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ICPAQGP 2001: Conference summary

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Abstract. I review recent progress in ultrarelativistic nucleus–nucleus collisions, and the connection of this field to modern QCD theory of deconfinement and/or chiral symmetry restoration. The talks at this Conference have shown a convergence of data and theory as far as the CERN SPS investigations at $\sqrt{s} = 17$ GeV are concerned; the parton–hadron phase boundary seems now located at $T = 170 \pm 10$ MeV. New data from RHIC and direct photon production results from CERN have been shown that point out the field's future direction: analysis of partonic matter at $T > 200$ MeV. Astrophysics analysis was shown to be linked crucially to further theoretical progress with non-perturbative QCD.

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1. Introduction

At the conclusion of this exciting week we have reflected upon virtually every aspect of matter governed by QCD, with theory addressing how quarks and gluons dress up or condense to create the relevant effective degrees of freedom, and experiment ascertaining such a QCD architecture in matter at high energy density. Obviously it is useless to attempt, at the end, a high speed movie of all we talked about. Let me, rather, begin with a general impression, namely that our field has passed a major milestone or watershed. Starting from this viewpoint I shall then concentrate on a few topics that either confirm that view or help to outline the next milestone. Besides, the real summary has been already given by Lerry McLerran [1], anyhow, and we may just augment the title of his talk, to read 'What have we learned from RHIC and CERN?' Because he implies the SPS results, both implicitly and explicitly, in his statement that 'matter has been produced at energy densities so high it can only be simply described in terms of quarks and gluons – a state of matter that is strongly interacting with itself.' So far the written version but from his talk I wish to recall a version of this argument that captured the consensus of this conference in a broader sense: 'About the public question as to whether or not we have discovered the Quark Gluon Plasma – let us relax. No reasonable person would doubt that the states of matter we are creating are most simply described by freely interacting quarks and gluons'.

This more daring statement recalls scientific common sense in its hidden reference to the principle of Occams razor or, in Kants terminology, 'zum Prinzip des zureichenden Grundes'. We have, indeed, 'sufficient reason' from a combination of multitude of observations at top SPS and at RHIC energy to assume that the primordial interaction volume reaches an energy density of several GeV/fm^3 thus acquiring not only longitudinal expan-

sion modes but also a significant partonic transverse and directed pressure until expansion lowers the energy density (after several fm/c of elapsed time) to about 1 GeV/fm^3 and temperature $T \approx 170 \pm 10$ MeV whence the QCD parton to hadron phase transition sets in. We have also arrived at an estimate of that temperature from bulk hadronization data, and observed characteristic modifications of vector meson production due to a dense medium in the vicinity of T_c. Up to this point the observations are *consistent* with the above QCD-guided scenario. I will return to more detail in §3. Thus far, no 'direct' unambiguous evidence for the partonic state of matter as the QGP or its pre-equilibrium precursors do not emit a QCD-specific, observable 'plasmon', as a consequence of QCD confinement. However this is not all the evidence we can expect: consider the possibility that forthcoming RHIC experiments identify a clear signal of electromagnetic black body radiation from the primordial fireball reflecting a temperature of, say, $T \approx 300$ MeV and that, indeed, this temperature matches the concurrent Bjorken estimate of the primordial energy density ε in an $\varepsilon = T^4$ relationship. Consider, further, the possibility that the present first hints of partonic-medium specific radiative energy loss of hard quarks and gluons (that we seem to receive from RHIC jet attenuation data) get confirmed at LHC energy by direct comparison of 100 GeV jet production yields in *pp* and *AA* collisions. I will address these topics in §4 but conclude, for now, that such or similar observations 'would finally satisfy our curiosity about ultra-high temperature QCD matter' (to quote F Wilczek), rendering Occams razor argumentation obsolete.

My introduction ends with an overall consideration of QCD theory that may be legitimite only at this occasion because of its simple-minded approach. We are all too familiar with the point of view still prevailing in conversations with colleagues from 'genuine' particle physics: deconfinement occurs simply and more or less automatically as a consequence of QCD asymptotic freedom [2]. One would then expect the cosmological confinement transition to occur at T well above 1 GeV, the observation of Hagedorns limiting hadronic temperature at 160–180 MeV remaining a puzzle. Nowadays we would reply that the QCD phase transformation occurs in the non-perturbative domain, indeed at the limiting temperature, and has nothing to do with asymptotic freedom. The latter domain will perhaps not even be reached at LHC energy because the corresponding energy density falls well above 1000 GeV/fm^3. Thus our field of research is not at all a subsection of *p*QCD – we even do not seem to approach the *p*QCD limit on the lattice even at $T = 4T_c$ [3] which is also important for the cosmological evolution in the nano- to microsecond era. All differentiation in the QCD phase diagram falls within non-perturbative QCD at finite T which thus represents the proper initiative of our field alone: our gluons are most likely to act in coupled modes featuring effective masses, our quarks are not really current quarks, the QGP is not really an ideal gas of point-like particles, and our hadrons, on the other side of transition, are far removed from theirs on shell vacuum properties. Thus our quest for the QGP has become both more fascinating and more tantalizing the farther it has dug into the real quasi-particle structure of QCD in the vicinity of T_{crit}. McLerran's colour glass condensate [1], and Learmann [4]–Rapps [5] 'parton–hadron duality' are vivid recent examples: we begin to learn what QCD matter consists of, and the canonical QGP emerges as perhaps an initial oversimplification. So let us relax about the question of whether we have 'discovered the quark gluon plasma'.

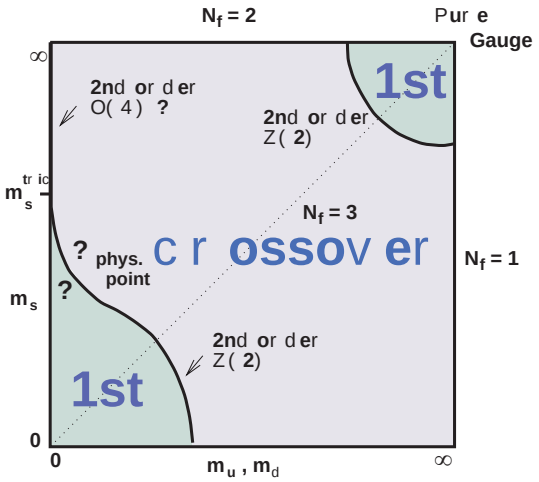


Figure 1. Lattice QCD at $T = T_c$ and baryochemical potential zero, showing the predicted order of the phase transformation in the plane of light vs. strange quark masses [3,4].

2. Theory

Watching the progress of lattice QCD concerning the expected nature of the parton–hadron phase transformation [4], one is amazed about the difficulties apparently surrounding the use of 'realistic' u,d,s quark masses, and the dependence of the transition order (cross-over, second, first order) on these masses [4], as shown in figure 1. We are at baryochemical potential $\mu = 0$, in the quenched approximation, and a first-order domain is visible at 'small' masses of all three flavours that even extends into the 'right' direction $m_s > m_u, m_d$. On the other hand, for rising m_s one expects to go through a boundary on which the transformation is second order, then to enter the cross-over domain. Thus there is a critical strange mass m_s^c, defining a critical point. However it is not yet settled whether the 'physical' strange mass exceeds m_s^c thus leaving us at present with a cross-over only (at $\mu = 0$), i.e., in the RHIC–LHC domain and in the cosmological expansion. Note that observables change rapidly during a cross-over, too, and that the familiar rapid rise of e.g. ε/T^4 as a function of T near T_c does not, by itself, signal a first- or second-order transition.

At this point I dare to ask a typical non-expert question: what exactly is the relationship between the lattice quark mass parameters and the 'physical' ones? In other words is it clear that the latter should be identified, in the end, with the 'current' quark masses ($m_u \approx m_d \approx 10$ MeV, $m_s \approx 150$ MeV)? Or is this lattice approximation at $T = T_c$ tacitly involving partially dressed quarks so that it is difficult to define what are the appropriate 'physical' masses in this theory?

Anyway, progressing to a non-vanishing baryochemical potential μ (at SPS and AGS we find that $\mu \geq 220$ MeV), one realizes that a variety of models [6] predict a first-order finite T phase transition at large μ. An interesting picture emerges on the μ–T plane. For the 'physical' m_s the first-order transitions at large μ should be connected with the cross-over expected from figure 1 at the $\mu = 0$ axis.

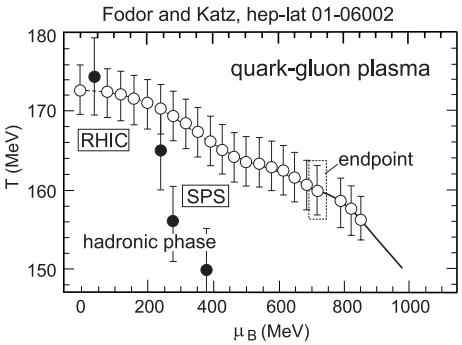


Figure 2. Lattice QCD at finite baryochemical potential, featuring a critical point at high μ_{B} and a cross-over toward lower μ_{B} [8]. Also shown are the values of (T, μ_{B}) observed from grand canonical statistical model analysis of bulk hadron production ratios at $\sqrt{s} = 130$, 18, 12 and 8 GeV (see text).

This suggests that the phase diagram features a critical end-point at a certain μ_E and T_E at which the line of first-order transitions (at higher μ and lower T) ends. At the end-point the transition is of second order, and if experiments could come near it one would expect to witness critical opalescence phenomena causing observable long range fluctuations. Such fluctuations are clearly absent at top SPS energy [7], and thus $\mu_E \gg 220$ MeV. Now, sensationally, Fodor and Katz [8] have presented a first treatment of lattice QCD at finite μ. Not explicitly presented at this conference, their approach was mentioned in the talks of Bass [9] and Stachel [10]. For more than a decade we are familiar with the statement that the important sampling Monte–Carlo technique of lattice QCD breaks down at $\mu > 0$. The reason is that the functional measure (the Dirac determinant) turns imaginary thus offering, partially, negative probability weight. The new idea consists of producing an ensemble of QCD configurations at $\mu = 0$ and $T = T_{\mathrm{c}}$, then to determine the Boltzmann weights [11] of these configurations at $\mu > 0$ (please consult their papers [8,11] for details).

The Fodor and Katz result is shown in figure 2. It represents the first QCD approach to the entire μ–T plane (some qualms concerning the employed quark masses remaining). The critical end-point is located at $\mu_E = 725$ MeV, $T_{E,\mathrm{c}} = 160$ MeV. Towards smaller μ the bars indicate the domains of the ensuing cross-over transition. The authors note that the end-point should move closer to the $\mu = 0$ axis once 'more realistic' quark masses get employed. Nevertheless, a new paradigm is born. Can experiments pass by this point, reaching such high T without far diminishing the initial $\mu_{\mathrm{B}} \approx 900$ MeV along the dynamical trajectory: a question to the hydrodynamical models of Srivastava *et al* [12]! The general question as to how far to the high μ_{B} side dynamical evolution of even the highest mass central *AA* collisions can proceed before entropy production forces it upward to high T also governs the other new QCD paradigm: experimental observation of the novel colour superconducting QCD states that were described by Schäfer [13] at this conference. A general question emerges: how much entropy is produced per unit compression of the initial projectile–target net baryon density? This question will force us to focus, again, on the hadronic matter equation of state, and on hadronic transmutation in a dense medium: outlining the effective in-medium hadronic degrees of freedom – yet another fascinating facet of QCD, chiral symmetry restoration.

However, before turning to this second major topic of this chapter, let me briefly describe the four 'data' points that I inserted into the Fodor and Katz μ–T diagram. They represent the results of a grand canonical statistical ensemble analysis of the bulk hadronic production yields, and yield ratios measured at RHIC ($\sqrt{s} = 130$ GeV) and at CERN ($\sqrt{s} = 18$, 12, 8 GeV). The final hadron species range from pions to multi-strange hyperons; their population appears to obey grand canonical order, according to phase space weights, as was described in the talks of Stachel [10] and Oeschler [14]. I will return to this physics in the next section, giving some appropriate detail but note, for now, that this analysis captures the parameters μ_{B} and T, prevailing 'at birth' of the finally observed bulk hadron population ratios. We see that, at top SPS and RHIC energy, this birthplace merges with the site of the QCD parton to hadron phase boundary in the μ–T plane. At $T = 170 \pm 10$ MeV we are at Hagedorns limiting hadronic temperature, and the hadronic population appears to be born directly at the QCD phase boundary [15]! On the other hand, the hadronic freeze-out μ_{B}, T parameters drop away steeply below the lattice QCD transition line at the lower SPS energies. Far below the T scale of figure 2 we have an AGS point at $T = 125 \pm 10$ MeV, $\mu_{\mathrm{B}} = 540$ MeV [16]. From these statistical model observations we derive, firstly, a confirmation of the QCD phase transition point at low μ_{B}, to occur at $T = 170 \pm 10$ MeV: a major breakthrough. However, at higher μ_{B} the bulk hadron population becomes stationary only far below the Fodor and Katz phase transformation line in the μ_{B}, T plane. The hadronic system thus appears to undergo significant rearrangement on its trajectory towards final stationarity at these lower incident energies. Recall now that it is at these lower SPS/upper AGS energies where we might suspect the primordial compression and heating dynamical trajectory to pass by the hypothetical critical QCD point, $T = 150$ MeV and $\mu_{\mathrm{B}} = 725$ MeV. A further question to theory: which observable features might reveal the long range critical fluctuations imprinted on the onward trajectory, not to be dampened by hadronic rearrangement?

This brings me to the second major topic of this chapter: hadrons in a medium of high-energy density and the advent of chiral restoration near $T = T_{\mathrm{c}}$. Let me proceed in three steps: hadrons in medium, high-energy density effects, chiral restoration. About the latter topic we witnessed a fascinating confrontation of theory below and above T_{c} in the talks of Rapp [5] and Learmann [4], indicating a novel concept of 'hadron–parton duality (equivalence)'. But a didactical glance at hadrons in nuclear matter near the ground state density encountered in the interior sections of nuclei may serve as a starting point. Recall the optical model in non-relativistic formulation [17]. In brief, the real part of the optical potential creates an effective mass of the hadrons which is lowered from the vacuum mass if the net potential is attractive; the generalization of the nuclear shell model into the continuum creates effective dynamical proton masses of about 800 MeV due to net attraction. Likewise, the new data from GSI indicate a lowering of the K^- mass in a baryonic medium of about twice the nuclear ground state density, due also to net attraction [18]. To first order the increased production rate of K^- in central AA collisions in the 1 GeV/nucleon energy domain, relative to pp collisions, may have, firstly, the to-be-expected origin in second generation ΔN, $\Delta\Delta$, $\pi\Delta$ collisions which already absorbed energy from the thermal bath (absent in pp collisions). Secondly, however, the K^- production rates near threshold benefit from the in-medium increase of available phase space: the attractive net potential 'lowers the floor' of available open phase space to negative energy, absent in the vacuum. The K^- is thus more copiously produced because thresholds shift down, an effect which looks like a lighter K^- although nothing has yet happened to the

intrinsic structure function. However, there is a third effect, much less trivial, from the imaginary part of the in-medium potential that represents coupling to absorptive, or inelastic in-medium modes: the kaon spectral function acquires an additional in-medium width that grows with the strength of the optical model imaginary part. It spreads out, with further effect on production/annihilation cross-sections and on branching ratios. Opposite effects act on the K^+ (net repulsion) but its production rates are influenced to a lesser degree by the spreading effect, due to a smaller imaginary potential. In total the K^- to K^+ production ratios in central *AA* collisions at GSI–SIS differ, by orders of magnitude, from the *pp* ratio at similar energy. The public attitude to blame these observations on a 'downward K^- mass shift' is an unfortunate shorthand reflection of a basically straightforward physics. It is an effect, in part, of a spreading width acquired in-medium.

At the much higher SPS energy the observations of CERN NA45 [19] clearly indicate that the invariant mass spectrum of vector meson decays to e^+e^- stays far above the cross-section expected from the cocktail of to-be-expected meson to e^+e^- cross-sections. Even if pion pair annihilation is taken into account, a serious discrepancy remains in the domain from about twice the pion mass to the ρ, ω, Φ domain as was shown in the talk of Damjanovic [20]. In due humbleness one might suggest to witness an extension of the non-relativistic optical potential effects to relativistic energy and higher energy density, approaching the critical QCD parameters. We have seen in figure 2 that the hadronic species population becomes stationary and, thus, observable near T_c at top SPS energy. These hadrons should, thus, be subject to the onset of QCD chiral restoration. Rapp [5] has presented to us the conclusion that chiral restoration models lead to a radicalization of the effects inflicted by the imaginary potential in non-relativistic physics. The spectral function of the ρ meson, in particular, broadens dramatically toward lower energy near T_c. Overall a satisfactory representation of the NA45 data is within sight, again without talking about vector mesons shifting near massless as was assumed in previous attempts employing the famous Brown–Rho downward mass scaling with net baryon density [21]. However, one of the spectacular challenges of this conference arose from the confrontation of Rapp's chiral restoration theory just below T_c, and Learmann's lattice QCD quark–antiquark correlation spectral functions in the vector channel far above T_c: their observable consequences in e^+e^- spectra are almost similar. Figure 3 shows Learmann's $q\bar{q}$ vector channel spectral functions at $T = 1.5$ and $3T_c$, respectively.

We observe a prominent peak in the ρ mass domain! It thus appears that the vector meson spectral function, quite broadened in chiral restoration theory at $T < T_c$, survives as a quark dynamical correlation far beyond T_c. In fact figure 3 shows that Learmann's spectral function also predicts the enhancement in the e^+e^- invariant mass cross-section downward of the ρ, ω, Φ domain that was reported by NA45. Hadron ghosts in $q\bar{q}$ correlations observed on the lattice at $T = 3T_c$: nobody ventured for a plausible explanation. A further new paradigm is born, and in due reflection of our lack of understanding it is called 'parton–hadron duality' [5]. What is indicated is that there might be more continuity of strong interaction degrees of freedom below and above T_c, with related quasi-particle structure on either side. I hope that the reader will now give me absolution for the casual terminology used in the introduction: 'relax about the QGP', i.e., we begin to see more details of QCD physics on either side of T_c: much more fascinating than the 1980s view of a transition between non-interacting hadron and parton gases. We derive the expectation that the trivial hadron gas picture at $T \leq T_c$ will also be shaken in due course. A funny gas anyway, with mean free path about equal to hadronic size, at the energy density

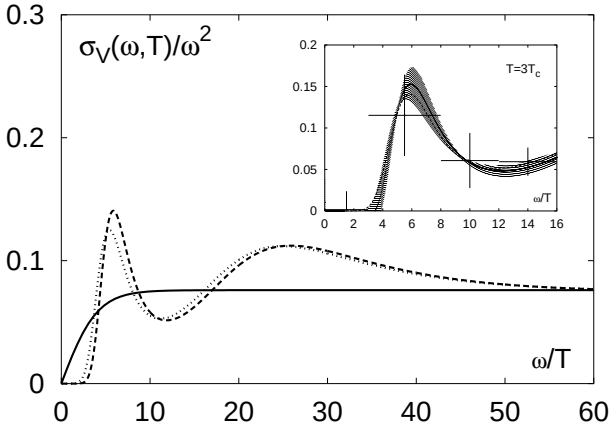


Figure 3. Lattice QCD at $T = 1.5$ and 3 T_c showing the $q\overline{q}$ spectral density in the vector correlator channel. The inset illustrates the numerical accuracy in the vicinity of the 'vector meson-like' peak [4].

of 0.6–0.8 GeV/fm^3 now expected to prevail at the hadronic side of the parton-to-hadron transformation [22].

A short glance at astrophysics and cosmology: to the very early expansion dynamics at $t \leq 10^{-20}$ s our present concerns bear no relevance as Jain [23] put it clearly in his talk. The quark–gluon QCD era begins well after the decoupling of the strong force from grand unification conditions, and after electroweak decoupling at $T \approx$300 GeV and $t \approx 10^{-12}$ s. But it lasts until about 10^{-5}s – a relatively long span on the overall time-scale. In its beginning the conditions of *p*QCD (asymptotic freedom) should prevail but with $T \leq 1$ GeV we enter the domain of effective QCD degrees of freedom, e.g. McLerran's colour glass condensate [1], lattice QCD [4] and QCD resummation techniques (see the talk of Mustafa [24]). In the immediate vicinity of T_c our present progress focuses on parton–hadron duality [5] and statistical hadronization [10,15,22], with the relativistic hydrodynamical model [12] interpolating from above to below T_c. At T well below 170 MeV but $\mu > 2$ GeV new QCD phases [13] are expected to exist. For the astrophysics theory community the latter sector is of foremost importance ($T \leq T_c$): the origin of the hadronic phase, and neutron stars plus their merger process, as we have learned from the talks of Bhattacharyya [25], Chakrabarty [26] and Goyal [27].

3. From AGS, SPS to RHIC: Experiments and data

At CERN important new data were obtained for direct photon production at top SPS energy, 158 GeV/A, and for electron pair production and hadronic multiplicities at two lower SPS energies, 80 and 40 GeV/A. At RHIC we could consider essentially all data as new and important (see McLerran's systematic evaluation [1]) but we saw first data from the run at $\sqrt{s} = 200$ GeV while the data at $\sqrt{s} = 130$ GeV are getting as complete as they could. Starting with SPS direct photons, Peitzmann [28] showed the final WA98 data which indicate a measurable excess over the background photon cocktail in central Pb+ Pb at 158 GeV/A, at intermediate transverse momenta, 1.5 to about 3.0 GeV/c.

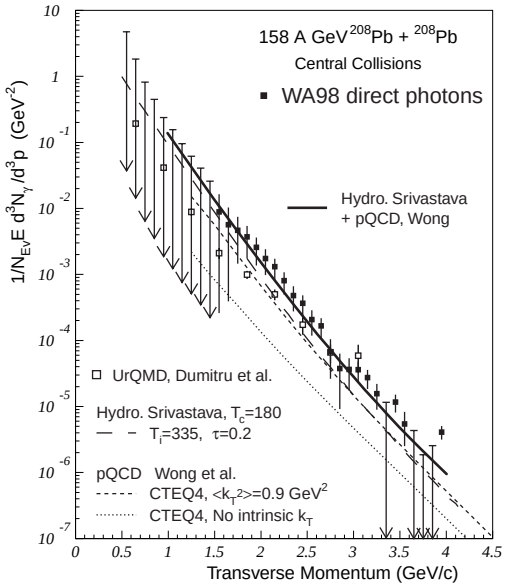


Figure 4. Direct photon production in central Pb + Pb collisions at 158 GeV/A from WA98 [28] compared with UrQMD, hydrodynamical model, and perturbative QCD (see text).

Figure 4 shows the p_{T} distribution including at lower p_{T} the upper limit estimates. The narrow logarithmic scale underemphasizes the sensitivity of those long expected data as far as model comparison is concerned. Not surprisingly, cascade models like UrQMD would have to fail, at least if most of the 'direct' photons really stem from an initial partonic phase which is essentially missed in cascades of initial 'strings' which are infertile for the duration of a so-called hadron formation time. It is, in fact, surprising that such models get tested here as they expressedly delay action until hadrons are formed! The hydrodynamical model intuitively looks more appealing as it explicitely merges a partonic with a hadronic phase. However, unfortunately, the model is not only sensitive to the two hotly desired parameters, the initial temperature T_{i} and the hadronization temperature T_{c}, but also to the equation of state on either side of T_{c}, and to the details of the phase matching. Thus, Srivastava and Sinha [29] get $T_{\mathrm{i}} > 250$ MeV for the present data whereas Huovinen *et al* [30] derive $T_{\mathrm{i}} = 210$–250 MeV. Perturbative QCD [31] underestimates the cross-section whereas it fits the $p+p$ and $p+C$ data. An initial temperature of about 240 MeV would be quite in line with the NA49 and WA98 total transverse energy measurement [32] for the Pb + Pb collision which leads to a Bjorken estimate of $\varepsilon_{\mathrm{i}} = 3.0 \pm 0.3$ GeV/fm^3. Putting $T_{\mathrm{c}} = 170 \pm 5$ MeV (see figure 2) and $\varepsilon_{\mathrm{c}} = 0.8 \pm 0.15$ GeV/fm^3 [15] one gets $T_{\mathrm{i}} = 237 \pm 25$ MeV, at top SPS energy, using $\varepsilon \approx T^4$. However, the hydrodynamics community would first try to converge before we can really fully enjoy this result. At RHIC, however, T_{i} should be much higher, thus also the early phase part of the cross-section and the reliability of analysis as Peitzmann [28] has shown us. I will return to RHIC direct photons in §4.

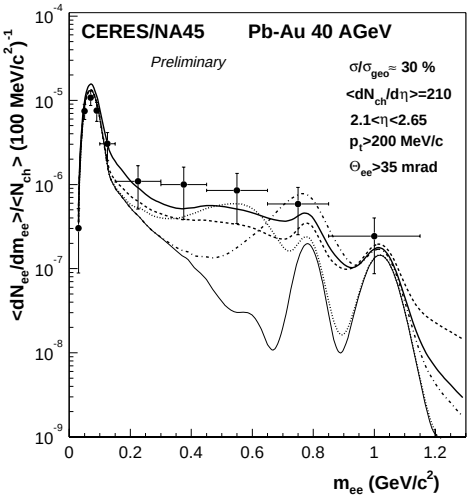


Figure 5. Invariant e^+e^- mass spectrum in the pion to Φ domain obtained by NA45/CERES [20] for central Pb + Au collisions at 40 GeV/A SPS energy. Lines show the hadronic decay cocktail (thin closed) plus addition of the vacuum ρ spectral function (dash–dot), of ρ with dropping mass (dotted) or with full in-medium spectral function (thick closed), as well as the lowest order *p*QCD rate (dashed). See text.

Let me turn to the other signal of electromagnetic radiation from the medium, e^+e^- invariant mass spectra. They reflect the integral effect of lepton pair emission over reaction time from early high density via hadronization, up until late freeze-out and free streaming stages, e.g., in the decay of Φ and ω. If a central $A+A$ collision was merely a superposition of hadronic reactions, as they occur in the vacuum, one would observe the hadronic decay cocktail but CERES/NA45 has shown [33] that this is not the case. Figure 5, from the talk of Damjanovic [20], gives the recent results for the 40 GeV/A run of the SPS, central Pb + Au collisions.

These tantalizing data repeat the message of the former [33] results at 158 GeV/A, a smooth spectrum far above the hadronic cocktail, no discernable peak, i.e., non-trivial behaviour from 0.3 to 0.8 GeV. Unfortunately the lack of statistics is also tantalizing: should this be the last word from the SPS? We meet again with the parton–hadron duality discussed by Rapp [5] as both the chiral model which employs a broadened in (hadron!) medium ρ spectral function and a *p*QCD model of parton medium radiation come near the data. Also lattice QCD should give a qualitative account of the data as Learmann [4] shows. Thus, finally tantalizing: there are hints at an understanding of the CERES data assuming an origin of the cross-section from both below and above T_c! This also refers to the aspect that the NA45 data at top SPS energy look similar within statistics although the primordial energy density (Bjorken estimate) is about 30% lower at 40 GeV/A as shown by NA49 [34].

In a way this duality also echos the past years of J/Ψ suppression discussion: deconfinement effect or hadronic co-mover interaction in a dense medium? The final NA50/NA38 data synopsis shown by Bordalo [35] who suggested the conclusion that only the models

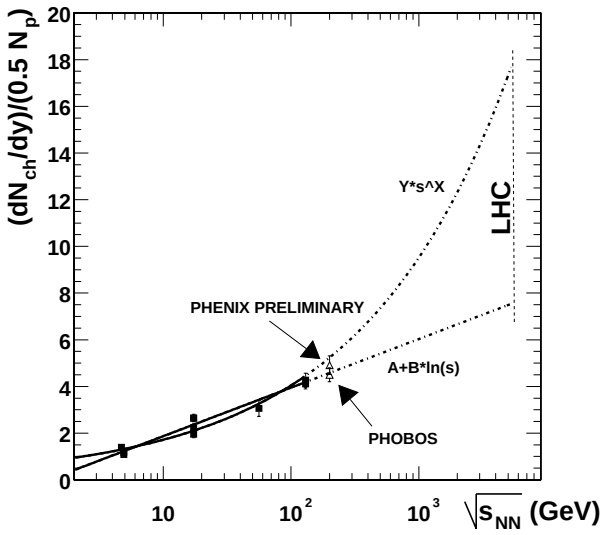


Figure 6. Charged particle density at mid-rapidity in central $A+A$ collisions at AGS, top SPS and three RHIC energies, also indicating conceivable extrapolations to LHC energy [39]. Data are normalized to participant nucleon pair number.

explicitly involving a partonic phase, by Nardi and Satz [36] and by Blaizot *et al* [37], really account for the final data (that have remained stationary since QM2001). Whereas Capella *et al* [38] might still object to this conclusion one might, indeed, formulate a general critique of the co-mover models, irrespective of their success in fitting the data. In all these models the main fraction of the hypothetical J/Ψ breakup occurs at absurd hadron density and energy density (well above 1 GeV/fm^3). The models have no intrinsic barrier against transporting hadrons up to primordial density and temperature where any assumed finite 'breakup cross-section' will dissolve J/Ψ: an apparent inconsistency of approach in view of the naive argument (that one dares only to mention in summary talks such as the present) that conditions sufficient to dissolve even the most compact hadron should, a forteriori, also break up all the co-moving hadrons or, at least, inflict serious in-medium modifications of their spectral functions [4,5]. However, more detailed data both for the lepton pair production in the lower mass domain and in the charmonium region would be extremely helpful in settling such unfortunate dualities in the theoretical interpretation. It would be most unfortunate if the SPS era ended without precise data on transverse momentum and rapidity dependence, both from NA45 and NA50.

The final topic of this section will be the bulk hadron production. A wealth of data is available now, both from SPS and RHIC. I apologize, in advance, as I will be able to cover only a small, subjectively selected subset only.

Figure 6 gives a synopsis of charged particle multiplicity density at mid-rapidity per participant pair from the talk of Silvermyr [39]: AGS, top SPS and the three RHIC energies including first data from the recent $\sqrt{s} = 200$ GeV run. Most remarkably the multiplicity stays much lower than expected before RHIC turn-on [40] – essentially proportional to

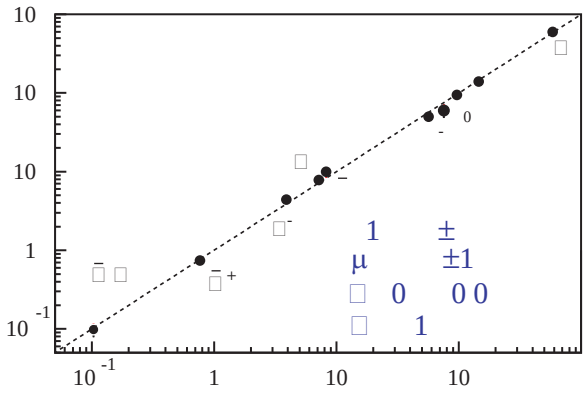


Figure 7. Grand canonical statistical model fit of Becattini [46] to hadron multiplicity data of NA49 [43], for central Pb + Pb collisions at 158 GeV/A.

ln(*s*). In hindsight we recall that this is basically the evolution law of multiplicities in elementary hadron collisions up to Tevatron energy. Albeit rediscovered, with a higher slope factor, in *AA* collisions this apparent universality makes us reflect again upon our expectations as of QM1999. We thought then that the 'onset' of hard QCD collisions in the RHIC energy domain should manifestly change the slope in $\sqrt{s}$, in essence, thus, as a consequence of progressing from non-perturbative ('soft') QCD to *p*QCD. The data indicate that nature smoothly interpolates between these seemingly separate drawers that might be an artifact of our present understanding. The final answer will come with LHC energy but figure 6 shows that the RHIC data at $\sqrt{s} = 200$ GeV begin to seriously constrain the extrapolation toward $\sqrt{s} = 5.5$ TeV, away from a power-law dependence. Apart from a profound challenge to theory this observation implies an important message concerning the design of ALICE at LHC – its overall granularity and tracking resolution (in various sub-detectors) were based on a 1996 'panic scenario' estimate of mid-rapidity charged particle density up to 8000. With daring extrapolation of present instrumentation technique this design faces the limits of foreseable state of the art development in detector building, as far as track reconstruction, two track separation, and raw data flux plus off-line analysis effort are concerned. From figure 6 we may now infer that charged particle density of 8000 is clearly ruled out by the new RHIC results (unless sensational new physics sets in), and that ALICE LHC physics will be well enjoyable.

Hagedorn's [41] statistical hadronization model has been around for more than 30 years now but the recent systematical data on hadron multiplicities, from pions to hyperons, and covering the AGS, three SPS and (at present) one RHIC energy, $\sqrt{s} = 130$ GeV, have provoked considerable progress. The present understanding of that model has been described to us by Stachel [10], Cleymans [42] and Oeschler [14], and new NA49 data concerning SPS central Pb + Pb collisions at $\sqrt{s} = 8, 12$ and 18 GeV were presented by Seyboth [43] whereas new STAR data were shown by Caines [44] and van Buren [45]. These data have been analyzed in the Gibbs grand canonical version of the statistical model. Figures 7 and 8 present examples, the first a fit by Becattini [46] to NA49 data [43] at top SPS energy. He derives a hadronic chemical freeze-out temperature of 159 ± 3 MeV employing an additional 'strangeness undersaturation' factor γ_s whereas Braun-Munzinger *et al* [16,47]

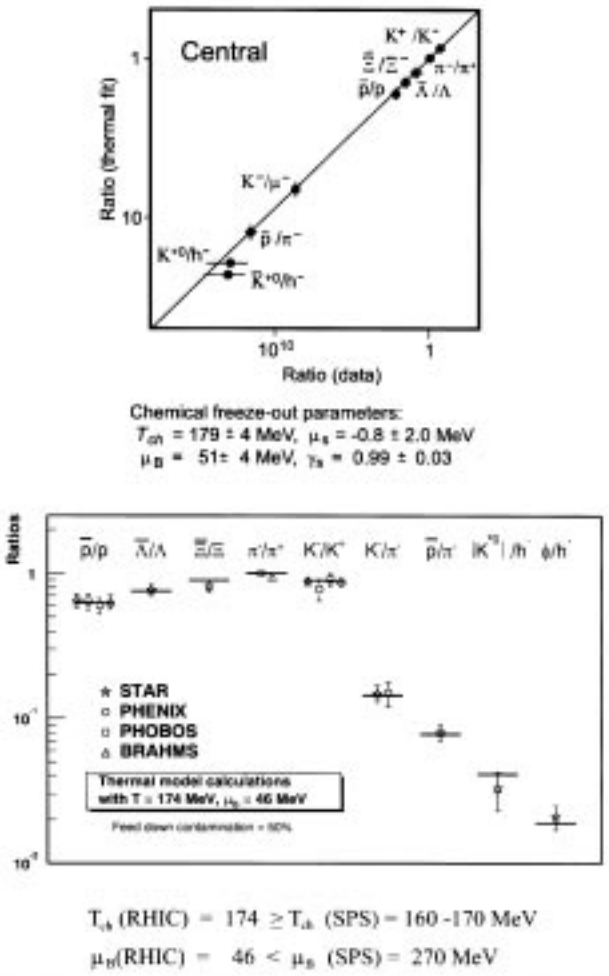


Figure 8. Hadron production systematics at $\sqrt{s} = 130$ GeV in central Au + Au at RHIC [44,45] confronted with the grand canonical model in formulations by Braun-Munzinger *et al* [47] (bottom) and by Xu and Kaneta [49] (top).

and Stachel [10] use $\gamma_s \equiv 1$ in their formulation of the model obtaining $T = 170 \pm 6$ MeV for basically the same data but including also the hyperon results of WA97 [48].

Figure 8 is taken from the talk of Caines [44] and shows the 130 GeV STAR data confronted with the above model [10,47] and with that of Xu and Kaneta [49], with nearly identical results, $T = 176 \pm 5$ MeV. These results lead to the points already shown in figure 2 which also include preliminary results of Becattini [46] for NA49 data at the lower SPS energies, 80 and 40 GeV/A. We see that the hadronic freeze-out conditions merge with the Fodor–Katz parton–hadron cross-over transformation at top SPS and at RHIC. This implies that the hadronic population freezes out from inelastic interaction (which would change the eventually observed population ratios) right at the phase transformation, and

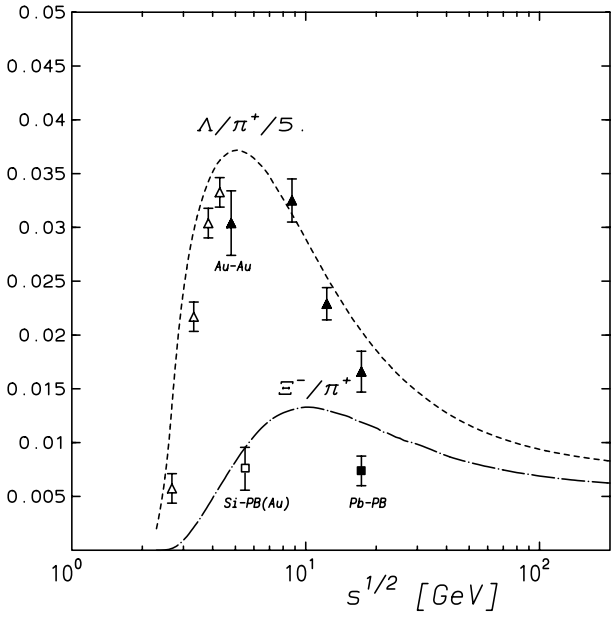


Figure 9. Hyperon to positive pion yield ratios (in 4π acceptance) from AGS and SPS experiments [43] compared to the statistical model interpolation of Braun–Munzinger *et al* [51].

that the statistical model temperature limit corresponds very closely to lattice T_c as we expected [15]. There may be RHIC data transcending this picture of statistical freeze-out universality – Caines reported first STAR data for the cascade hyperon exceeding the statistical limit [44]. If confirmed, and augmented by the forthcoming STAR Omega production results, we would have to consider additional, 'direct' production mechanisms [50] adding further interest in hyperon production.

Another interesting aspect of bulk hadron multiplicity systematics is the energy dependence of total strangeness production relative to the light quark yield, i.e., the 'Wroblewski' ratio $\lambda = 2(s+\overline{s})/(u+\overline{u}+d+\overline{d})$. From the former AGS data reported by E917 and E810 as combined with the new SPS NA49 data at the three CERN energies, Seyboth [43] showed that the K^+/π and the Λ/π ratios exhibit a maximum at about $\sqrt{s} \approx 8$ GeV. These data are shown in figure 9.

Note that at such low $\sqrt{s}$ the 'associated production' pair K^+ and Λ carry the main fraction of $(s+\overline{s})$. Such a strangeness maximum can semi-quantitatively also be understood in the framework of the statistical model, chiefly as a consequence of the evolution of the baryochemical potential, from about 550 MeV at AGS to about 230 MeV at top SPS energy, as was shown by Cleymans [42]. In fact figure 9 includes the statistical model results of Braun-Munzinger and collaborators [51] who employed an interpolation of T, μ_B values that were obtained by all the existing statistical model fits, such as figures 7 and 8, including an AGS analysis of central Si + Au collisions at 14.6 GeV/A [16] which resulted in $T = 125$ MeV, $\mu_B = 540$ MeV [10].

Now to the crucial question: does this behaviour connect to an 'onset' of the partonic phase, at such intermediate energies? The answer is no and yes. No because the statis-

tical model *predicts* nothing, it only *reacts* to the data describing a hadronic equilibrium ensemble that knows nothing (except, perhaps, by a minor strangeness undersaturation, Becattini's γ_s [46]) about its prehistory, 'just' reflecting a global order among all species that is captured by the grand canonical parameters, T and μ_B. The latter falls monotonically with increasing $\sqrt{s}$ because it reflects the relative density of net baryon number to total quark number, i.e. $(q-\overline{q})$ to $(q+\overline{q})$ where the former term is fixed by the initial valence quarks but the latter term grows like the pion multiplicity. This grows smoothly with $\sqrt{s}$ as we saw in figure 6, no first-order effect of a phase change being visible.

Now, however, for the 'yes' answer: while μ_B falls to zero steeply and monotonically, T saturates at $T = T_c$! Hagedorn's [41] limiting hadronic temperature sets in. This is, of course, a property of a hadron gas alright, but exactly this property signals the onset of a partonic phase located above, as the limiting temperature is reached. We know now that toward top SPS the three relevant temperatures become equal: T (therm. model) $= T$ (Hagedorn) $= T_c$ (QCD), see figure 2. Clearly the discussion will go on: Gazdzicki and Gorenstein [52], in particular, stress the affirmative answer: if the primordial fireball could stay in a hadronic phase its temperature would keep rising (in ignorance of Hagedorn) to $T = 250$ MeV or so, the $(K^+ + \Lambda)/\pi$ ratio would also keep rising further instead of bending over already at such low $\sqrt{s}$. This maximum thus appears to signal the advent of the hadronic phase boundary.

I end this long section formulating the present conclusion from all these CERN data, and their continuation at RHIC: they are, in their combination, all consistent with the impression derived from figure 2. The system leaves the hadronic phase towards the upper SPS energy range, in central *AA* collisions.

4. New physics at RHIC and toward LHC

As I have said in the introduction I consider Lerry McLerran's talk [1] as the real conference summary about what we have learned from RHIC, and it would be silly to dilute it by repetition. However let me address the physics yet to come from RHIC, and end with a further forward look, to LHC.

Let us return to direct photons. The WA98 results have pioneered this field but the relatively fragile signal plus the present state of the art in theory did not (yet) leave us with a firm conclusion as Peitzmann showed [28]. We might expect an initial partonic temperature of about 235 MeV at top SPS energy but of about 275 MeV at top RHIC energy – a much more pronounced partonic phase black-body radiation would result.

Figure 10 shows Peitzmann's RHIC prediction [28]: the direct photons now amount to about 10% of the π^0 decay background (this was about 2.5% at the SPS) and one thus expects to obtain a p_T spectrum from 1 to 4 GeV/c which, according to theory, is dominated by thermal parton radiation above about 2.5 GeV/c. There remains Srivastava's warning [53] that we have to expect significant pre-equilibrium contributions from the early parton cascade, but every signal from the partonic phase is welcome, to reject finally the hypothesis that the signal could be of some hadronic origin. Thus if the analysis succeeds to pin down an initial 'temperature' approaching 300 MeV everybody would agree that 'it is silly to try to describe the matter in terms of anything but its quark and gluon degrees of freedom', to quote McLerran [1]. Thus PHENIX might provide us with the 'smoking gun' signal that the wider community keeps demanding.

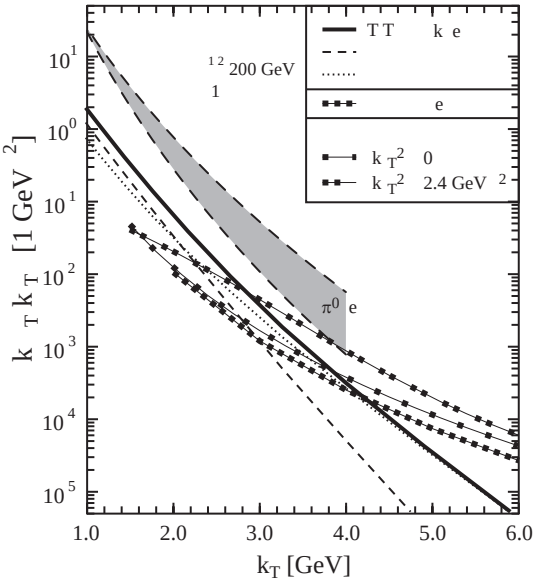


Figure 10. Expected direct photon transverse momentum spectrum for central Au + Au at top RHIC energy [28] also showing neutral pion decay yield and various model predictions (see text).

Furthermore it would be interesting if a first estimate of the bottonium cross-section could be determined at RHIC. A few hundred Y to dilepton decays are expected per RHIC year at design luminosity [54] after proper consideration of branching ratios, detector acceptance and dead time etc. just at the very limit of feasibility but PHENIX and STAR will certainly try. Note that Y suppression should only set in at $T_i > 2T_c$ which might or might not be reached at $\sqrt{s} = 200$ GeV [1] but is clearly expected for LHC. Thus if the 'standard pQCD' yield, corresponding to the above estimate, could be observed at RHIC, it would help to place an upper limit on the initial energy density, and set the stage for observation in ALICE.

Much closer to realization should be an accurate STAR measurement, not only of the omega and antiomega yield and ratio but of the omega transverse mass spectrum. Already at top SPS energy WA97 has reported [55] a remarkably low inverse slope parameter, well below the systematic trend of hadronic slopes increasing with mass as an effect of collective radial expansion flow, an effect that was ascribed to an early decoupling of the low cross-section hyperon in a scenario of 'explosive' hadronic phase expansion [56]. The observed omega slope $T = 230$ MeV would then give an estimate of 'primordial flow' prevailing right at hadronization, i.e., from a preceeding hypothetical partonic expansion mode, amounting to $\beta_T = 0.27$ only [57]. At RHIC one would expect a significantly higher value as the system spends more time in the partonic phase. This is shown in figure 11 for the hydrodynamical model of Srivastava *et al* [12] – hadronization sets in after about 5–7 fm/c have elapsed! This model could clearly make a prediction of the average transverse velocity prevailing during the hadronization period. We might, thus pick up another observable quantity characterizing the situation at hadronization!

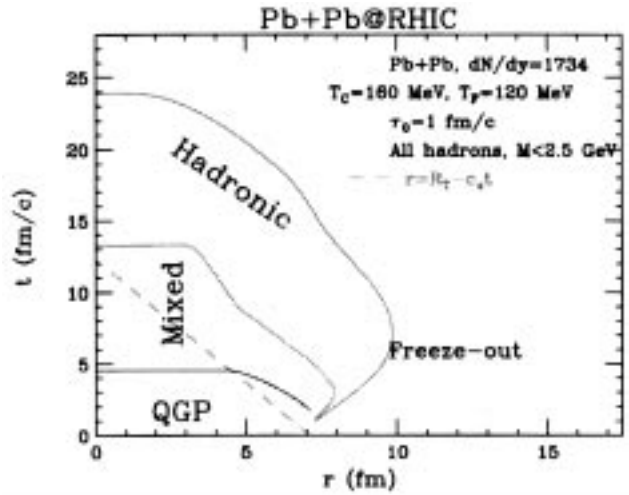


Figure 11. Contours in space and time of the expanding 'fireball' created in a central collision at top RHIC energy as predicted by the hydrochemical model of Srivastava*et al* [12,29]. Hadronization assumed to occur at $T_c = 160$ MeV, final decoupling to free streaming at $T_F = 120$ MeV.

A last remark concerns the topic of jet attenuation due to leading parton radiative energy loss in the traversed medium. McLerran has given an analysis [1] of the apparent high p_T hadron suppression effect of PHENIX [58] and STAR [44], in comparison to $p\bar{p}$ hadron production at similar $\sqrt{s}$. As remarkable as these data are, they nevertheless offer an indirect view of jet dynamics only, somehow an observation through a keyhole. It would be more satisfactory to directly observe the jet cross-section but this is an extremely difficult task at RHIC energy – the jet fragmentation hadrons have relatively low multiplicity and are not very narrowly focused – hard to disentangle from the background. This is a signal, finally, that will be unique to LHC, both for ALICE and CMS observation. Jets of 100 GeV total transverse energy should occur within acceptance once in about 10^4 central Pb+Pb collisions at LHC, and at such E_T the jet produces an almost unmistakable topological track pattern. Still the straightforward approach is tedious: first measure the inclusive jet production cross-section as a function of E_T in pp collisions (note also that the LHC energy is 14 TeV in pp but 5.5 TeV in Pb–Pb), then turn to central Pb–Pb for the corresponding jet E_T spectrum. Attenuation would reflect in an effective suppression of the latter yield – but we know from the CERN J/Ψ suppression effort that such a procedure might be cumbersome. However, Lokhtin [59] has suggested at this conference a more elegant approach that inherits its basic idea from current directed flow experiments: consider semi-central collisions, determine the reaction plane by a suitable detector system (e.g. the photon multiplicity array PMD prepared for ALICE by the India groups [60]), and measure the jet cross-section relative to that plane which fixes the collision geometry, thus enabling one to observe jets which have transversed more or less distance in the fireball. An interesting alternative to the straightforward approach in which one would need to interpolate between LHC pp and Pb–Pb energies thus picking up uncertainties as all LHC research covers an, at first, unknown territory.

These sketchy remarks should suffice to indicate that our field is indeed blessed with a wealth of present and future, exciting research questions and opportunities. Already we have ample evidence suggesting that we should finally part with the initial oversimplification: that at the QCD critical temperature (that we know now!) a transition should occur from an ideal hadron gas to an ideal gas of massless gluons and ideal QCD current quarks. This 1980s paradigm has served its purpose: it has focused an ever increasing research community, from theory and experiment, to investigate strongly interacting matter at high energy density – extended QCD matter with all its emerging subtleties. This conference has provided us with both a fascinating and challenging survey of present accomplishments and future research frontiers. In the end we express our sincere gratitude to our Indian colleagues, as hosts and organizers!

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