Quark-Gluon Plasma - New Frontiers

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Abstract. As implied by organizers, this talk is not a conference summary but rather an outline of progress/challenges/“frontiers” of the theory. Some fundamental questions addressed are: Why is sQGP such a good liquid? Do we understand (de)confinement and what do we know about “magnetic” objects creating it? Can we understand the AdS/CFT predictions, from the gauge theory side? Can they be tested experimentally? Can AdS/CFT duality help us understand rapid equilibration/entropy production? Can we work out a complete dynamical “gravity dual” to heavy ion collisions?

Heavy ion experiments continue to surprise us. At this conference SPS experiments provided first dilepton flows from NA60, and “conical flow” from CERES. STAR and PHENIX at RHIC showed a lot of new data on jet quenching and jet correlations. Apparent absence of color Casimir factors in gluon/quark jets plus “conical flow” suggests sound radiation rather than gluonic one. Heavy quark quenching is another part of this puzzle: and we learned that up to a half of single electrons at the highest $p_t$ came from b quarks, we may soon learn the rate of b quenching. With coming LHC and the long-awaited low energy scan at RHIC, we will surely have more surprises ahead.

The situation in theory is still profoundly affected by the paradigm shift occurred around 2003, to the strong-coupling regime. We are still in so-to-say non-equilibrium transition, as huge amount of physics issues required to be learned. Some came from other fields, including physics of strongly coupled QED plasmas and trapped ultracold gases with large scattering length. String theory provided a remarkable tool – the AdS/CFT correspondence – which related heavy ions to the fascinating physics of strong gravity and black holes. Another important trend is that transport properties of QGP and non-equilibrium dynamics came to the forefront: and for those the Euclidean approaches (lattice, instantons) we used before is much less suited than for thermodynamics. All of it made the last 5 years the time of unprecedented challenges.

1. Pushing hydrodynamics beyond the O(10%) level

It is well known by now that hydro description of the QGP phase supplemented by hadronic cascades [1] provides excellent description of RHIC data. Radial and elliptic flow of various secondaries, as a function of centrality, rapidity or energy are reproduced.
till $p_t \sim 2 GeV$, which is 99% of particles. Contrary to predictions of some, CuCu data match AuAu well, so Cu is large enough to be treated hydrodynamically. New hydro phenomenon – the “conical flow” [2] from jets – got strong conformation at QM08 from 3-particle data from STAR and PHENIX.

Thus sQGP is the most perfect liquid known; before discuss why is it so, let us see how perfect is it? New round of studies last year focused on this issue, using the so called second order formalism, which includes viscosity and relaxation time parameters on top of ideal hydro. P. and U.Romatschke [3] were first, and they found that the best fits to $v_2(p_t)$ is at $\eta/s \sim .03$, smaller than the famous AdS/CFT result [4] $\eta/s = 1/4\pi$. Small viscosity effects in flow were also found by Teaney and Dusling [5] and by Chaudhuri (see his talk here): with tensor correction at the freezeout time dominating $v_2(p_t)$ as Teaney originally suggested. D.Molnar (see his talk here) have demonstrated nice agreement between cascades and hydro for $v_2(p_t)$, provided cross sections/viscosity are appropriately tuned. (Song and Heinz – see talk here – found for some reason larger viscous corrections to flow.)

Now, is the accuracy level really allows us to extract $\eta/s$? The uncertainties in initial state deformation are at the 10% level (see Venugopalan’s talk), thus comparable to the viscosity effect. EoS can probably be constrained better (lattice?). I think uncertainties related to freezeout – not yet discussed at all – can also be reduced down to few percent level, provided more efforts to understand hadronic resonances/interactions at the hadronic stage will be made. At the moment a safe statement is $\eta/s \sim 0.1$ and below .2 or so: while the exact value is still lacking ‡.

Can viscosity be even smaller, $\eta/s < 1/4\pi$? In fact, as Lublinsky and myself [6] discussed, the AdS/CFT gravity spectral densities predicts that effective momentum-dependent viscosity $\eta(k)$ is decreasing with momentum k, from its famous value $1/4\pi$ at k=0. We dont understand its physics: but if so this is very important at very early stages, for most peripheral collisions (thin almond), affecting the famous $v_2$($centrality$) curves on which hydro results are heavily based.

2. A magnetic side of sQGP

Long ago G.’t Hooft and Mandelstam [8] tried to explain confinement by a “dual superconductor” made of Bose-condensed magnetically charged objects. Seiberg and Witten [9] have famously shown how it works in the N=2 super Yang Mills theory. Liao and myself [10] proposed a new view on sQGP, based on electric-magnetic duality/competition, see Liao’s talk and also works by Zakharov et al [11].

As Dirac famously shown, quantum mechanics demands that electric and magnetic coupling constants are related by the celebrated quantization condition, which in

‡ Unfortunately I am skeptical about magnitude of systematic errors of any lattice results for $\eta/s$ (such as [7]): while the correlation functions themselves are quite accurate, the spectral density is obtained by rather arbitrary choice between many excellent possible fits.
quantum field theory setting require them to run in the opposite directions:

$$\alpha(\text{electric})\alpha(\text{magnetic}) = 1 \quad \beta(\text{electric}) + \beta(\text{magnetic}) = 0 \quad (1)$$

Thus when $\alpha(\text{electric}) = e^2/4\pi$ is small (at high $T$), $\alpha(\text{magnetic}) = g^2/4\pi$ should be strong. As $T$ decreases toward $T_c$, electric one decrease and magnetic one grows, till monopoles take over quarks and gluons: see schematic phase diagram shown in Fig.1(a). Recent lattice data [12] provided dramatic conformation of this scenario. Fig.1(b) shows two sets of these data, and the correlation (and thus magnetic coupling) is indeed stronger at higher $T$. Furthermore, the correlation function for 50-50 mix of electric/magnetic plasma obtained in our Molecular Dynamics (MD) simulation Fig.1(c) has the same shape and magnitude, provided one compare at the same value of the magnetic plasma parameter $\Gamma \equiv \alpha(\text{magnetic})/(\frac{3}{4\pi n})^{1/3}/T$: its extracted values are shown in Fig.1(d). It is very nice to find always $\Gamma > 1$, which means that magnetic component of sQGP is also liquid not gas, thus it does not spoil the “perfect liquid” at RHIC. One may further think that viscosity has a minimum where both electric quasiparticles (quarks) and magnetically ones (monopoles) have similar difficulty propagating. We infer from lattice data that such electric-magnetic equilibrium is at $T \approx 1.5T_c$, right in middle of the RHIC domain.

Transport properties for novel types of plasmas, including electric and magnetic charges, have been calculated by Liao and myself [10]: and $\eta$ is indeed minimal for most symmetric mixture 50-50%. Before we turn to these results, let me qualitatively explain why in this case the diffusion/viscosity is maximally reduced. Imagine one of the particles - e.g. a quark. The Lorentz force makes it rotate around a magnetic field line, which brings it toward one of the nearest monopoles. Bouncing from it, quark will go along the line to an antimonopole, and then bounce back again: like electrons/ions do in the so called “magnetic bottle” §. Thus in 50-50 mixture all particles can be trapped between their dual neighbors, so that the medium can only expand/flow collectively.

Our MD results are shown on viscosity-diffusion plane in Fig.2 by three lines: they are compared to those from the AdS/CFT correspondence in weak and strong coupling as well as with empirical values from RHIC experiments (gray oval). The dashed curve in the left lower corner is for $N=4$ SUSY YM theory in weak coupling: both quantities are proportional to the same mean free path. These weak coupling results are quite far from empirical data from RHIC in the right upper corner. (Viscosity estimates follow from deviations of the elliptic flow at large $p_t$ from hydro predictions and diffusion constants are estimated from $R_{AA}$ and elliptic flow of charm.) The strong-coupling AdS/CFT results (viscosity according to [4] with $O(\lambda^{-3/2})$ correction, diffusion constant from [16]) are represented by the upper dashed line, going right through the empirical region. Our MD results – three solid lines on the right – are close to the experiment as well, especially the version with the equal mixture of EQPs and MQPs.

The last point I would like to make is the electric-magnetic competition mentioned above. An electric charge entering a region with magnetic field makes Larmor semicircle

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§ By the way, invented in 1950’s by one of my teachers G.Budker.
and gets reflected back. Thus electric plasma (or Bose condensate) is trying to expel magnetic field into flux tubes. We know how this works in superconductors or in (e.g. solar) plasmas. Dual to that: magnetic plasma expels the electric field. It does happen not only in a condensate (dual superconductor) phase at $T < T_c$, but in a QGP phase as well, under conditions derived in [13]. See Liao’s talk here which explains how this phenomenon explains unusual behavior of the heavy quark potentials at $T \approx T_c$. 

Figure 1. (a)from [10]: Schematic phase diagram on a (“compactified”) plane of temperature and baryonic chemical potential $T - \mu$. The (blue) shaded region is “magnetically dominated”, $g < e$, 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” indicate electric-magnetic equilibrium. The solid lines show phase transitions, while the dash-dotted line is a deconfinement cross-over line. 
(b)Monopole-antimonopole correlators versus distance: points are lattice data [12] for SU(2) pure gauge theory, for the lowest and highest temperatures, $T = 1.1T_c$ and $T = 3.8T_c$. The dashed lines are our fits from which magnetic couplings are extracted. 
(c) Monopole-antimonopole correlator, from our MD simulations [14].
(d)Effective magnetic plasma parameter $\Gamma_M$ at various temperatures.[14]
Figure 2. Transport summary from [10]: $\log(1/(\eta/s))$ v.s. $\log(1/(2\pi T D))$ including results from our MD simulations, the AdS/CFT calculations, the weakly coupled CFT calculations, as compared with experimental values, see text.

3. AdS/CFT duality: conformal plasma in equilibrium

Relation between RHIC physics and string theory was already discussed at the previous QMs. Instead of an introduction (Rajagopal’s talk here may have some), I will provide some “intuitive picture” for non-experts. Let me start with the finite-T Witten’s settings in which most pertinent calculations are done, shown in Fig.3. The upper rectangle is the 3-dimensional space boundary $z=0$ (only 2 dim shown), which is flat (Minkowskian) and corresponds to “our world” where the gauge theory lives. Lower black rectangles (reduced in area because of curvature) is corresponding patch of the horizon (at $z=z_h$) of a black hole whose center is located at $z=\infty$. Studies of conformal plasma famously started from evaluation of the Bekenstein entropy [15], $S=A/4$ with $A$ being the black patch area.

(For non-experts: this setting can be seen as a swimming pool, with our gauge theory living on its surface, $z=0$, at the desired temperature $T$. While pool’s bottom is infinitely hot, strong gravity stabilizes this setting, even thermodynamically.)

Fig.3(a) shows a setting of heavy quark quenching [17]: a quark is being dragged (at some height $z_m$ related to the quark mass) by an “invisible hand” (to the left): its electric flux goes into the 5-th dimension, into the so called “trailing string”. Its weight forces it to fall to the bottom (horizon). (Think of a heavy quark as a ship diligently laying underwater cable to the pool’s bottom.) The cost of that is the drag

$$dP/dt = -\pi T^2 \sqrt{g^2 N_c} \frac{v/2}{\sqrt{1-v^2}}$$

|| The exception is heavy quark diffusion constant calculated by Casalderrey and Teaney[16] which needs more complicated settings, with a Kruskal metric connecting a World to an Anti-world through the black hole.
connected to the diffusion constant via Einstein relation, a nontrivial successful check on two very different calculations.

Another form of relaxation is studied via propagating “bulk waves” (b): massless ones may have spin S=0 (dilaton/axion), 1(vector) or 2 (gravitons). Absorptive boundary condition at the horizon (black bottom) leads to spectra of “quasinormal modes” with the imaginary part \( \text{Im}(\omega_n) \sim \pi T n \), setting the dissipation timescale of various fluctuations. An exceptional case S=2 has two near-zero modes, corresponding to only two propagating “surface waves”, the longitudinal sound and transverse “diffuson”. Absorption at the bottom (horizon) of both famously gives the viscosity \( \eta/s = 1/4\pi[4] \).

The waves may have real (timelike) 4-momentum or virtual (spacelike) one\(^+\). Rather complete spectra of quasinormal modes and spectral densities for S=0,1,2 correlators are available, unfortunately extracted numerically. The case (c) – a “falling stone” – perhaps represent colorless (no strings attached) “mesons”, released to plasma and relaxing.

The dashed lines in Fig.3 corresponds to the next-order diagram, describing back reaction of the falling bulk objects onto the boundary, the observation point denoted by a small open circle. This fields may also have spins 0,1 or 2, providing 3 pictures known as a (4-d) “holograms” of the bulk. Contrary to our intuition (developed from our limited flat-world experience), the hologram is not a reduced reflection of more complete 5-d dynamics in the bulk, but in fact represents it fully. This phenomenon – the AdS/CFT duality – is a miracle occurring due to near-black-hole setting.

These holographic images are what the surface observer will see. Image of the trailing string was calculated in [18, 19]: the recent example at nonzero \( T \) is shown in Fig.4(b,c): it accurately displays hydro conical flow. For a hologram of the stone Fig.3(c) see recent paper [20]: but to our knowledge the holographic “back reaction” of the falling waves remains to be done.

How these predictions are related to experiment? Apart of those shown in Fig.2, important test is whether the drag force indeed depends only on the velocity (rather than momentum): can be done via single electrons from \( c \) and \( b \) decays. Another challenge is to test if the effective viscosity is indeed decreasing with increasing gradients as AdS/CFT nontrivially indicate [6]: it can be inferred from elliptic flow at more peripheral collisions (thinner “almond”).

4. AdS/CFT duality: equilibration and sGLASMA

New challenging frontier is AdS/CFT out of equilibrium, addressing initial equilibration and entropy production. As explained in Venugopalan’s talks, “glasma” is a non-equilibrium gluonic state between the collision moment and equilibrated QGP, which so far is modeled by random glue via classical Yang-Mills eqn in weak coupling. However

\[\text{Quasinormal modes are those which do not conserve the norm of the wave: it is like decaying radioactive states in nuclear physics which are distinct from scattering ones, with real energies.}\]

\[\text{+ This case, named DIS in AdS, is discussed here by E.Iancu.}\]
Figure 3. Schematic view of the relaxation settings, a string (a), a wave (b) or a particle (c) fall into the 5-th dimension toward the black hole.

Figure 4. (a) From [21]: The hologram of a falling string. The contours show the magnitude of the Poynting vector $T^0i$ in the transverse plane. The direction of the momentum flow is indicated by arrows. (b) From [19]: hologram of the trailing string, the normalized energy density for one quark (supersonic jet) with $v = 3/4$ at nonzero $T$. (c) same as (b) for the Poynting vector.

the corresponding “saturation scale” $Q_s$ at RHIC is only about 1-1.5 GeV – not far from parton momenta in sQGP, the perfect liquid as one knows – so one may wander if a strongly coupled regime should be tried instead.

This is what I propose to call sGLASMA frontier: AdS/CFT is the tool to use. It means that one has to start with high energy collision inside cold $T = 0$ AdS$_5$ (the vacuum, or a bottomless pool) and then dynamically solve two difficult problems: (i) explain why “collision debris” may act like a “heater” imitating black/hot patch of Fig.3; (ii) find a consistent solution with “falling bottom”, $z_h(\text{time})$, and find its hologram describing hydro explosion/cooling.

Example of recent progress on the former (i) front are works by S.Lin and myself [21] and more recently by Hofman and Maldacena[22]. One may view them as steps toward a “strongly coupled collider physics”, with a single pair of heavy quarks jets produced. Like in Lund model (Pythia), they are connected by a flux tube (string), which is however not breaking but rather falling into the 5-th $z$ direction, Fig.5(a). For one string one can both solve eqns of falling and then find its (gravitational) hologram [21]. The result is an explosion shown in fig.4(a), which is however non-thermal and thus non-hydrodynamical.

Temperature/entropy only appear when a horizon (also called “trapped surface”) is dynamically created leading to the information loss. A lot of work was done
Figure 5. Schematic view of the collision setting. Setting of the sGLASMA studies: (a) a single pair of heavy quark jets, moving with velocities $v$ and $-v$ and creating falling string. Multiple strings create a 3-d falling membrane (2d shown), which is (b) first far from trapped surface and then very closed to it (c).

on gravitational collapse, there are black holes in the Universe and, with modified multidimensional gravity, people are thinking about their possible formation in LHC experiments. However, in AdS/CFT language we are sure that each RHIC heavy ion collision event does produce a black hole, but with an effective gravity (imitating QCD) in the imaginary (unreal) 5-th dimension. In heavy ion context, Sin, Zahed and myself [23] first argued that exploding/cooling fireball on the brane is dual to departing black hole, formed by the collision debris and then falling toward the AdS center. A specific solution they discussed in the paper was a brane departing from a static black hole, which generated a “spherical” solution (no dependence on all 3 spatial coordinates) with a time-dependent $T$ (which however is more appropriate for cosmology but not heavy ion applications). These authors also discussed other idealized settings, with d-dimensional stretching, corresponding for d=1 to a collision of two infinite thin walls and subsequent Bjorken rapidity-independent expansion, with 2d and 3d corresponding to cylindrical and spherical relativistic collapsing walls.

Instead of solving Einstein equations with certain source, describing gravitationally collapsing “debris” of the collision, Janik and Peschanski [24] applied an “inverse logic”, extrapolating into the bulk the metric which yield expected hydrodynamical solution at the boundary. They found asymptotic (late-time) solution corresponding to 1+1-dim rapidity-independent Bjorken expansion. It indeed has a departing horizon at $z_h \approx \tau^{1/3}$. Important feature of this leading order solution is that while the horizon is stretching in one direction it is contracting in others keeping the total horizon area constant: this is entropy conservation. The first subleading terms $O(\tau^{-2/3})$ has been calculated by Sin and Nakamura [25] who identified them with the viscosity effects, although the viscosity value was only fixed by still further term by Janik et al. However they eventually concluded [26] that the expansion series are inconsistent beyond the first few orders. I always argued this should be the case: a near-horizon singularity which they see as a problem just shows inevitability of the matter presence: pure gravity simply is not enough.

Further work toward working out a “gravity dual” to heavy ion fireball is ongoing: let me show just a sketch of our current work. If many strings are falling together their
combined gravity is non-negligible – they are partly falling under their own weight. So one should solve non-linearized Einstein eqns, which tell us that (from the viewpoint of distant observer) extra weight may actually slow down falling, eventually leading to near-horizon levitation. The trapped surface is moving first upward (shown at the bottom of Fig.5(b)) toward the falling membrane, till two collide, get close and fall together, see Fig.5(c). After that distant observer finds a thermal hydrodynamical explosion as a hologram. This is the case at mid-rapidity but never in the fragmentation regions.

Finally, let me mention a separate direction by Kajantie et al [27] addressing these issues in the 1+1 dimensional world. It is easier to work out math in this case: but shear viscosity is absent in it and bulk viscosity is prohibited by conformity, so it is a cute toy case without dissipation.

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