STRONGLY COUPLED QUARK-GLUON PLASMA: THE STATUS REPORT

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RHIC data have shown robust collective flows, strong jet and charm quenching, and charm flow. Recently "conical flows" from damped jets were seen. Non-Abelian classical strongly coupled plasmas were introduced and studied via molecular dynamics, with first results for its transport (diffusion and viscosity) reported. Quantum-mechanical studies reveal the survival for $T > T_c$ of the lowest binary states, including colored ones, and also of some manybody ones such as baryons. "Polymeric chains" $\bar{q}.g.g...q$ are also bound in some range of T, perhaps the progenitors of the QCD strings. AdS/CFT applications advanced to a completely new level of detail: they now include studies of thermal heavy quark motion, jet quenching and even conical flow. Confinement is however still beyond simply strong coupling: its de-facto inclusion the so called AdS/QCD approach is so far added as a model, while true understanding may probably only come from further insights into the monopole dynamics.

Keywords: Quark-gluon plasma, strong coupling, AdS/CFT correspondence, heavy ion collisions

1. Why strongly coupled?

A realization [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 [4] (at which the abbreviation sQGP was established) and multiple other meetings since.

In the intervening three years we had to learn a lot, some new some from other branches of physics which happened to have some experience with strongly coupled systems. Those range from quantum gases to classical plasmas to string theory. In short, there seem to be not one but actually two difficult issues we are facing. One is to understand why QGP at $T \sim 2T_c$ is strongly coupled, and what exactly it means. The second large problem is to understand what happens at the deconfinement, at $|T - T_c| \ll T_c$, which may be a key to the famous confinement problem.

As usual, progress proceeds from catching/formulating the main concepts and qualitative pictures, to mastering technical tools, to final quantitative predictions: and now we are somewhere in the middle of this process. The work is going on at many fronts. At classical level, first studies of the transport properties of strongly coupled non-Abelian plasmas have been made. Quantum-mechanical studies of the bound states above T_c have revealed a lot of unusual states, including "polymeric chains". At the quantum field/string theory front, a surprisingly detailed uses of AdS/CFT correspondence has been made. And yet, to be honest, deep understanding is still missing: e.g. we don't know what the CFT plasma is made of.

The list of arguments explaining why we think QGP is strongly coupled at T above T_c is long and constantly growing. Let me start with its short version, as I see them today.

1.Collective phenomena observed at RHIC lead hydro practitioners to a conclusion that QGP as a "near perfect liquid", with unusually small *viscosity-to-entropy ratio* $\eta/s = .1 - .2 << 1$ [5] in striking contrast to pQCD predictions. Not only light jets, but also charmed ones are strongly quenched. Charm diffusion constant D_c deduced from its flow is an order of magnitude lower than pQCD estimates [6].

2. Combining lattice data on quasiparticle masses and interparticle potentials, one finds a lot of quasiparticle bound states [7]. The same approach explains why $\eta_c, J/\psi$ remains bound till near $3T_c$, as was directly observed on the lattice [8] and perhaps experimentally at RHIC. The resulting resonances enhance transport cross sections [2,9] and may lead to a liquid-like behavior. Similar thing does happen for ultracold trapped atoms, due to Feshbach-type resonances at which the scattering length $a \to \infty$.

3.The interaction parameter $\Gamma \sim < potential\,energy > / < kinetic\,energy >$ in sQGP is obviously not small. Classical e/m plasmas at the comparable coupling $\Gamma \sim 1 - 10$ are good liquids too.

4. Exact correspondence between a conformal (CFT) $\mathcal{N}=4$ supersymmetric Yang-Mills theory at strong coupling and string theory in Anti-de-Sitter space (AdS) in classical SUGRA regime was conjectured by Maldacena [10]. The results obtained this way on the $g^2 N_c \to \infty$ regime of the CFT plasma are all close to what we know about sQGP. Indeed, it has a very similar thermodynamics and is a good liquid with record low viscosity as well. Recent works (see below) added to the list parametrically large jet quenching and small diffusion constant for heavy quarks.

5.[a] The N=2 SUSY YM ("Seiberg-Witten" theory) is a working example of confinement due to condensed monopoles[11]. If it is also true for QCD, at $T \to T_c$ magnetic monopoles must become light and weakly interacting at large distances due to U(1) beta function. Then the Dirac condition forces electric coupling g be large (in IR).

2. Collective flows in heavy ion collisions

This meeting is mostly theoretical in nature, and thus I would not go into details of heavy ion phenomenology. Collective flows, related with explosive behavior of hot matter, were observed at SPS and RHIC and are quite accurately reproduced by the ideal hydrodynamics. The flow affect different secondaries differently, yet their spectra are in quantitative agreement with the data for all of them, from π to Ω^-. At non-zero impact parameter the original excited system is deformed in the transverse plane, creating the so called elliptic flow. It is described by the parameter $v_2(s, pt, M_i, y, b, A)$ $=< cos(2\phi) >$, where ϕ is the azimuthal angle and the others stand for the collision energy, transverse momentum, particle mass, rapidity, centrality and system size. Hydrodynamics explains well all of those dependences, for about 99% of the particles[b].

New hydrodynamical phenomenon suggested recently [12], is the so called *conical* flow which is induced by jets quenched in sQGP. Although the QCD Lagrangian tells us that charges are coupled to gluons and thus it is gluons which are to be radiated, at strong coupling those are rapidly quenched. Effectively the jet energy is dumped into the medium and then it transformed into coherent radiation of sound waves, which unlike gluons are much less absorbed and can survive till freezout to be detected. As shown in Fig.1, this seem to be what indeed is observed.

Antinori and myself [13] suggested to test it further by b-quark jets, which can be tagged experimentally even if not ultrarelativistic: the Mach cone should then shrink, till it goes to zero at the critical velocity $v = c_s = 1/\sqrt{3}$. Gluon radiation behaves oppositely, expanding with *decreasing* v, and never shrinks to zero. Casalderrey and myself[14] have shown, using conservation of adiabatic invariants, that fireball expansion should greatly enhance the sonic boom[c].

[a]This part is presented at this conference for the first time.
[b]At large $p_t > 2GeV$ a different regime starts, related with jets.
[c]The reason is similar to enhancement of a sea wave such tsunami as it goes onshore.

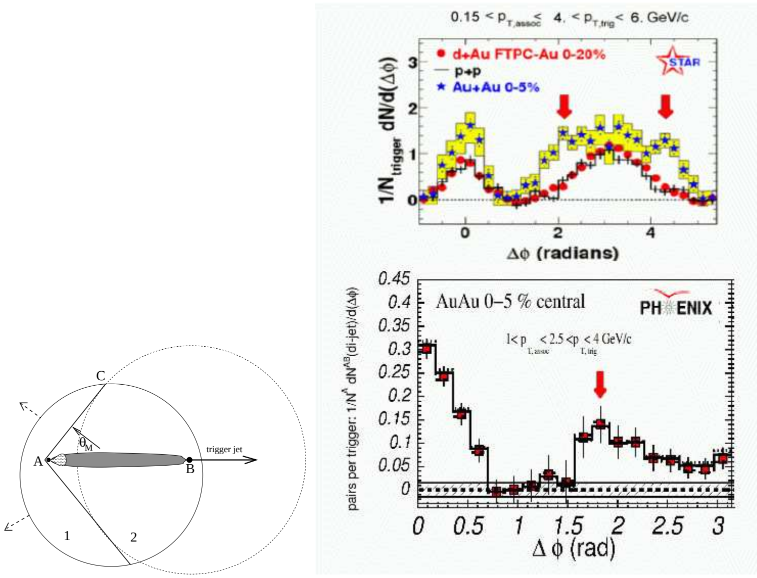

Fig. 1. (a) A schematic picture of flow created by a jet going through the fireball. The trigger jet is going to the right from the origination point B. The companion quenched jet is moving to the left, heating the matter (in shadowed area) and producing a shock cone with a flow normal to it, at the 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. Classical strongly coupled non-Abelian plasmas

In the electromagnetic plasmas the term "strongly coupled" is expressed via dimensionless parameter $\Gamma = (Ze)^2/(a_{WS}T)$ characterizing the strength of the interparticle interaction. Ze, a_{WS}, T are respectively the ion charge, the Wigner-Seitz radius $a_{WT} = (3/4\pi n)^{1/3}$ and the temperature. Γ is convenient to use because it only involves the *input* parameters, such as the temperature and density. 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 regime for $\Gamma > 300$.

Gelman, Zahed and myself [15] proposed a model for the description of strongly interacting quarks and gluon quasiparticles as a classical and non-relativistic Non-Abelian Coulomb gas. The sign and strength of the inter-

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particle interactions are fixed by the scalar product of their classical *color vectors* subject to Wong's equations. The EoM for the phase space coordinates follow from the usual Poisson brackets:

$$\{x^m_{\alpha\, i}, p^n_{\beta\, j}\} = \delta^{mn}\delta_{\alpha\beta}\delta_{ij} \quad \{Q^a_{\alpha\, i}, Q^b_{\beta\, j}\} = f^{abc}\, Q^c_{\alpha\, i} \tag{1}$$

For the color coordinates they are classical analogue of the SU(N_c) color commutators, with f^{abc} the structure constants of the color group. The classical color vectors are all adjoint vectors with $a = 1...(N_c^2 - 1)$. For the non-Abelian group SU(2) those are 3d vectors on a unit sphere, for SU(3) there are 8 dimensions minus 2 Casimirs=6 d.o.f.[d].

The model was studied using Molecular Dynamics (MD), which means solving numerically EoM for $n \sim 100$ particles. It also displays a number of phases as the Coulomb coupling is increased ranging from a gas, to a liquid, to a crystal with anti-ferromagnetic-like color ordering. There is no place for details here: in Fig.2 one can see the result for diffusion and viscosity vs coupling: note how different and nontrivial they are. When extrapolated to the sQGP suggest that the phase is liquid-like, with a diffusion constant $D \approx 0.1/T$ and a bulk viscosity to entropy density ratio $\eta/s \approx 1/3$. The second paper of the same group[15] discussed the energy and the screening at $\Gamma > 1$, finding large deviations from the Debye theory.

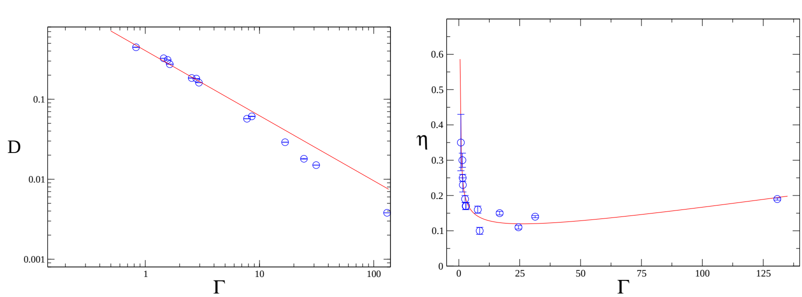

Fig. 2. The diffusion constant (a) and shear viscosity (b) of a one species cQGP as a function of the dimensionless coupling Γ. Blue points are the MD simulations; the red curve is the fit.

[d] Although color EoM do not look like the usual canonical relations between coordinates and momenta, they actually are pairs of conjugated variables, as can be shown via the so called Darboux parameterization.

4. Quantum mechanics of the quasiparticles

In the deconfined phase, at $T > T_c$, the basic objects are dressed quarks and gluons. Even perturbatively they get masses $M_{eff} \sim gT$ [16] and dispersion curve close to that of massive particle. However it follows from lattice measurements [17] (admittedly, with still poor accuracy) that (i) masses are very large, about $M_{eff} \approx (3-4)T$; and (ii) quarks and gluons have very close masses, in contrast to pQCD prediction. Thus, in first approximation, quasiparticles are rather non-relativistic.

As emphasized by Zahed and myself [7], a gas of such heavy quasiparticles cannot generate the pressure observed in other lattice works. The resolution of a puzzle may be found if there are multiple bound states of the quasiparticles, which also contribute to pressure.

The existence of bound states also follows from the interaction deduced for static quarks. For marginal states, with near-zero binding, those should be applicable. The most obvious state to think of is charmonium, which had a long story of a debate whether it will survive in QGP or not. The answer depends on which is the effective potential: in contrast to many earlier works we pointed out [2] that one has to remove the entropy term and use the "energy" potentials $V(T,r) = F - TdF/dT$, not the free energy ones $F(T,r)$ which are directly measured from Wilson/Polyakov lines. This leads effectively to deeper potentials and better binding, so J/ψ survives till $T = (2-3)T_c$. This was confirmed by direct calculation of spectral densities by maximal entropy method [8]. It also nicely correlates well with surprisingly small J/ψ suppression observed at RHIC, where $T < 2T_c$.

It was then pointed out in [7] that also multiple binary *colored* bound states should exist in the same T domain. Since QGP is a deconfined phase, there is nothing wrong with that, and the forces between say singlet $\bar{q}q$ and octet qg quasiparticle pairs are about the same. Liao and myself [18] have also found survival of the s-wave baryons $(N, \Delta ...)$ at $T < 1.6T_c$.

A particularly interesting objects are *multibody* [18] bound states, such as "polymer chains". Those can be "open strings" $\bar{q}gg..gq$ or closed chains of gluons (e.g. very robust ggg state we studied). Their binding *per bond* was proven to be the same as for light-quark mesons, and both are bound till about $1.5T_c$ or so. They have interesting AdS/CFT analogs (see below) and they also can be viewed as precursor to the formation of the QCD strings from the deconfined phases.

A curve of marginal stability (CMS) is not a thermodynamic singularity but it often indicates a change of physics. Zahed and myself [2] argued that resonances can strongly enhance transport cross section near multiple

CMS's and thus explain small viscosity. Rapp and van Hees [9] studied $\bar{q}c$ resonances, and found enhancement of charm stopping.

Similar phenomenon does happen for ultracold trapped atoms, which are extremely dilute but due to Feshbach-type resonances at which the scattering length $a \to \infty$ they behave like very good liquids with small viscosity, see[19].

One notable colored bound state is a diquark qq, the main player in color superconductivity at high density and low T. Diquarks are weaker bound than mesons[e] and are expected to melts right above the deconfinement transition. In my recent paper[20] I argued that may bring color superconductivity into strongly coupled regime as well. The usual BCS theory of superconductors are then inapplicable: it is also weak coupling theory.

Fortunately superfluidity of ultracold fermionic strongly coupled atoms have been studied recently experimentally. The system is known to enter the universal strongly coupled regime as their scattering length a gets large, and therefore it is possible to use some universal properties to get such properties as the slope of the critical line of color superconductivity, $dT_c/d\mu$. I also deduced limitations on the critical temperature of color superconductivity itself and conclude that it is limited by $T_{CS} < 70\, MeV$.

5. AdS/CFT correspondence at finite *T*

Thermodynamics of the CFT plasma was studied started from the early work[21], its result is that the free energy (pressure) of a plasma is

$$F(g, N_c, T)/F(g = 0, N_c, T) = [(3/4) + O((g^2 N_c)^{-3/2})] \tag{2}$$

which compares well with the lattice value[f] of about 0.8.

Heavy-quark potentials in vacuum and then at finite T [22] were calculated by calculating the configuration of the static string, deformed by gravity into the 5-th dimension. Let me write the result schematically as

$$V(T, r, g) \sim \frac{\sqrt{g^2 N_c}}{r} exp(-\pi T r) \tag{3}$$

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 [23] noticed that summing

[e] Due to extra 1/2 in color Casimirs.

[f] Not too close to T_c, of course, but in the "conformal domain" of $T = few\, T_c$, in which p/T^4 and ϵ/T^4 are constant.

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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 [24] why a field of the dipole is $1/r^7$ at large distance[25], not $1/r^6$. Debye screening range can also be explained by resummation of thermal polarizations [3].

Zahed and myself [26] 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

$$V(T,r,g) \sim \sqrt{(g^2 N_c)[1 - \vec{v}_1 * \vec{v}_2 + (spin - spin) + (spin - orbit)]}/r \quad (4)$$

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[g]. No results on that are known from a gravity side, to my knowledge.

Bound states Zahed and myself [3] 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 $J >> \sqrt{g^2 N_c}$, otherwise one has the famous "falling on a center" solutions[h]: 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 [27] 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 [24] 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" $\bar{q}.g.g...q$ discussed above. For the endpoints being static quarks and the intermediate gluons conveniently replaced by adjoint scalars, Hong, Yoon and Strassler [28] have studied such states and even their formfactors.

Transport properties of the CFT plasma was a subject of recent breakthroughs [i]. The (already famous) work by Polykastro, Son and

[g] Note that in a quarkonium their scalar product is negative, increasing attraction.
[h] Note that all relativistic corrections mentioned above cannot prevent it from happening.
[i] The works which appeared between the conference and the time when this summary is written are included.

Starinets[29] have calculated viscosity (at infinite coupling) $\eta/s => 1/4\pi$ which is in the ballpark of the empirical RHIC value. It taught us that gravitons in the bulk at large distances are dual to phonons on the brane. Dual to a viscous sound absorption is thus interception of gravitons by the black hole.

Heavy quark diffusion constant has been calculated by Casalderrey-Solana and Teaney [30]: their result is

$$D_{HQ} = \frac{2}{\pi T \sqrt{g^2 N_c}} \tag{5}$$

which is parametrically 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 in that Kruskal coordinates are used, which allows to consider the inside of the black hole and *two* Universes (with opposite time directions) simultaneously, see Fig.3a. This is indeed necessary [j] in any problems when a *probability* is evaluated, because that contains both an amplitude and a conjugated amplitude at the same time.

Jet quenching studies[32–36] have been reported by L.Yaffe, see his talk for details. The result for the drag force is

$$\frac{dP}{dt} = -\frac{\pi T^2 \sqrt{g^2 N_c} v}{2\sqrt{1 - v^2}} \tag{6}$$

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 shown in Fig.3, a and b.

This result is valid only for quarks heavy enough $M > M_{eff} \sim \sqrt{g^2 N_c} T$ and is obtained in a stationary setting, in which a quark is dragged with constant by "an invisible hand" via some rope through QGP, resulting in constant production of a string length per time, see Fig.3b . I have borrowed it from the paper by Friess et al [37], who have made the next (and technically much more difficult) step, namely solving the Einstein equation with this falling string as a source and found corrections to the metric $h_{\mu\nu}$ and thus the matter stress tensor on the brane. Quite remarkably, when they analyzed harmonics of this stress at small momenta they have seen the "conical flow"! And, as one can see from plots for "subsonic" $v < 1/\sqrt{3}$, the Mach cone disappear in this case, as argued in [13].

[j] One such problem is evaluation of the so called $\hat{q}$ parameter: two lines of the loop should also belong to *two* different Universes, not one as assumed in [31]. It remains unknown whether similar calculation in Kruskal geometry would produe the same result or not.

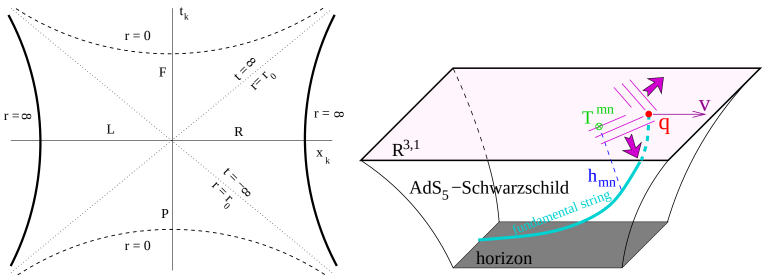

Fig. 3. (a) (from [30]): In Kruskal coordinates one can study two Universes at the same time, shown right and left, and the evaluated Wilson line contains static quarks on their boundaries. (b) (from [37]) The dragged quark trails a string into the five-dimensional AdS bulk, representing color fields sourced by the quark's fundamental charge and interacting with the thermal medium. The back gravity reaction describes how matter flows on the brane.

The ultimate goal would be a complete "gravity dual" to the whole RHIC collision process, in which thermalization and subsequent hydro explosion will be described via dynamical production of a black hole, as emphasized by Nastase [38]. Sin, Zahed and myself [39] further argued that exploding and cooling fireball on the brane is dual to departing black hole, formed by collision debris falling into the AdS center. Janik and Peschanski [40], found that the Bjorken expansion can be mapped into a metric with a departing *horizon*[k].

6. AdS/QCD

"Holographic" ideas have been also used for theories more resembling QCD. There are famous papers on it; my favorite is Sakai-Sugimoto model[49] with light quarks, deconfinement and chiral symmetry restoration. The closest to RHIC physics is nice paper by Peeters et al[50] which document how light mesons (e.g. ρ) get T-dependent masses after they survive deconfinement.

Quite intriquing is also a "bottom-up" approach, in which the violations of comformity of AdS/CFT is introduced explicitly. Confinement forbids QCD phenomena from exploring large distances. In the now popular "holographic" language, it means that all object we study are somehow prevented from going too far into the 5-th coordinate z into the IR. First attempts to model confinement (used mostly for QCD spectroscopy) used just such a cut-off, at some $z = z_0$.

[k]However they solve vacuum Einstein eqns without any matter: their departing horison is due to acausal time dependence of the central black hole (the stack of branes).

Recently three groups suggested different arguments that confinement induces a *quadratic* potential in z. Karch et al [41] have argued that this is needed to get correct dependence of the Regge trajectories on particle spin S and principal quantum number n. In my paper [42] the probe for confinement are instantons, and it was first argued that their size should be identified to the 5-th coordinate z. The proposed potential consists of two parts, related to asymptotic freedom[l] and confinement

$$V_{eff}(z) = V_{AF} + V_{conf} = -\beta_0 log(z) + 2\pi\sigma z^2 \quad (7)$$

where $\beta_0 = (11/3)N - (2/3)N_f$ and the coefficient of the quadratic term was proposed previously in [43], it contains the string tension σ. The reason (and coefficient[m]) for quadratic behavior is not ad hoc, but because a it is related with a VEV of a *dual superconductor*; it is in excellent agreement with lattice datat on instanton size distribution.

Andreev and Zakharov [44] put the quadratic potential into metric, and calculated a number of string-based potentials and spatial Wilson lines. However if it is in metric, wrong Regge trajectories follows[41] and also one cannot have non-universal coupling just mentioned: so I think it should be put into some extra potential instead.

7. (Post)Confinement and monopoles

Here comes an old question: is there any progress in understanding confinement, as well as the deconfinement transition region, at $T \approx T_c$?

Recent lattice data have revealed a puzzling behavior of static $\bar{Q}Q$ potentials, which I call "postconfinement". At $T = 0$ we all know that a potential between heavy quarks is a sum of the Coulomb and a confining $\sigma(T = 0)r$ potential. At deconfinement $T = T_c$ the Wilson or Polyakov lines with a static quark pair has vanishing string tension; but this is the free energy $exp(-F(T, r)) =< W >$. Quite shockingly, if one calculates the *energy* or *entropy* separately (by $F = E - TS$, $S = -\partial F/\partial T$) one finds [45] a force between $\bar{Q}Q$ to be more than twice $\sigma(T = 0)$ till rather large distances. The total energy added to a pair is surprisingly large reaches

[l] I found it remarcable that both other groups igore asymptotic freedom and deviations from conformity in UV. The corresponding coupling constants for any operator is related to its perturbative anomalous dimension.

[m] It is similar but not the same as the one proposed in [41], which should not surprise us, as the constant depends on how strongly the object studied is coupled to confinement-related condensates. For example, for glueball Regge trajectories (including the Pomeron and the 2++ glueball) the Regge slope is already significantly different.

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about $E(T = T_c, r \to \infty) = 3 - 4\,GeV$, and the entropy as large as $S(T = T_c, r \to \infty) \sim 10$. Since this energy of "associated matter" is about 20 times larger than T, any separation of two static quarks must be extremely suppressed by the Boltzmann factor exp(-E/T). (As T grows, this phenomenon disappears, and thus it is obviously related to the phase transition itself.)

Where all this energy and entropy may come from in the deconfined phase? It can only be long and complicated QCD string connecting two static quarks. We already mentioned that such strings can be explained by a "polymerization" of gluonic quasiparticles in sQGP.

Let us now add a twist to this story related with magnetic excitations, the monopoles[n]. According to t'Hooft-Mandelstamm scenario, confinement is supposed to be due to monopole condensation. Seiberg-Witten solution for the N=2 SYM is an example of how it is all supposed to work: it has taught us that as one approaches the deconfinement transition the electrically charged particles – quarks and gluons – are getting heavier while monopoles gets lighter and more numerous. Although I cannot go into details here, we do have hints from lattice studies of monopoles and related observables that this is happening in QCD as well.

Let us now think what all of it means for the sQGP close to T_c. Even at classical level, it means that one has a plasma with both type of charges – *electric and magnetic* – at the same time, with the former dominant at large T and the latter dominant close to T_c.

A binary dyon-dyon systems have been studied before , but not many-body ones. The first numerical studies of such systems (by molecular dynamics) are now performed by (Stony Brook student) Liao and myself [46]. We found that a monopole can be trapped by an electric static dipole, both classically and quantum mechanically. We also found that classical gas of monopoles leads to electric flux tubes[o] because monopoles scatter from the electric flux tube back into plasma, compressing it. Whether monopoles are condensed or not is not crucial.

Are ther bound states of electric and magnetic quasiparticles? Yes, there are a lot of them. A surprize is that even finite-T instantons can be viewed

[n]Recall that they appear naturally if there is an explicit Higgs VEV breaking of the color group. We cannot discuss in detail a QCD setting: the reader may simply imagine a generic finite-T configuration with a nonzero mean $< A_0 >$, an adjoint Higgsing leaving $N_c - 1$ U(1) massless gauge fields. These U(1)'s corresponds to magnetic charges of the monopoles. In AdS/CFT language one may simply considered N_c branes to be placed not at exactly the same point in the orthogonal space.
[o]Those are dual to magnetic flux tubes in solar classical plasmas.

as being made of N_c selfdual dyons [47], attracted to each other pairvise, electrically and magnetically. Not only such baryons-made-of-dyons have the same moduli space as instantons, the solutions can be obtained vis very interesting AdS/CFT brane construction [48]. Many more exotic bound states of those are surely waiting to be discoverd.

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