corresponding to thermal fireball, was suggested by Nastase.\(^{31}\) Sin, Zahed and myself\(^{32}\) pointed out that exploding/cooling fireball on the brane is dual to \textit{departing} black hole, falling toward the AdS center. Although specific solution discussed in that paper has a brane departing from a static black hole, corresponding to spherically symmetric solution with a time-dependent \( T \), we also suggested three d-dimensional toy problems, corresponding for \( d=1 \) to a collision of two walls and subsequent Bjorken rapidity-independent expansion, with 2d and 3d corresponding to cylindrical and spherical collapses. Janik and Peschanski\(^{39}\) soon found asymptotic (late-time) solution corresponding to \( d=1 \) rapidity-independent Bjorken expansion. It indeed has a departing \textit{horizon} at the 5-th distance \( z_h \sim \tau^{1/3} \) Further discussion of the first subleading terms \( O(\tau^{-2/3}) \) has been made by Sin and Nakamura\(^{40}\) who identified them with the viscosity effects, although without any preference for its particular value. Janik\(^{42}\)
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derived next sub-sub-leading term $O(\tau^{-4/3})$ and provided some argument why viscosity should be what was found in equilibrium. Lin and myself have discussed a process of BH formation, by studying motion of various objects in the 5-th direction. They concluded that all strings, closed or open, quickly form a thin shell (or 3d-membrane) of matter, which is gravitationally collapsing toward the AdS center, and related its EoM to Israel junction equations for the motion of collapsing shell.

Princeton group pointed out that global static black-hole-AdS metric can be seen from viewpoint of a moving observer, which is nevertheless living in asymptotically flat Minkowskian world. This provides nice analytic solution with incoming and then departing BH, corresponding to $d=3$ spherical explosion at the boundary. This explosion is however exactly reversible, conserving the entropy. Elliptic deformation of this solution leads to hydrodynamics with dissipation. First the value of the damping for corresponding modes have not matched the expected CFT viscosity, but this was then corrected by Michalogiorgakis and Pufu, and Siopsis who pointed out that the usual Dirichlet condition on the boundary are to be modified.

§5. Summary of transport properties

Finally, we would like to compare our results with those obtained using the AdS/CFT correspondence and also with empirical data about sQGP from RHIC experiments. Those are summarized in Fig.2(b), as a log-log plot of properly normalized (heavy quark) diffusion constant and viscosity.

The dashed curve in the left lower corner is for $\mathcal{N}=4$ SUSY YM theory in weak coupling, where viscosity is from and diffusion constant from. The curve has a slope of one on this plot, as in weak coupling both quantities are proportional to the same mean free path. Note that weak coupling results are quite far from empirical data from RHIC, shown by a gray oval in the right upper corner. Viscosity estimates follow from deviations of the elliptic flow at large $p_t$ from hydro predictions while diffusion constants are estimated from $R_{AA}$ and elliptic flow of charm.

The curve for strong-coupling AdS/CFT results (viscosity according to with $O(\lambda^{-3/2})$ correction, diffusion constant from), shown by upper dashed line, is on the other hand going right through the empirical region. At infinite coupling this curve reaches $s/\eta = 4\pi$ which is conjectured to be its bound. Our MD results – three solid lines on the right – correspond to our calculations with different ratio of electric/magnetic quasiparticles. The overall behavior of these so different approaches, as well as proximity to the empirical range, is very encouraging.

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