EPJ Web of Conferences **364**, 01001 (2026)
Quark Matter 2025
https://doi.org/10.1051/epjconf/202636401001

Our contribution to cosmology - The origin of matter and radiation

Reinhard Stock[1,*]

[1]Institut fuer Kernphysik, Goethe Universität, Frankfurt am Main, Germany

Abstract. I review the strong-interaction sector of the cosmological evolution from early microsecond to early milliseconds in which we encounter the Quark-Gluon Plasma of non-perturbative QCD, followed by its hadronization at Hagedorn temperature, and finally the baryon-antibaryon annihilation leaving a small excess of nucleons, and radiation fields: the content of the present Universe.

1 Introduction

At the opening of this Quark Matter Conference I wish to direct our attention to the accomplishments that our field has been blessed with over the last decades, deciphering the nature and properties of strongly interacting matter inbetween the extremes of asymptotically free partons of QCD, and *cold* nuclear and atomic matter: in fact, our matter. Where do we come from? In order not to go overbord with enthusiasm, let us more humbly refer to the cosmological origin of the proton and the neutron, and the cosmic radiation fields of photons and neutrinos. That is enough for the dynamical evolution of the Universe to build a world from. Our key accomplishment has been to develop and understand the physics of non-perturbative QCD, its matter, the Quark-Gluon Plasma (QGP) and its thermodynamic and hydrodynamic properties, and its phase transformation to hadrons, from experiments at RHIC and LHC, and related theoretical study. Finally we know now how to extrapolate from our "small Bangs" at colliders, to the "Big Bang" expansive evolution which features a third essential stage (after plasma and hadronization): the near-universal baryon-antibaryon annihilation, from which the surviving protons emerge as a tiny 10^{-9} excess over antiprotons. These protons (neutrons) exist until today; they build our world. They are the last gift of non-perturbative QCD to the evolution of the Universe.

This is the theme of my talk: the period during which the cosmic temperature drops from 300 to 10 MeV, roughly corresponding to the time interval from one microsecond to a few milliseconds on the cosmic time scale. Our progress lets us see much deeper into the early history of the Big Bang, or let us better say: it fills this period with hitherto unknown physics! When it comes, for example, to the origin of cosmic radiation even modern cosmology textbooks offer the profound answer *somewhere in the early Big Bang*. We are now prepared to change that!

There is one outstanding document that will be familiar to most of you: Steven Weinberg's masterwork *The First Three Minutes* of 1977, the front page of which we show in Fig. 1. Its major physics deals with the second-to-minute era, during which the interaction between

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[*] e-mail: stock@ikf.uni-frankfurt.de

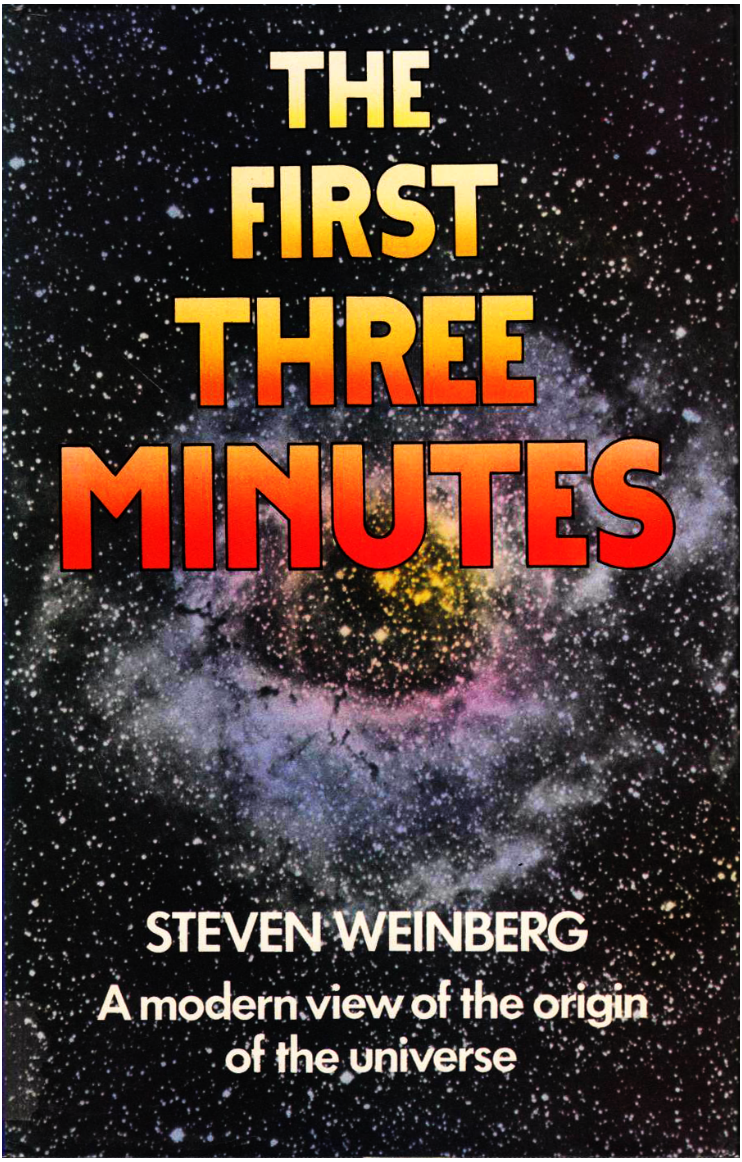


Figure 1. Fig. from https://en.wikipedia.org/wiki/The_First_Three_Minutes [1].

MeV-type photons and nucleons leads to the formation of light nuclei, notably the present about 20% abundance of Helium in the interstellar gas (of hydrogen), as well as other light nuclei, which could then be measured with precision, leading to the first estimate of the number-density ratio between photons and protons, entering that stage, to be about 10^9 to one, then of unknown origin. Now we could write a new such textbook, with front page suggested in Fig. 2, "The First Milliseconds, A Modern View of the Origin of Matter and Radiation", illustrated with the TPC image of a central Au+Au collision recorded by STAR at top RHIC energy. In the following I will briefly outline the content.

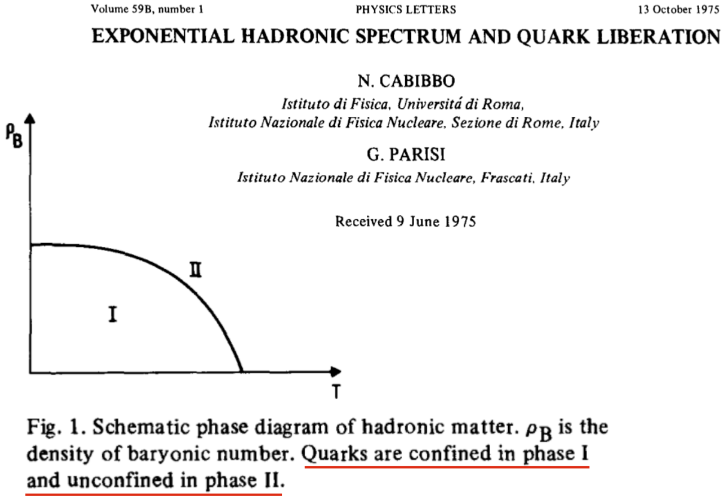
Figure 2.

2 Stage 1: The Quark-Gluon Plasma of non-perturbative QCD

You are familiar with this physics so I only recollect its highlights. We are dealing here with the temperature range of a few 100 MeV, corresponding to energy densities of a few GeV/fm^3 in the collisional "fireball" volume that forms after an initial short interpenetration and equilibration phase (still the topic of intense theoretical work). As such it falls deeply into the sector of non-perturbative QCD. This is, by itself, a completely new view. At the time of Weinbergs book, 1977, the "asymptotic freedom" property of QCD was just discovered, to occur as a consequence of the running coupling constant of QCD, which fades away at very high momentum transfers. On this basis Collins and Perry had predicted in 1975 [2] a deconfined Quark-Gluon Universe at a temperature in the multi-GeV range: a "perturbative QCD" parton-gas state. Not so. It has turned out through two decades of experimental work at Brookhaven and CERN, and corresponding theoretical developments of relativistic viscous hydrodynamics that the fireball volume can be described, after its initial formation period, as a much colder, near ideal QGP liquid, a completely unexpected, novel state of non-perturbative QCD. It owes the term "near-ideal" to its near-minimal specific shear viscosity η/s, the quantity that controls the rate at which non-equilibrium properties of the initial fireball liquid, such as elliptic flow anisotropies, get dissipated away during expansion. The resulting hydrodynamic expansion at low η/s thus preserves the signals imprinted at its initialization, modulo the small dissipation effects that thus get quantified. These, elliptic and higher flow-anisotropy modes resulting from the primordial fireball geometry do, in turn, lead to a determination of η/s: the situation is "self-analyzing".

A further macroscopic property of the QGP was discovered, and studied at RHIC and LHC, the "opacity" of the QGP medium toward parton transport as quantified by the transport coefficient $\hat{q}$ that describes the energy loss per unit pathlength of a quark produced in the course of the hard (perturbative-QCD) collisions during the initial interpenetration phase, while it imbeds in the co-travelling expanding QGP medium of "soft" origin. This quantity is studied by jet spectroscopy, where suitable trigger configurations select jet-production geometries where one jet arm traverses the fireball matter whereas the other goes directly to detection. There is a famous prediction by Majumder, Müller, and Wang [3] in 2007 stating that specific shear viscosity and transport opacity should be inversely related to each other, which is perfectly borne out by the experimental results.

You are familiar with all this physics. It implies that the Universe was occupied from nano- to micro-seconds by the novel state of a non-perturbative QCD parton liquid, of course imbedded in the other particles of electromagnetic and weak interaction (this could perhaps change the properties of the QGP by a small fraction–as remains to be clarified). The almost ideal QGP fluid was our first fundamental discovery as concerns the state of the early microsecond Universe.



Volume 59B, number 1 PHYSICS LETTERS 13 October 1975

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

N. CABIBBO
Istituto di Fisica, Universitá di Roma,
Istituto Nazionale di Fisica Nucleare, Sezione di Rome, Italy

G. PARISI
Istituto Nazionale di Fisica Nucleare, Frascati, Italy

Received 9 June 1975

Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

Figure 3. Phase diagram of non-perturbative QCD as suggested by Cabibbo and Parisi [5] in 1975.

3 Stage 2: Hadronization and Hagedorn's Temperature

As the QGP expands the mean interparton distance increases but this cannot continue forever because of the "horror vacui" of colour charges, an expression of the confinement property of QCD. Thus the quarks must neutralize, and one realizes that the most elementary neutral objects can be either colour or anti-colour triplets (the "Mercedes-star" in the classical circle of colour), or colour-anticolour pairs. These states are the hadrons: baryons and mesons, respectively. The cosmic inventary must undergo a phase transformation, obviously located at the so-called limiting temperature of hadrons, T about 160 MeV, that was discovered by Hagedorn in the late 1950s [4]. He had developed the Statistical Model of "fireball formation" applied to hadron production in multiparticle-production p+p collisions at the CERN PS synchrotron, in which an exponentially increasing state density of hadrons and resonances created the saturation temperature, which he considered to be the maximal T available for strongly interacting systems. However, in 1975 N. Cabibbo and G. Parisi [5] published a Phys. Lett. article (that was little noticed at first), in which they reinterpreted Hagedorn's observations as the indication of a deconfinement transition to "free" quarks occurring at about 160 MeV. Moreover they first suggested the phase diagram that we employ until today, as shown in Fig. 3. Actually it employs, as one coordinate, not the baryochemical potential μ_B as we do but the related net baryon-number density. Note that in this phase diagram, the Hagedorn temperature of about 160 MeV corresponds to zero net baryon number, $\mu_B = 0$: the conditions encountered in the cosmic evolution! In the laboratory, such conditions are realized in high-energy electron-positron-annihilation reactions, and we show in Fig. 4 the LEP data at 91.2 GeV C.M. energy, confronted with a prediction [6] by the revived Statistical Hadronization Model (SHM), which gives an amazing account of the multiplicity data for about 25 hadronic species that stretch over four decades. The derived temperature is 159.3 MeV: Hagedorn!

The so-called grand canonical variant of the SHM [7, 8] has been successfully applied to many sets of hadron multiplicities observed in central A+A collisions. As an example we show in Fig. 5 the SHM results of Andronic, Braun-Munzinger, and Stachel [9] applied to a synopsis of RHIC Au+Au central collision data at 200 GeV, again obtaining T about 160 MeV. Although μ_B is not quite zero at this energy we see the first 6 entries in the figure, particle-antiparticle ratios, all closely approaching unity. At the LHC μ_B is practically zero, and T near 160 MeV: the conditions at about 5 microseconds in the cosmological evolution. And we learn from the SHM fits that the prevailing energy density is about 0.5 GeV/fm^3, which fits well with the interior density of the proton. Note that the proton is an exceedingly complicated object (as shown, e.g., by decades of electron-proton scattering experiments), well in keeping with the view offered here that it may be seen as a "droplet" of neutralized QGP-liquid matter, an equally complex non-perturbative QCD object. With the proton/neutron, the "evolutionary potential" of the Universe takes a fundamental forward step: we encounter the emergence of novel physical entities such as interior/exterior, finite size, radius, surface, and colour-charge neutralization taming the strong force fields in its interior such that only relatively weak outward forces remain: we are ready for nuclei, in which the strong and electromagnetic force fields cooperate, and onwards to atoms and molecules.

Hadronization creates a state of chemical equilibrium among the states of the hadron-resonance spectrum, for reasons that are still under discussion. Modern Lattice QCD sees hadronization as a "mere" rapid crossover transition [10], challenging the former view as a genuine phase transition, in which the hadrons are "born into equilibrium" as Hagedorn saw it. But this does not resolve the equilibrium question as even a crossover including confinement vis a vis the hadron/resonance spectrum "waiting" on the other side could proceed under phase-space dominance, in a multiparticle extension of Fermis Golden Rule, thus creating an equilibrium population. Whatever the final answer will be: the perfect success of the SHM equilibrium-ensemble description gives us confidence to apply this model in trying to understand the next big stage of cosmology, to which we shall turn now.

4 Stage 3: The Grand Annihilation and Meson Decay: Cosmological Freeze-Out

In our A+A collisions the fireball decays through expansion with negligible inelastic rearrangement (except resonance decay) directly to detection because of the short fireball lifetime $t < 10^{-22}$s. Whereas the duration of the Big Bang hadronization period alone is about 5 microseconds [11]: the expansive evolution of the Universe is increadibly much slower. The high hadronic density after hadronization will thus prevail for considerable time, during which the system adapts its chemical equilibrium to the slow fall-off of density and temperature. This invites a dramatic annihilation process of baryons with antibaryons, with no inverse reactions at the "low" temperatures below 160 MeV (unlike it was for the light quarks before hadronization). One of the great mysteries of the Universe unfolds. For a "creatio ex nihilo" one would expect the total baryon and antibaryon numbers to be equal but it turns out that there is an excess of one baryon per about 10^9 baryon-antibaryon pairs in the Universe at 5 microseconds, of unknown origin. The $B - \bar{B}$ annihilation goes to photons and neutrinos, via an intermediate state of 3 pions. Likewise, all the mesons created in the course of hadronization decay to photons and neutrinos. In all: our present matter and radiation fields emerge in the early millisecond era. And, however small, relatively, the fraction of surviving protons/neutrons may be: at the end there are about 10^{80} of them, an unfathomable number. And, moreover, an interesting one: it turns out that the corresponding average hadronic energy density of the Universe amounts to about 5% of the so-called "critical mass" in General Relativity where a universe has Euclidian geometry and turns from eventually collapsing to expanding. A surprising "near miss" on a scale of 80 orders, clearly holding some yet unknown message.

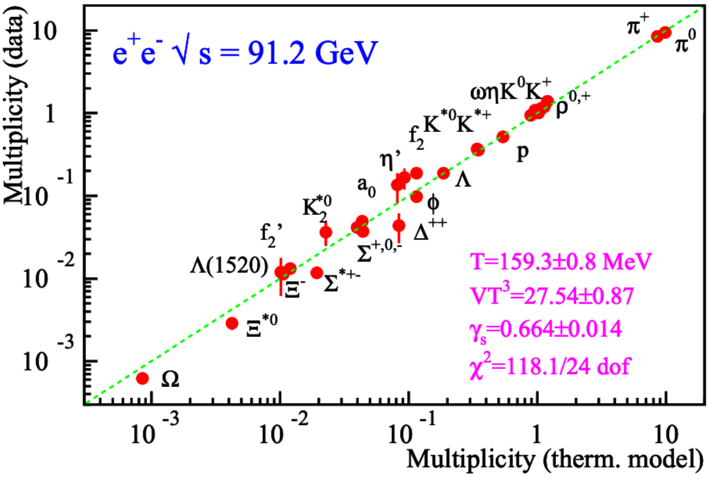


Figure 4. Hadron multiplicities in electron-positron annihilation at LEP analysed with the canonical Statistical Hadronization Model [6].

The statistical-model application to cosmic freeze-out has been studied by J. Rafelski and his group [12]. We show in Fig. 6 the time and temperature dependence of the light-quark baryochemical potential, which starts near zero in the QGP phase and ends up at constituent quark mass at about 10 milliseconds: the surviving protons are alone in the physical vacuum, to build our world.

A final look at the resulting photon- and neutrino-radiation fields that occupy this vacuum: their number densities result from the immediate post-hadronization stage, both from $B - \bar{B}$ annihilation and meson decay, and can be estimated to amount to about 5×10^8 per cubic meter. Multiplying with the estimated volume of today's observable Universe one arrives at a total number of about 10^{90}, each. The average thermal energy at 2.7 K has gone down to 2.4×10^{-4} eV, but initially it must have amounted to about 50 to 100 MeV. What has become of these 12 orders of magnitude in kinetic energy? Surprisingly this turns out to be another unresolved question of cosmology [13]. In Newtonian physics one would argue that the energy got expended in expanding the Universe against gravitational attraction, so it would now reside in potential energy. However, in relativistic cosmology the Universe is not an expanding ball filled with particles and doing work against gravitational pressure. What expands is space-time itself, and energy conservation is non-trivial to demonstrate [13]. The common parlance that this expansion of space "stretches" the wavelength of the photons offers little insight.

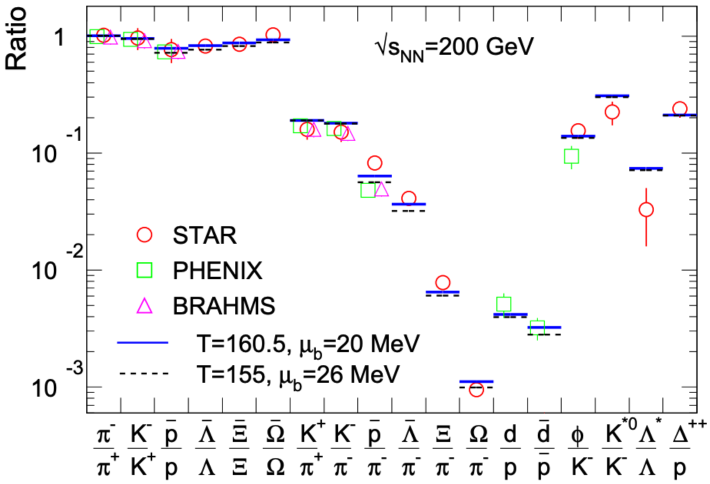


Figure 5. Hadron production at top RHIC energy analysed with the grand canonical Statistical Hadronization Model [9].

We have come a long way. But I hope to have convinced you that a long, hitherto barely understood period of the cosmological evolution has been, at least qualitatively, well understood. Also exposing remaining fundamental questions of cosmology that wait for an answer. So, writing the book that we somewhat provocatively titled in Fig. 2 could now be undertaken.

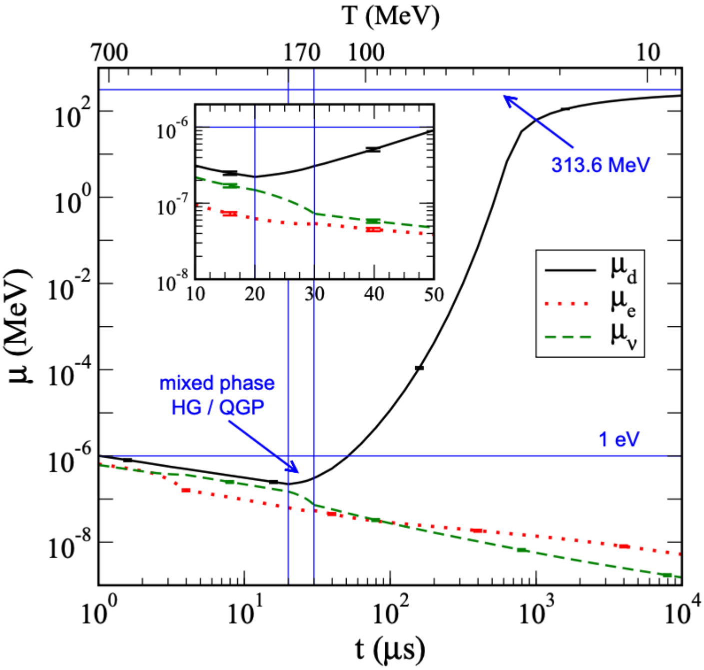


Figure 6. Time dependence of the light-quark baryochemical potential of the Universe, from Quark-Gluon Plasma to freeze-out time [11].

References

[1] S. Weinberg, “The First Three Minutes. A Modern View of the Origin of the Universe,” (Basic Books, 1977)

[2] J. C. Collins and M. J. Perry, Phys. Rev. Lett. **34** (1975), 1353 doi:10.1103/PhysRevLett.34.1353

[3] A. Majumder, B. Muller and X. N. Wang, Phys. Rev. Lett. **99** (2007), 192301 doi:10.1103/PhysRevLett.99.192301 [arXiv:hep-ph/0703082 [hep-ph]].

[4] R. Hagedorn, Nuovo Cim. Suppl. **3** (1965), 147-186 CERN-TH-520.

[5] N. Cabibbo and G. Parisi, Phys. Lett. B **59** (1975), 67-69 doi:10.1016/0370-2693(75)90158-6

[6] F. Becattini, Nucl. Phys. A **702** (2002), 336-340 doi:10.1016/S0375-9474(02)00720-0 [arXiv:hep-ph/0206203 [hep-ph]].

[7] F. Becattini, Z. Phys. C **69** (1996) no.3, 485-492 doi:10.1007/BF02907431

[8] A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Nature **561** (2018) no.7723, 321-330 doi:10.1038/s41586-018-0491-6 [arXiv:1710.09425 [nucl-th]].

[9] A. Andronic, P. Braun-Munzinger and J. Stachel, Nucl. Phys. A **772** (2006), 167-199 doi:10.1016/j.nuclphysa.2006.03.012 [arXiv:nucl-th/0511071 [nucl-th]].

[10] A. Bazavov *et al.* [HotQCD], Phys. Rev. D **90** (2014), 094503 doi:10.1103/PhysRevD.90.094503 [arXiv:1407.6387 [hep-lat]].

[11] M. J. Fromerth, I. Kuznetsova, L. Labun, J. Letessier and J. Rafelski, Acta Phys. Polon. B **43** (2012) no.12, 2261-2284 doi:10.5506/APhysPolB.43.2261 [arXiv:1211.4297 [nucl-

th]].

[12] J. Rafelski, J. Birrell, A. Steinmetz and C. T. Yang, Universe **9** (2023) no.7, 309 doi:10.3390/universe9070309 [arXiv:2305.09055 [hep-th]].

[13] Misner, C.W. and Thorne, K.S. and Wheeler, J.A. and Kaiser, D.I., Gravitation, Princeton University Press 2017.