The Mini Bang and the Big Bang: From Collider to Cosmology

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1 Introduction

Collisions of two nuclei at ultra-relativistic energy such as in RHIC and/or LHC are expected to lead to a new state of matter, usually referred to as Quark Gluon Plasma (QGP). Although there is a fair amount of controversy about the exact nature of the phase transition from hadrons to QGP, there is little doubt that QGP has been found.

Lattice calculations [1–3] tend to indicate that at small hadronic chemical potential but high temperature the transition is like a crossover, such that after the transition no memory is left over of the matter before the transition. This scenario is applicable, it is argued, both at LHC and in the very early universe, about a microsecond after the Big Bang.

Recent discoveries at RHIC clearly establish that QGP behaves as a perfect fluid with η/s satisfying the AdS/CFT limit of 0.08, almost zero [4, 5]. This phenomenon almost uniquely comes from the elliptic flow characterised by v_2 the flow velocity. Higher order flow components v_n $(n = 3\ldots)$ are extremely important as amply demonstrated by [6, 7] PHENIX and STAR at RHIC and ALICE, ATLAS and CMS at LHC [8].

It has been pointed out by the present author and his collaborators that the thermometric signals such as γ, $\mu^+\mu^-$ are rather efficient signals of QGP, especially of the early times, almost immediately after QGP is formed. It was further pointed out [9] that the ratio $\gamma/\mu^+\mu^-$ will have the added advantage of universality in the sense that being a ratio, the dependence on boundary conditions, such as model dependent initial temperature, initial time etc. get cancelled out, thus effectively turning the ratio more sensitive to the actual state of the matter.

Finally the scenario of quark hadron phase transition around a microsecond after the Big Bang—what possible relics can be left over today? Recent work of Boeckel

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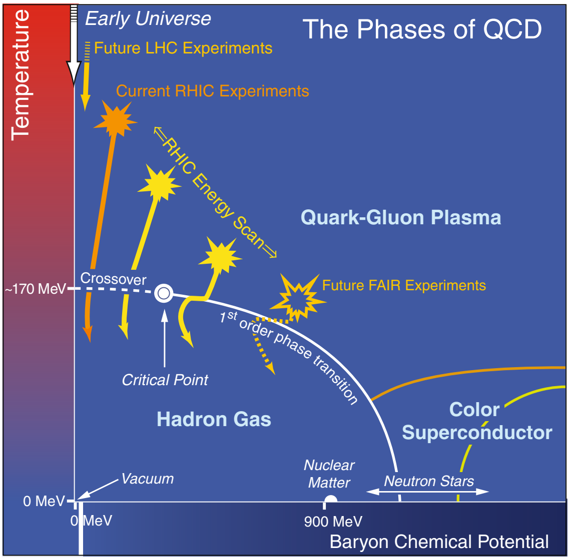


Fig. 1 The phases of QCD

and Schaffner-Bielich [10] has demonstrated that a little inflation (7e-foldings) will force μ/T to be of the order of unity, precipitating a first-order phase transition from quark to hadrons at this primordial epoch.

Our previous work [11, 12] and this work [10] predict a large number of very interesting relics; I argue that if the relics are found that will corroborate a first order phase transition scenario.

2 Dileptons and Photons

In Fig. 1 the QCD phase diagram is shown in all its glory. Over the years this so called "cartoon" has evolved to a level of sophistication or complication, depending on one's taste, that it is no longer funny, at all!

We see at the top extreme left, the microsecond old universe "crossing over" to the hadronic world, a little on the right (along the baryonic chemical potential axis) LHC making the reverse journey from hadrons to quarks along the crossover critical temperature. RHIC energy regime takes us to the edge of the crossover and then, along the phase boundary "rainbow" we meet up with the future FAIR experiment and then at very low temperatures but very high baryonic chemical potential we encounter the neutron star regime even the land of Quarkonium, colour superconductivity and all kinds of exotica!

It has been amply demonstrated by lattice calculations [1–3] that the energy density scaled by T^4, ε/T^4 as a function of the temperature turns invariant of the temperature beyond some critical temperature T_c, Fig. 2, either the standard critical

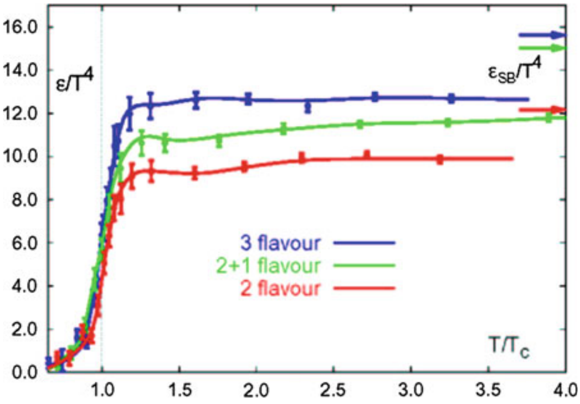


Fig. 2 Temperature dependence of the scaled energy density as predicted by lattice QCD

temperature of a first order phase transition or the so called crossover critical temperature, just discussed. What is referred to as (2+1) flavour implies that unlike the other two lines which deals with zero quark mass, one flavour, strange quark in this case has finite mass, leading to crossover.

In Fig. 3 the diagrams in lowest order involved in photon and dimuon productions from QGP are shown. It was shown by the present author [9] that the cross section of production of the just mentioned thermometric signals vary as T^4 in the QGP sector. Thus the ratio $R(\gamma/\mu^+\mu)$ will saturate to a constant value signaling *the onset of QGP*. For the simplest case, with some approximation

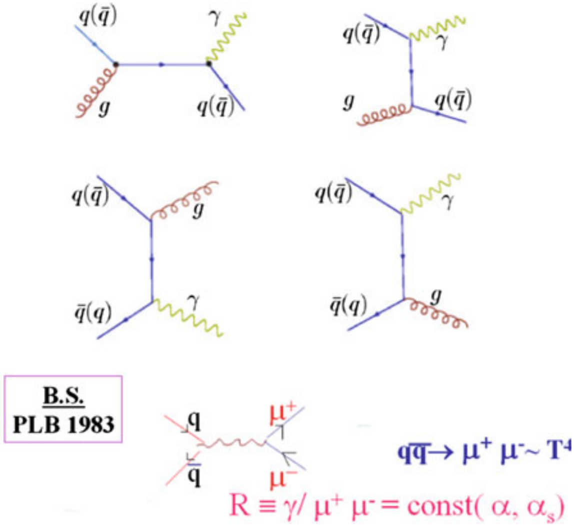
$$R(\gamma/\mu^+\mu) \approx 2/\alpha \propto s\ln(1/\alpha s) \tag{1}$$

The ratio is modified in form [13] with the addition of more sophistication but essentially, the message remains the same.

In Fig. 4 even at SPS, we present the data from the Pb+Pb run of WA98 at 17.3 GeV/A; the fits to the data using the Parton Cascade model for hard scattering leading to hard photons and the standard [14, 15] hydrodynamical model leading to thermal photons are shown. It is already clear even at SPS energies that neither the thermal alone nor just hard scattering will fit the data, rather a combination of the two does the job well. We have mentioned many times [14, 15] that the typical window of p_T for thermal photons lie within $1.5 \leq p_T \leq 3.5$ GeV. Clearly, even at SPS, for relatively low $p_T \simeq 1.5$ GeV, as expected, hard photons have virtually no role, but still thermal photons fall short of the data, whereas for high p_T regime ≈ 3.5 GeV, hard photons are crucial. It tells us that even at SPS energies we have to have thermal photons and hard photons cannot be neglected.

Thus, we already see the tantalising hint of QGP photons at SPS; this point was emphasized by Srivastava and Sinha [16].

Fig. 3 Light from QGP



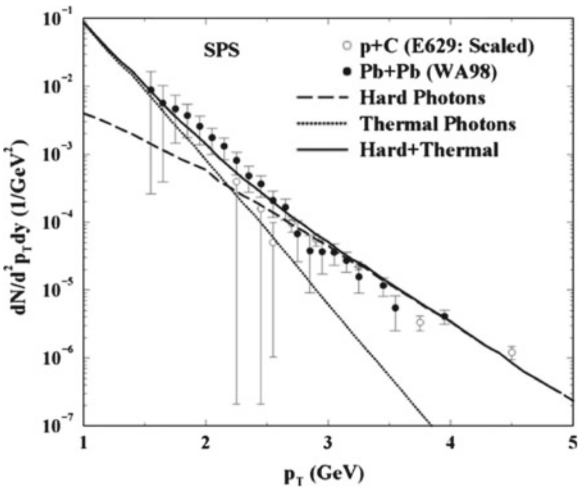


Fig. 4 Photons at SPS

In Fig. 4 data from PHENIX at $\sqrt{s}\ =\ 200$ GeV/A (RHIC energies) is shown, emphasizing the above points more substantially: The ratio

$$R_{\rm em} = \frac{d^2 N_\gamma}{d^2 p_T dy} \Bigg/ \frac{d^2 N_\gamma^*}{d^2 p_T dy} \tag{2}$$

$\gamma/\mu^+\mu^-$, as has already been mentioned, is an excellent handle for determining the initial temperature.

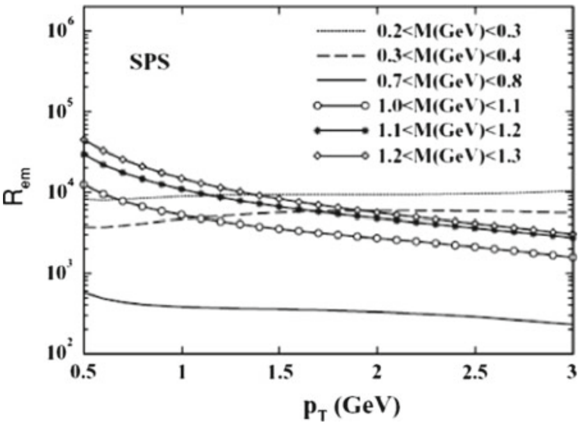


Fig. 5 The thermal photon to dilepton ratio R_{em} as a function of transverse momentum p_T for various invariant mass windows

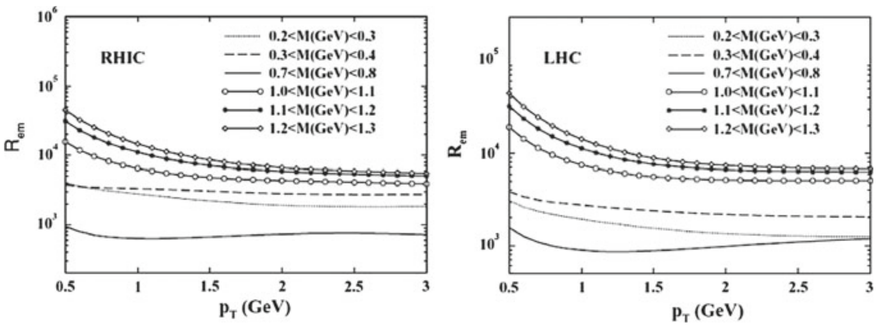


Fig. 6 The thermal photon to dilepton ratio R_{em} at RHIC (*left*) and LHC (*right*)

It is clear (Figs. 5, 6) that the quantiy R_{em} reaches a plateau beyond $p_T \approx 1.5$ GeV for all three cases of SPS, RHIC and LHC. Interestingly enough the degree of flatness goes up with energy, as we go from SPS to RHIC to LHC. The difference in R_{em} in the plateau originates from different values of the initial temperature, thus, it can be a measure of T_i. However, the ratio is largely independent of T_c, transverse velocity v_0 even being independent of the equation of state. It is further observed [17] that R_{em} is a sensitive measure of flow as well.

3 Universality of η/s

By 2004, RHIC experiments determined and reported several key properties of the hot dense matter. Its opacity to energetic quarks and gluon indicates extremely high

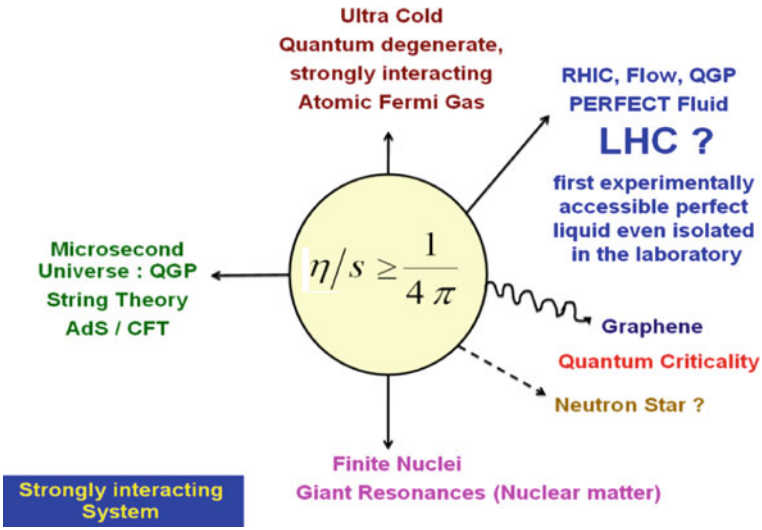


Fig. 7 The η/s saga

density. Hydrodynamic descriptions reproduce the data in general from the early times, through expansion, cooling and hadrons formation. One has to take into account the elliptic flow, and there comes viscosity per entropy η/s. The above, just mentioned is only possible if η/s is close to zero.

Thus the significant discovery is that the QGP at RHIC is not the weakly interacting gas of almost free moving quarks and gluons one would have naively expected from the characteristic of asymptotic freedom. Instead, it is strongly coupled.

The strong coupling [18] further implies that some correlation among the quarks and gluons may survive within the plasma phase near T_c and produce multiparticle interaction with near neighbours. Indeed, lattice QCD studies of energy density correlations in a QGP at temperatures $1 \ldots 2T_c$ show correlation peaks. This kind of correlation is rather similar to short range order observed in ordinary liquids near the liquid gas phase transition.

On the other hand, ultracold quantum degenerate, strongly interacting atomic Fermi gases also give rise to a very small value of η/s.

The so called Kovtun, Son and Starinets (KSS bound) for strongly coupling behavior of conformal gauge theories has a bound for η/s, the so called AdS/CFT limit $\eta/s \geq 1/4\pi = 0.08$. In Fig. 7 we display a large number of systems, very different from each other manifest this universal property of $\eta/s \approx 0.08$, even graphene.

It is not obviously clear as to the fundamental source of this universality, I only suspect, as was just pointed out, it has to do with the strong correlation around some critical point, somewhat independent of the very nature of interaction, as long as it is strongly correlated. This was most brilliantly pointed out by Efimov [19].

In Figs. 8, 9, 10, 11 the significance of η/s, especially with a value near the AdS/CFT level ($\eta/s \approx 0.08$) for understanding elliptic flow is displayed.

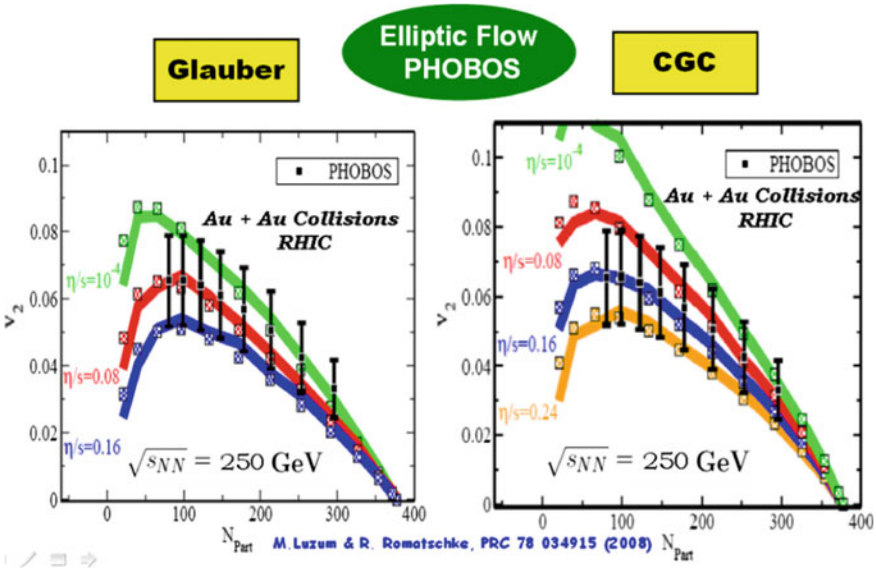


Fig. 8 Hydrodynamic models to experimental data on charged hadron integrated elliptic flow by PHOBOS

The ratio η/s is uniquely suited to determine how strongly the excitations in a quantum fluid interact. We determine η/s in clean undoped graphene using quantum kinetic theory. It is remarkable that η/s in this case comes close to a lower bound conjectured in the context of the quark gluon plasma [20].

It is thus remarkable that both the coldest and hottest matter on earth exhibit very similar elliptic flow patterns with η/s near the conjectured lower bound of AdS/ CFT. It will be most interesting to find out how the "flow" at LHC is different from RHIC [21]. In particular, does η/s change with energy?

Recently, Chaudhuri and Sinha [22] investigated the effect of viscous drag on photons and dileptons [23]. The space-time evolution of the fluid was obtained by solving Israel-Stewart's second-order hydrodynamics; the details of which are given in Ref. [22]. The equations are solved with the code AZHYDRO Kolkata developed at the Cyclotron Centre, Kolkata. The results are shown in Figs. 11, 12. It is quite remarkable that η/s for QGP at LHC energies is remarkably close to strongly coupled QGP produced in RHIC collisions; though the initial temperature is much higher at LHC. This is a unique property of η/s which need to be investigated at a fundamental level [24].

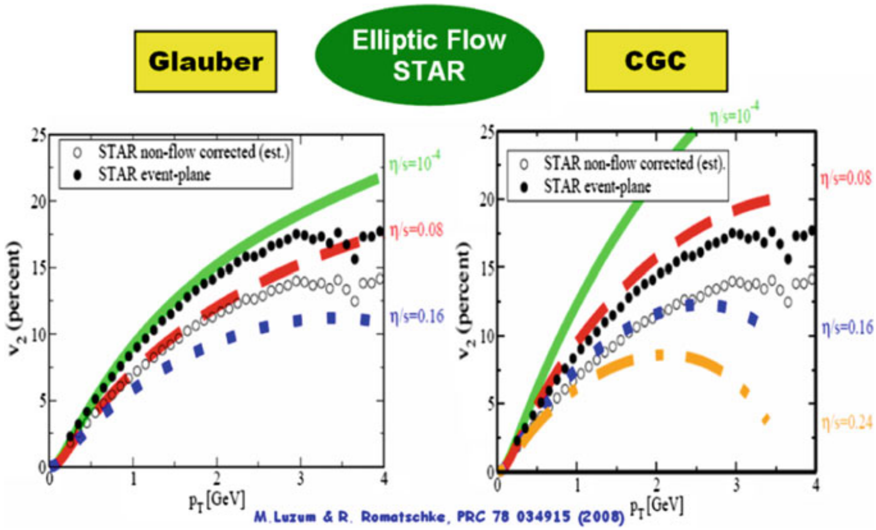


Fig. 9 Hydrodynamic models to experimental data on charged hadron minimum bias elliptic flow by STAR

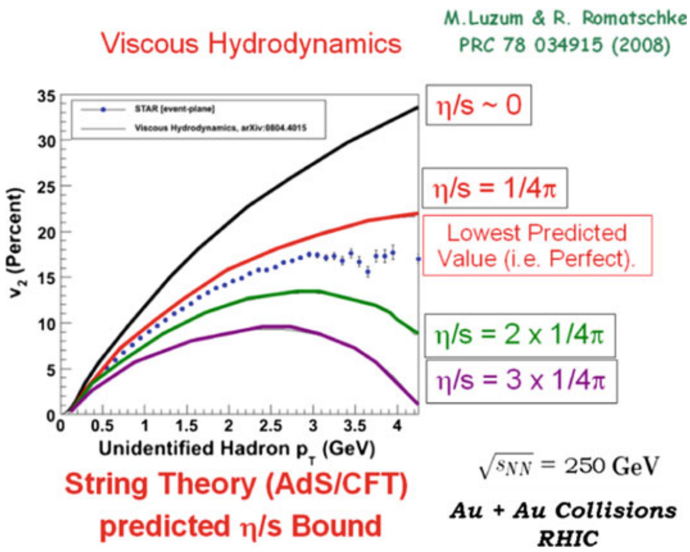


Fig. 10 Quark-Gluon Plasma: a perfect fluid

4 From the Terrestrial Light to the Cosmic Light

The evolution of the universe during the QCD phase transition is governed by Einstein's equations

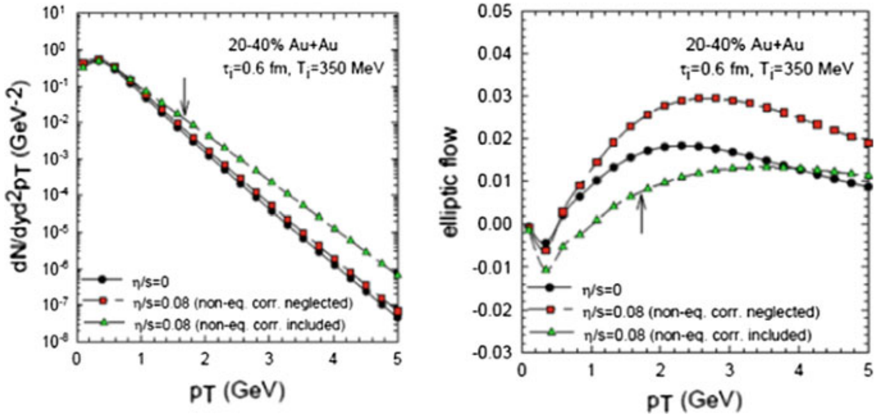


Fig. 11 Effect of viscosity on photon spectra and elliptic flow. Validity of hydrodynamics requires that non-equilibrium contribution to photon spectra is smaller than the equilibrium contribution. For AdS/CFT limit of viscosity to entropy ratio, $\eta/r = 1/4\pi$, hydrodynamics is applicable only in a limited p_T region (marked by *arrow*). It is important to have a consistent model, e.g., neglect of non-equilibrium correction to distribution function can lead to increased elliptic flow

Production rate of dileptons of in variant mass M from the QGP phase can be approximated as

$$E\frac{dN}{dM^2d^3p} \approx \frac{\alpha^2}{8\pi^4}\sum e_q^2 f_{\text{neq}}(E)$$

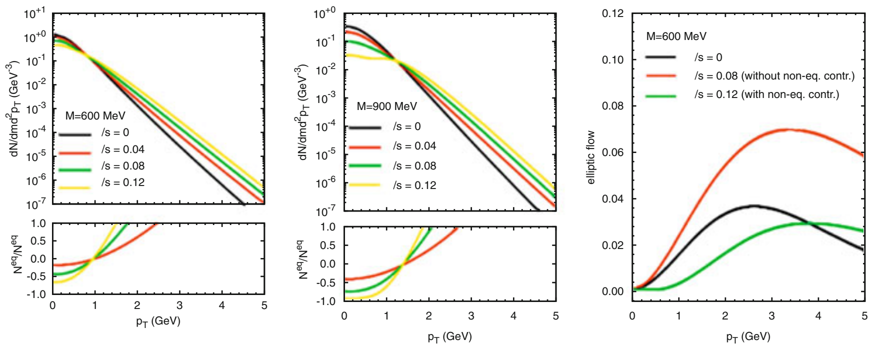


Fig. 12 Viscous effects on dilepton production. Similar to photons, viscous effects on dilepton production is also large. p_T spectra are hardened, elliptic flow is reuduced. Also, viscous hydrodynamics remains applicable only in a limited p_T range. The applicability range increases with invariant mass

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi\rho}{3m_{\text{Pl}}^2}$$

$$\frac{d(\rho R^3)}{dt} + P\frac{dR^3}{dt} = 0 \quad (3)$$

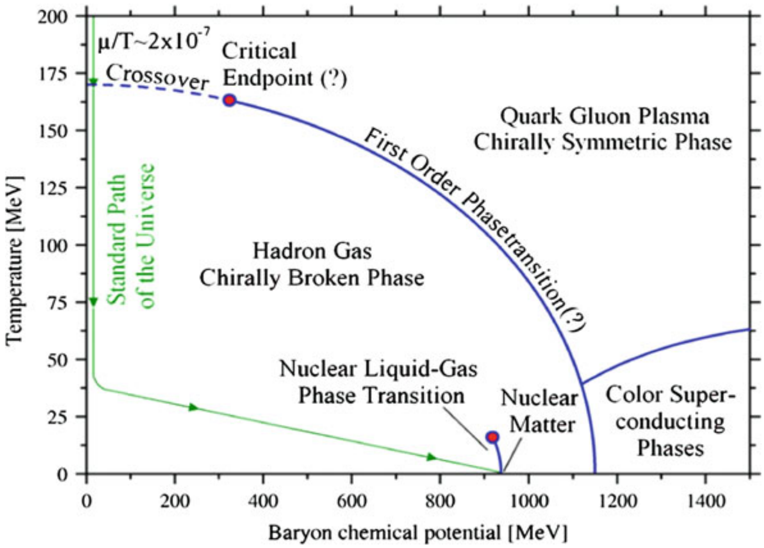


Fig. 13 Sketch of a possible QCD phase diagram with the commonly accepted standard evolution path of the universe as calculated, e.g., in [25] depicted by the green path. *Source* Refs. [25, 26]

with ρ, the energy density, P, the pressure and m_{Pl} is the Planck mass. A simple equation of state with a bag constant B is used.

$$\begin{aligned} \varepsilon &= 3aT^4 + B \\ P &= aT^4 - B \qquad\qquad t = 0.74/T^2 \end{aligned} \tag{4}$$

In Fig. 13, the standard scenario of the universe, crossing over at a temperature beyond the critical end point is shown. The universe as it goes over to the hadronic world in a crossover scenario erases its immediate past memory and thus, no relics of this transition remains with the world.

Recently however, Boeckel and Schaffner [26] have demonstrated that introducing a little inflation, $N = 7$ e-foldings, we can resurrect a first-order phase transition of the quark hadron phase transition, see Fig. 14.

It is shown by them and by us [11, 12] that the relics of this first-order phase transition are the best witness of the order of the phase transition. Crossover will lead to no surviving relics from the quark hadron phase transition in today's universe! First-order phase transition on the other hand will necessarily leave a rich harvest of relics.

We give a few examples.

Some time ago Bhattacharya et al. [28, 29], using chromo electric flux-tube examined the survivability of quark blobs or quark nuggets with time. We wanted to examine, in particular, the survivability of these nuggets even in the present day universe. The guiding equations are essentially of the structure of the famous Saha equations

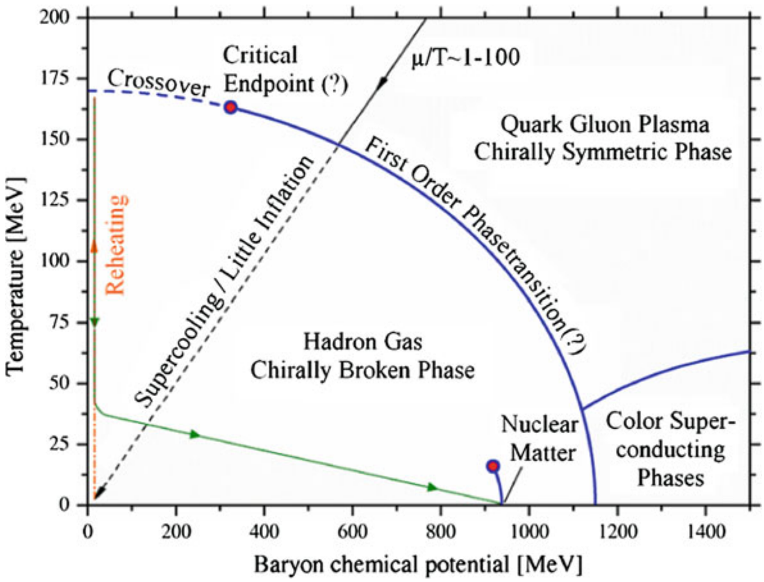


Fig. 14 Sketch of a possible QCD phase diagram with the evolution path of the universe in the little inflation scenario. *Source* Ref. [26]

of thermalisation:

$$\frac{dN_B}{dt} = \left(\frac{dN_B}{dt}\right)_{\rm ev} + \left(\frac{dN_B}{dt}\right)_{\rm abs}$$

For further details, I refer to [27, 28].

In Fig. 15 the survivability is clearly demonstrated for $N_B > 10^{43}$; N_B is the baryon number of the quark nugget; (please recall a quark has the baryon number of 1/3).

In Ref. [26] the relevance of dark energy and a first-order phase transition is pointed out. Boeckel and Schaffner have discussed this issue of dark energy in great detail.

Banerjee et al. [28], on the other hand, have demonstrated the most natural explanation of these surviving nuggets as the evolutionary product of metastable false vacuum domains, the so called strong quark nuggets. Indeed these nuggets are in fact the Massive Compact Halo Objects, MACHO [29, 30], very identifiable relics of the cosmic quark-hadron phase transition. These MACHO objects, it was argued [29, 30], can comfortably be candidate for Cold Dark Matter and that the total number of MACHOs is about 10^{23-24}.

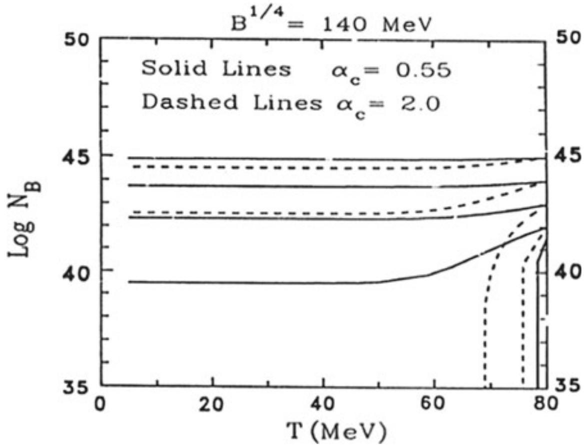


Fig. 15 Baryon number of quark nuggets in the present universe

5 Epilogue

Our epilogue is through the looking glass (Lewis Carroll):
"ALICE IN THE QUARK LAND"

"The time has come", the Walrus said,
"To talk of many things
Of shoes—and ships—and sealing wax—
Of cabbages—and kings—
And why the sea is boiling hot—
And whether pigs have wings."

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