Boiling Quarks, Melting Hadrons

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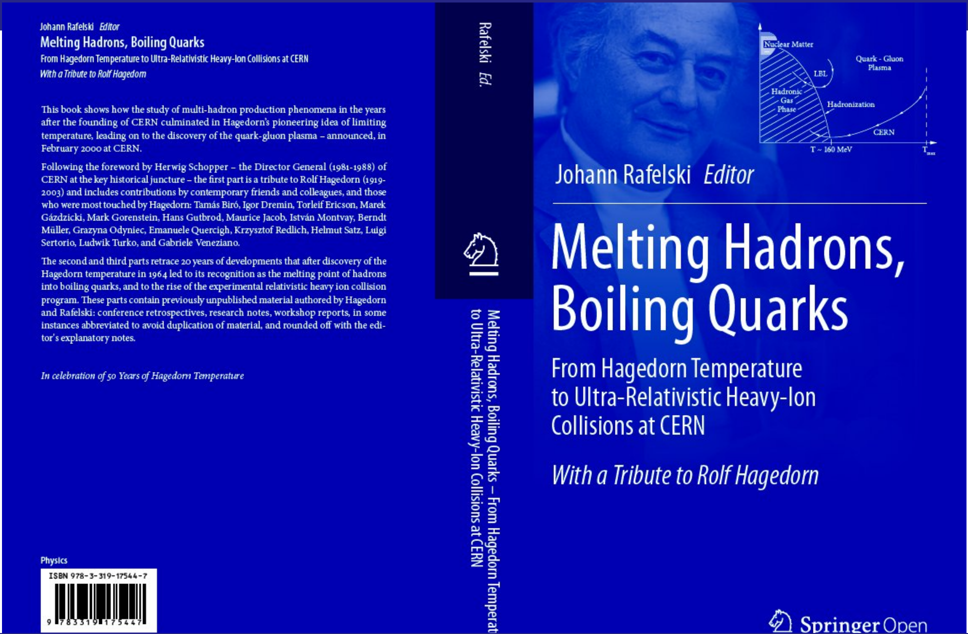
June 2, 2015


Johann Rafelski Editor
Melting Hadrons, Boiling Quarks
From Hagedorn Temperature to Ultra-Relativistic Heavy-Ion Collisions at CERN
With a Tribute to Rolf Hagedorn
This book shows how the study of multi-hadron production phenomena in the years after the founding of CERN culminated in Hagedorn's pioneering idea of limiting temperature, leading on to the discovery of the quark-gluon plasma – announced, in February 2000 at CERN.
Following the foreword by Herwig Schopper – the Director General (1981-1988) of CERN at the key historical juncture – the first part is a tribute to Rolf Hagedorn (1919-2003) and includes contributions by contemporary friends and colleagues, and those who were most touched by Hagedorn: Tamás Biró, Igor Dremin, Torleif Ericson, Marek Gázdzicki, Mark Gorenstein, Hans Gutbrod, Maurice Jacob, István Montvay, Berndt Müller, Grazyna Odyniec, Emanuele Quercigh, Krzysztof Redlich, Helmut Satz, Luigi Sertorio, Ludwik Turko, and Gabriele Veneziano.
The second and third parts retrace 20 years of developments that after discovery of the Hagedorn temperature in 1964 led to its recognition as the melting point of hadrons into boiling quarks, and to the rise of the experimental relativistic heavy ion collision program. These parts contain previously unpublished material authored by Hagedorn and Rafelski: conference retrospectives, research notes, workshop reports, in some instances abbreviated to avoid duplication of material, and rounded off with the editor's explanatory notes.
In celebration of 50 Years of Hagedorn Temperature
Physics
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Rafelski Ed.
Melting Hadrons, Boiling Quarks – From Hagedorn Temperat
to Ultra-Relativistic Heavy-Ion Collisions at CERN
Nuclear Matter
Quark - Gluon Plasma
LBL
Hadronic Gas Phase
Hadronization
CERN
T ~ 160 MeV
Johann Rafelski Editor
Melting Hadrons, Boiling Quarks
From Hagedorn Temperature to Ultra-Relativistic Heavy-Ion Collisions at CERN
With a Tribute to Rolf Hagedorn
Springer Open

1964/65: Two new fundamental ideas

- Quarks → Standard Model of Particle Physics
- Hagedorn Temperature → New State of Elementary Matter

Topics today:

1. 50 years ago – Melting hadrons: birth of hadronic matter
2. 35 years ago – Boiling quarks: hadrons dissolve into quarks at Hagedorn Temperature $T_{\rm H}$
3. 15 years ago – Quark-gluon plasma discovery
4. Today – Searching telltales of QGP in the Universe

Particle production

WITHDRAWN

Hagedorn 1960-1964: Fermi-Landau fireballs produce too few pions – need distinguishable particles $\rightarrow$ Hagedorn limiting T

9716/TH.483
12 October 1964

PRELIMINARY VERSION

THERMODYNAMICS OF D I S T I N G U I S H A B L E PARTICLES – A KEY TO HIGH ENERGY STRONG INTERACTIONS ?

R. Hagedorn
CERN – Geneva

A B S T R A C T

A new kind of thermodynamical model for strong interactions at high energies is proposed. We start from the fact that strong interactions produce so many possible particle states (from π over its resonances to nucleons, strange particles and their resonances, up to highly excited "fireballs") that in an actual process each of these states practically never occurs more than once. We use this in order to treat the very first instant of a high-energy collision by statistical thermodynamics of a system of an illimited number of d i s t i n g u i s h a b l e particles. The model shows surprising properties : there exists a universal highest possible temperature T_0 of the order of 150-200 MeV (corresponding to $\approx 10^{12}$ °K) which governs all high-energy processes of strongly interacting particles, independently of the actual energy and independently of the particle number, from cosmic ray jets down to elastic scattering.

ARCHIVES

Remarks to the "PRELIMINARY VERSION" of

THERMODYNAMICS OF D I S T I N G U I S H A B L E PARTICLES – A KEY TO HIGH ENERGY STRONG INTERACTIONS ?

R. Hagedorn

I have written and distributed this paper too early. The logical difficulty mentioned on p. 41 has been removed as follows and the result is disappointing :

Now everything depends on the asymptotic behaviour of the mass spectrum $\rho(m)$

1) if $\rho(m)$ grows faster than exponentially, log Z diverges for all $T > 0$. No thermodynamics is possible.

within a few months

65/166/5 - TH. 520
25 January 1965

STATISTICAL THERMODYNAMICS OF STRONG INTERACTIONS AT HIGH ENERGIES

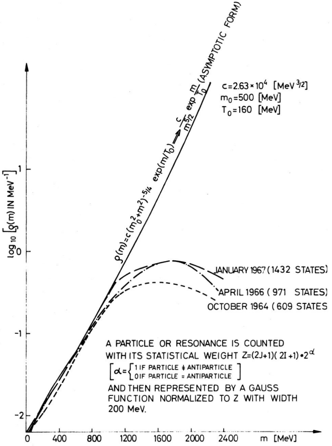
R. Hagedorn
CERN - Geneva

A B S T R A C T

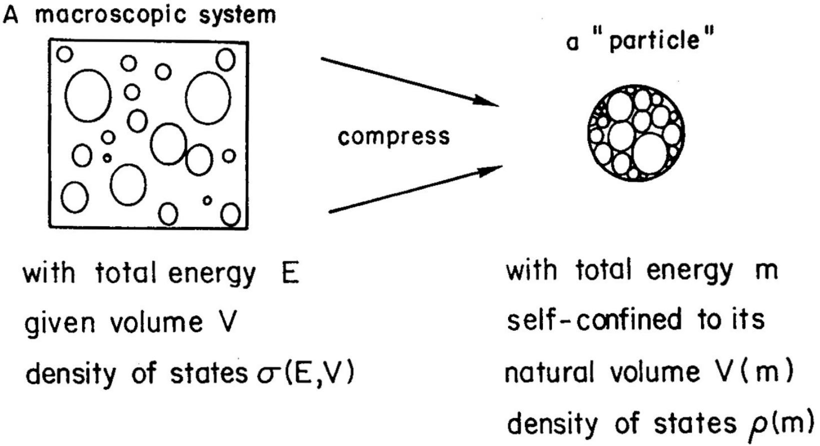
In this statistical-thermodynamical approach to strong interactions at high energies it is assumed that higher and higher resonances of strongly interacting particles occur and take part in the thermodynamics as if they were particles. For $m \to \infty$ these objects are themselves very similar to those which shall be described by this thermodynamics. Expressed in a slogan: "We describe by thermodynamics fire-balls which consist of fire-balls, which consist of fire-balls, which ...". This principle, which could be called "asymptotic bootstrap", leads to a self-consistency requirement for the asymptotic form of the mass spectrum. The equation following from this requirement has only a solution if the mass spectrum grows exponentially:

$$\rho(m) \xrightarrow[m \to \infty]{} \text{const.}\, m^{-5/2} \exp\left(\frac{m}{T_o}\right).$$

T_o is a remarkable quantity: the partition function corresponding to the above $\rho(m)$ diverges for $T \to T_o^-$. T_o is therefore the highest possible temperature for strong interactions. It should - via a Maxwell-Boltzmann law - govern the transversal momentum distribution in all high energy collisions of hadrons (including e.m. form factors, etc.). There is experimental evidence for that, and then T_o is about 158 MeV ($\approx 10^{12}$ °K). With this value of T_o the asymptotic mass spectrum of our theory has a good chance to be the correct extrapolation of the experimentally known spectrum.

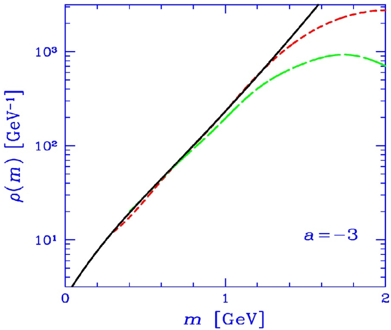


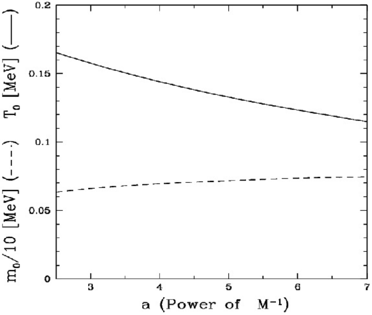
SBM=Statistical Bootstrap Model



Idea yields exponential mass spectrum

Exponential mass spectrum defines T_{H}





From pp to **elementary matter**

SN collapse at origin of the long standing interest in ultra-high density 'nuclear' matter, quark matter stars proposed: D. D. Ivanenko, D. F. Kurdgelaidze: "Hypothesis concerning quark stars," Astrophysics **1**, 251 (1965). **Lab:** Presumption that when big nuclei collide matter is compressed prevails till Hagedorn-Montvay-JR (1978) show that energy flows into production of particles akin to the pp case. **This is how hadronic matter differs from all other forms of matter.**

Hadronic Matter at Extreme Energy Density

Edited by

Nicola Cabibbo
University of Roma, Italy

and

Luigi Sertorio
University of Turin, Italy

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Proceedings of the Workshop on Hadronic Matter at Extreme Energy Density, held at the Ettore Majorana Center, Erice, Italy, October 13–21, 1978.

CERN-TH-2605, Dec 1978. 99pp.

THERMODYNAMICS OF NUCLEAR MATTER FROM THE STATISTICAL BOOTSTRAP MODEL

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CERN, Geneva, Switzerland

ABSTRACT

We study the properties of nuclear matter within the framework of a modified and generalized statistical bootstrap model in which the volume of a fireball grows with its mass. We find that the such described nuclear matter can exist in two phases. In particular we consider in a numerical example the high temperature ($T \le T_0 \approx 150$ MeV) regime of the gaseous phase with a density of less than ~ 0.75 of normal nuclear density.

1. INTRODUCTION

In order to understand high-energy heavy ion collisions or even perhaps high-energy hadron-nucleus scattering, we must study the equations of state of nuclear matter. From the point of view of a theoretical physicist, the inverse statement is even more natural: our ideas about the properties of nuclear matter at high and low densities and temperatures can be tested in high-energy nucleus-nucleus and hadron-nucleus collisions. Moreover, this knowledge is certainly essential in order to understand the properties of hadronic many-body objects in astrophysics, such as neutron stars, the Universe at early time, stellar collapse and perhaps even quasars.

While we are aware of the possible richness of the nuclear matter properties, in our approach to these problems we will concentrate on the gross features of nuclear matter that follow when we incorporate into the description the following basic properties:

1) conservation of baryon number and clustering of nucleons (i.e., attractive forces leading to many-body clusters with well-defined baryon number);
2) nucleon (isobar) excitations and internal cluster excitations (i.e., internal degrees of freedom that can absorb part of the energy of the system at finite temperature, thus transforming kinetic energy into mass);
3) approximate extensivity of nuclear matter (volume roughly proportional to baryon number, i.e., effectively a short-range repulsion);
4) co-existence of a pion gas when the temperature is not equal to zero (and behaving properly even in the absence of nuclear matter);

Our present work should be most trustworthy in the domain of high temperatures and moderately high density, where details of the interaction, Fermi and Bose statistics, as well as the quark structure of nucleons, are most likely negligible. Also not considered explicitly is the isospin of the nuclei.

In order to derive the physical properties of such a system which are independent of a particular choice of the two-body and multibody interaction we employ a technique ("bootstrap") developed for similar problems in elementary particle physics -- here, however, sufficiently modified to suit the different physical environment. An additional motivation in this direction is the recent recognition that the understanding of nuclear matter at the saturation point depends very sensitively on the character of the two-body potential at short distances which is not well defined by two-body reactions. It is possible to view the bootstrap technique only as a convenient way to introduce some physical properties which cannot be so easily defined by the choice of a specific potential but which globally might even be more important than details of the two-body force.

Let us now explain the general idea of the bootstrap description of the nuclear matter. Consider an assembly of b nucleons. We can view it as an assembly of $(b/2)$ two-particle clusters ... or also as two $(b/2)$-nucleon clusters -- all possible divisions will contribute to the number of states of the b nucleon system. In turn, each cluster containing b_i nucleons can be viewed in a similar fashion. It is simple to write an equation characteristic of such a system; neglecting for the moment all further degrees of freedom but the baryon number b, the number of states will be

Hagedorn Temperature $T_{\rm H}$
Singular point of partition function

$$Z_1(\beta,V)=\int \frac{2V^{\rm ex}_\mu p^\mu}{(2\pi)^3}\tau(p^2)e^{-\beta_\mu p^\mu}d^4p\,.$$

Inserting $1=\int\delta_0(m^2-p^2)dm^2$

I replacing $\tau(m^2)dm^2$ by $\rho(m)dm$

$$Z_1(\beta,V)=\frac{V^{\rm ex}T}{2\pi^2}\int m^2\rho(m)K_2(m\beta)dm\,.$$

$$Z_1(\beta,V)\underset{T\to T_0}{\sim} C\int_M^\infty m^{3/2-a}e^{-(\beta-\beta_0)m}dm+C\,.$$

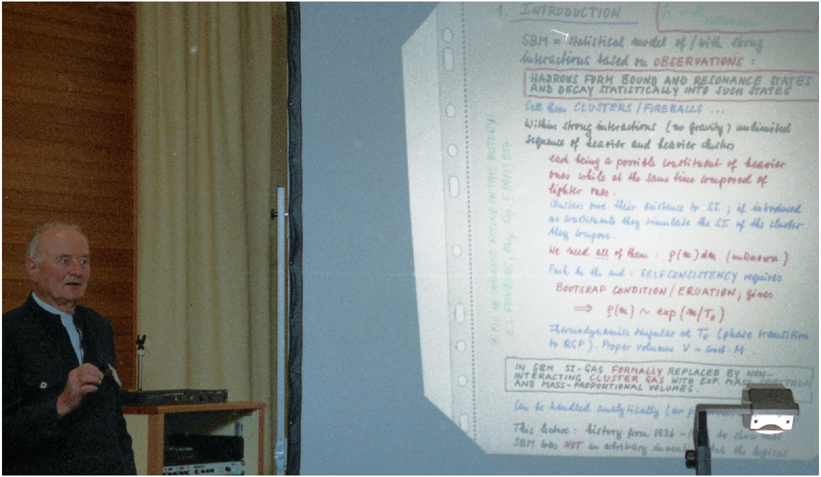
$$Z_1(\beta,V)\underset{T\to T_0}{\sim}\begin{cases}C+C\Delta T^{a-5/2}\,, & a\neq 5/2\\ C-\ln\dfrac{\Delta T}{T_0}\,, & a=5/2\end{cases}$$

a	P	n	ε	$\delta\varepsilon/\varepsilon$	$C_V=d\varepsilon/dT$
1/2	$C/\Delta T^2$	$C/\Delta T^2$	$C/\Delta T^3$	$C+C\Delta T$	$C/\Delta T^4$
1	$C/\Delta T^{3/2}$	$C/\Delta T^{3/2}$	$C/\Delta T^{5/2}$	$C+C\Delta T^{3/4}$	$C/\Delta T^{7/2}$
3/2	$C/\Delta T$	$C/\Delta T$	$C/\Delta T^2$	$C+C\Delta T^{1/2}$	$C/\Delta T^3$
2	$C/\Delta T^{1/2}$	$C/\Delta T^{1/2}$	$C/\Delta T^{3/2}$	$C+C\Delta T^{1/4}$	$C/\Delta T^{5/2}$
5/2	$C\ln(T_0/\Delta T)$	$C\ln(T_0/\Delta T)$	$C/\Delta T$	C	$C/\Delta T^2$
3	$P_0-C\Delta T^{1/2}$	$n_0-C\Delta T^{1/2}$	$C/\Delta T^{1/2}$	$C/\Delta T^{1/4}$	$C/\Delta T^{3/2}$
7/2	$P_0-C\Delta T$	$n_0-C\Delta T$	ε_0	$C/\Delta T^{1/2}$	$C/\Delta T$
4	$P_0-C\Delta T^{3/2}$	$n_0-C\Delta T^{3/2}$	$\varepsilon_0-C\Delta T^{1/2}$	$C/\Delta T^{3/4}$	$C/\Delta T^{1/2}$

energy density diverges for $a<7/2$. Thus only for $a<7/2$ can we expect T_0 a maximum temperature.

From J. Rafelski and R. Hagedorn: Thermodynamics of Hot Nuclear Matter in the Statistical Bootstrap Model 1979, in memorial volume.

Valedictorian Lecture 1994



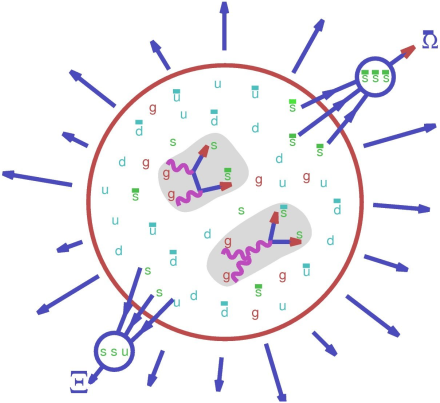
Boiling quarks

THE ROOTS:

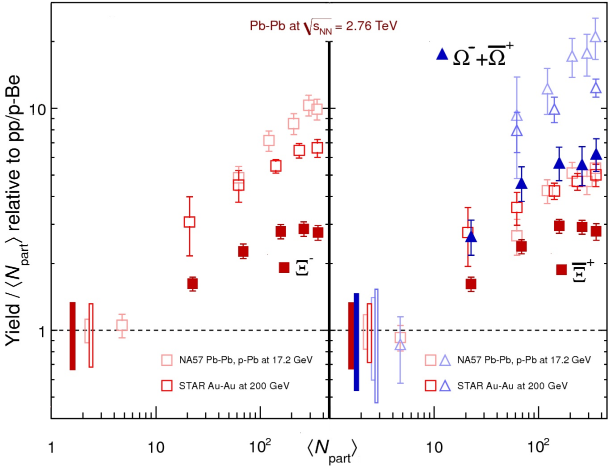
- Cold quark matter in diverse formats: 1965 $\longrightarrow$
- Hot interacting QCD quark-gluon plasma: 1979 $\longrightarrow$
- Formation of QGP in relativistic nuclear (heavy ion collisions) 1979 $\longrightarrow$
- Experimental signatures: Strange antibaryons 1980 $\longrightarrow$
- Materialization of QGP: 1982 $\longrightarrow$
  Statistical Hadronization Model (SHM)

⟶JR 1980; T. Biro, J.Zimanyi, P. Levai

Cooking strange quarks → strange antibaryons

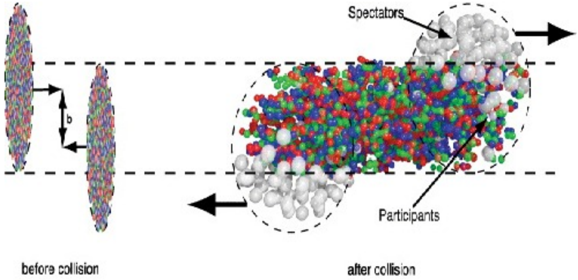


Prediction: 1980 JR; 1982 JR,Berndt Müller; 1986 P. Koch, BM, JR; Present day results



PARTICLE YIELDS: INTEGRATED SPECTRA

Particle yields allow exploration of the source bulk properties in the co-moving frame – collective matter flow dynamics integrated out. This avoids the dynamical mess:



Our interest in the bulk thermal properties of the source evaluated independent from complex transverse dynamics is the reason to analyze integrated spectra.

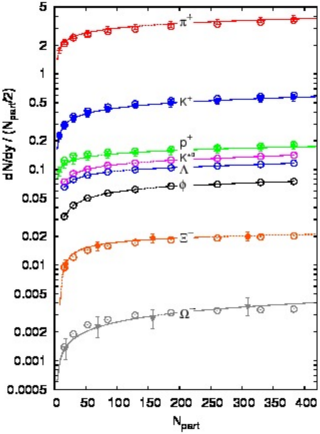
(FERMI) STATISTICAL HADRONIZATION MODEL (SHM)

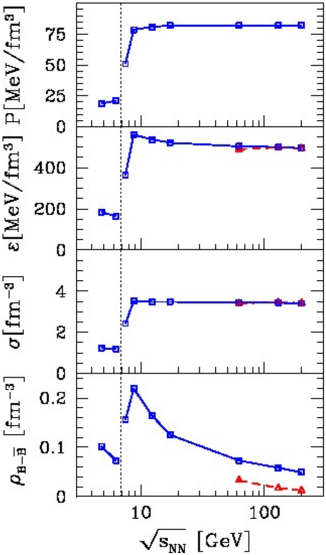
Very strong interactions: equal hadron production strength irrespective of produced hadron type particle yields depending only on the available phase space

- Fermi: Micro-canonical phase space
  sharp energy and sharp number of particles
  E. Fermi, Prog.Theor.Phys. 5 (1950) 570: HOWEVER

  Experiments report event-average rapidity particle abundances, model should describe an average event
- Canonical phase space: sharp number of particles
  ensemble average energy $E \to T$ temperature
  T could be, but needs not to be, a kinetic process temperature
- Grand-canonical – ensemble average energy and number of particles: $N \to \mu \Leftrightarrow \Upsilon = e^{(\mu/T)}$

Examples: data (LHC) AGS,SPS,RHIC bulk properties





QGP+ Statistical Hadronization Model =Hadron Gas Abundances without Hadron Gas

Why the hadronic gas description of hadronic reactions works: the example of strange hadrons

Received 28 August 1985

P. Koch and J. Rafelski
Institute of Theoretical Physics and Astrophysics, University of Cape Town, Rondebosch

The degree to which, in hadronic reactions, the strangeness quark flavour is equilibrated in its abundance with the light quarks' flavours is proposed as a measure of the relevance of gluonic degrees of freedom in hadronic reactions. The transitory presence of gluons manifests itself by generating strange quark abundance near the hadronic gas equilibrium in pp and pN reactions. Nucleus–nucleus collisions below 5 GeV/n appear to be in the regime of individual nucleon collisions in which the intrinsic QCD degrees of freedom are frozen. In consequence, the measured strangeness abundance in these nuclear collisions falls short of the values expected from the hadronic gas equilibrium. Should the quark–gluon plasma state be formed at higher energies, the signal for this process would be the equilibration of total strangeness abundance almost as if an equilibrated hadronic gas had been formed. Anomalies in the abundance of strange antibaryons remain the characteristic and global signal of plasma state formation.

S. Afr. J. Phys. 9 (1986) 8–23

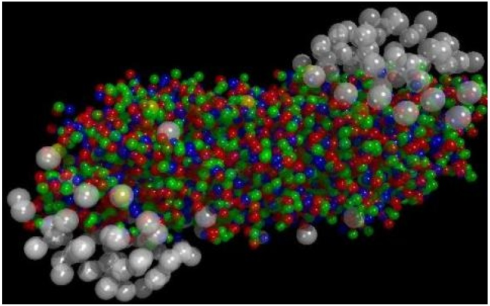
1. Introduction

The observation that soft multihadron production ($p_\perp <$ 1 GeV) shows many features of an underlying statistical reaction mechanism has inspired Hagedorn's Statistical Bootstrap [1, 2] long before anything about quantum chromodynamics (QCD) was known. But since QCD has been accepted as the underlying gauge field theory of strong interactions, it seems today rather 'oldfashioned' to treat high energetic hadronic collisions in the framework of phenomenological statistical models. A contrary understanding may be adopted following the present discussion. Our point of view is that the transitory formation of a quark–gluon plasma-like state is the prerequisite in order that statistical models can be used. The number of accessible states in hadronic reactions may be many times larger than a naive hadronic phase space counting indicates and a statistical description may indeed also be necessary in order to describe the hadronic interactions. The whole hadronic reaction

CERN press office

New State of Matter created at CERN

10 Feb 2000



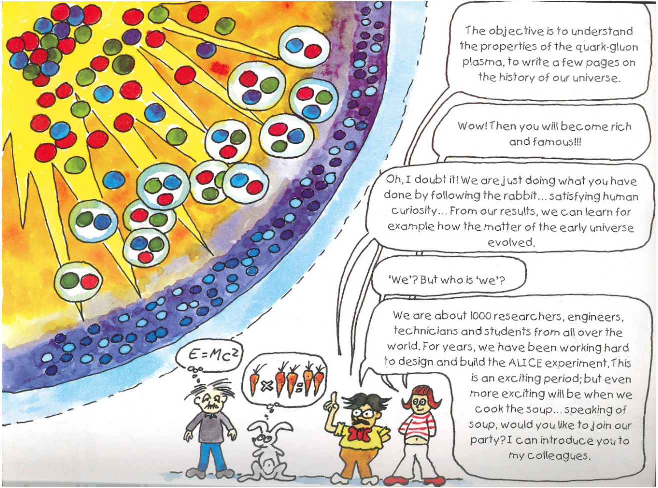
At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

Preeminent signature: Strange antibaryon enhancement

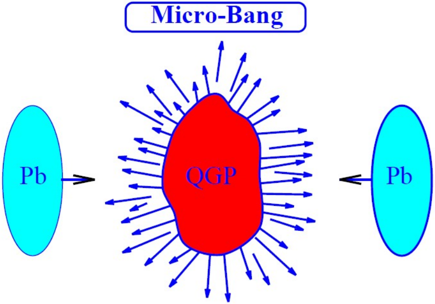
9AM, 18 April 2005; US – RHIC announces QGP Press conference APS Spring Meeting

Preeminent signature: honey that flows

LHC-Alice enters:

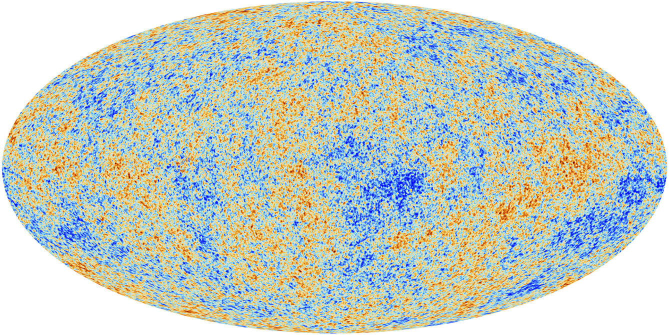


Today new question:



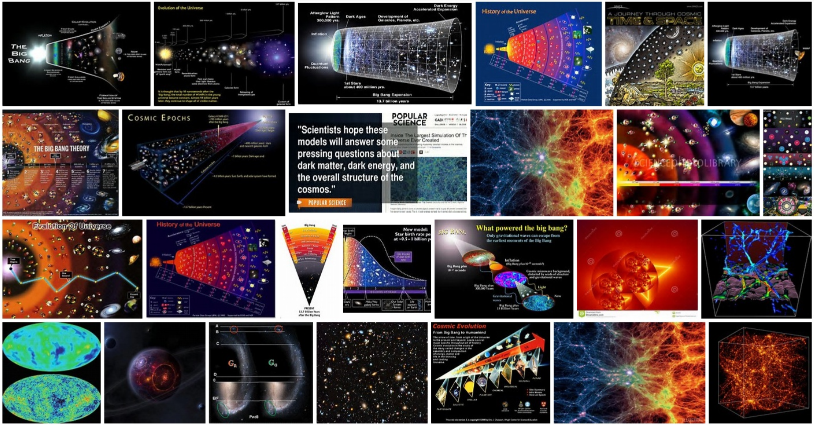
Big-Bang	Micro-Bang
$\tau \simeq 30\mu s$	$\tau \simeq 5\ 10^{-23} s$
$N_B / N \simeq 10^{-10}$	$N_B / N \simeq 0.001$

Do we see QGP in the sky?



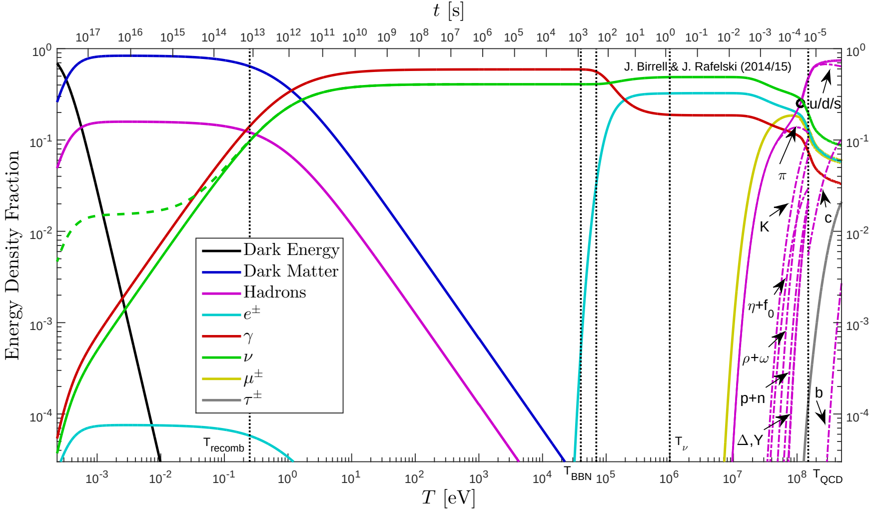
Photons freeze-out around 0.25 eV and today they make up the $T_\gamma = 0.235$ meV (2.7° K) Cosmic Microwave Background (CMB). The CMB is one of the anchors of observational cosmology Could CMB connect to early Universe QGP era? Let us search the web!

Image: ESA and the Planck Collaboration



Stunning graphics! But nothing addressing the question. Thus we (Jeremiah Birrell and JR) tried to remedy the situation.

Result: time evolution of the energy density composition



Input into the image

- FRW Cosmology
- Disappearing Particles:
  Degrees of Freedom and Reheating
- Our contributions: connecting the Eras
  - From the beginning to QGP hadronization
  - Matter-antimatter annihilation era
  - Onset of neutrino free-streaming
  - Big-Bang nucleosynthesis and disappearance of practically all matter (e^+e^- annihilation)
  - Emergence of free streaming dark matter, baryons follow
  - Photon Free-streaming – Composition Cross-Point
  - Dark Energy Emerges – vacuum energy

FRW Friedmann–Lemaitre–Robertson–Walker (FRW) cosmology assumes a) Homogeneous and b) Isotropic Einstein Universe, metric:

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2(\theta)d\phi^2)\right]$$

$a(t)$ determines the distance between objects at rest in the Universe frame (comoving).Skipping $g^{\mu\nu} \rightarrow R^{\mu\nu}$

$$G^{\mu\nu} = R^{\mu\nu} - \left(\frac{R}{2} + \Lambda\right) g^{\mu\nu} = 8\pi G_N T^{\mu\nu}, \quad T^\mu_\nu = \mathrm{diag}(\rho, -P, -P, -P)$$

Definitions: Hubble parameter H and deceleration parameter q:

$$H(t) \equiv \frac{\dot{a}}{a}; \quad q \equiv -\frac{a\ddot{a}}{\dot{a}^2} = -\frac{1}{H^2}\frac{\ddot{a}}{a}, \Rightarrow \dot{H} = -H^2(1+q).$$

Two dynamically independent Einstein equations arise: eliminate G and get

$$q = \frac{1}{2}\left(1 + 3\frac{P}{\rho}\right)\left(1 + \frac{k}{\dot{a}^2}\right).$$

Flat ($k = 0$) metric is favored in the ΛCDM analysis by PLANCK (arXiv:1303.50761502.01589):

Degrees of Freedom – disappearing particles

adiabatic Universe with comoving entropy conserved:

The effective number of entropy degrees of freedom, g_*^S, defined by:

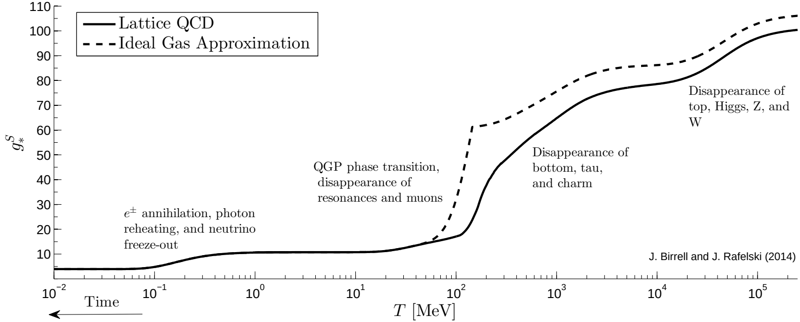
$$S = \frac{2\pi^2}{45} g_*^S T_\gamma^3 a^3 .$$

For ideal Fermi and Bose gases

$$g_*^S = \sum_{i=\text{bosons}} g_i \left(\frac{T_i}{T_\gamma}\right)^3 f_i^- + \frac{7}{8} \sum_{i=\text{fermions}} g_i \left(\frac{T_i}{T_\gamma}\right)^3 f_i^+ .$$

g_i are the degeneracies, $f_i^\pm$ are (known) functions valued between 0 and 1 that turn off the various particle species as the temperature drops below their mass. Entropy redistributed among coupled dof's $\rightarrow$ reheating: e.g. when e^+e^- annihilated only γ reheated, already free-streaming neutrino temperature lower by factor $R_\nu = (4/11)^{1/3} = 0.714$.

Degrees of freedom as function of T_γ



Ideal gas approximation is not valid during QGP phase transition and equation of state from lattice QCD must be used [1]. At and above 300 MeV non-rigorous matching [2] with perturbation calculations may impact result.

[1] *S. Borsanyi, Nucl. Phys. A904-905, 270c (2013)*

[2] *Mike Strickland (private communication of results and review of thermal SM).*

Checking the ‘contents’ of the Universe

Cosmic neutrino background (CNB) contributes to dynamics of expansion influencing temperature fluctuations in CMB

- ‘Effective’ number of neutrinos – measurable – is defined comparing the relativistic energy density to the energy density of one SM neutrino flavor, with the standard $e^+e^- \to \gamma's$ photon reheating ratio $R_\nu = (4/11)^{1/3}$ allowed for.

$$N_\nu \equiv N_{eff} \equiv \frac{\rho_r}{\frac{7}{120}\pi^2\left(R_\nu T_\gamma\right)^4}.$$

- Planck satellite: $N_\nu = 3.36 \pm 0.34$ (CMB no priors) and $N_\nu = 3.62 \pm 0.25$ (CMB $+ H_0$) [1]. In latest release $\delta N_\nu \simeq 0.3 \pm 0.25$.

[1] *Planck Collaboration, Astron.Astrophys. 571 (2014) A16*

Is the understanding of neutrino freeze-out accurate?

- The computed best value is $N_\nu = 3.046$ (some flow of $e^{\pm}$-pair into ν) [1]. Only drastic changes in neutrino properties and/or physical laws can change this value noticeably $[2]$.
- Consistent $\delta N_\nu > 0$ – is there ‘Darkness’ content in the Universe? New relativistic particles in the early Universe modify N_ν fractionally, see e.g. $[3]$.

[1] *G. Mangano et. al., Nucl. Phys. B* **729**, *221 (2005)*
[2] *J. Birrell, C. T. Yang and JR, Nucl. Phys. B* **890**, *481 (2014) [1406.1759 [nucl-th]]*
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Are there additional dark degrees of freedom

Darkness Candidates

a) ‘True’ Goldstone bosons related to symmetry breaking in reorganization of QCD vacuum structure. My favorite candidate, theoretical details need work.

b) Super-WI neutrino partners. Connection to deconfinement not straightforward.

Massive $m > \mathcal{O}$(eV) sterile ν not within ‘Darkness’ context. Mass must emerge after CMB decouples, $m < 0.25$ eV. Allowing higher ‘sterile mass’ requires full reevaluation of many steps in the analysis including key elements we do not control (PLANCK CMB fluctuations).

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Quark–gluon plasma as the possible source of cosmological dark radiation

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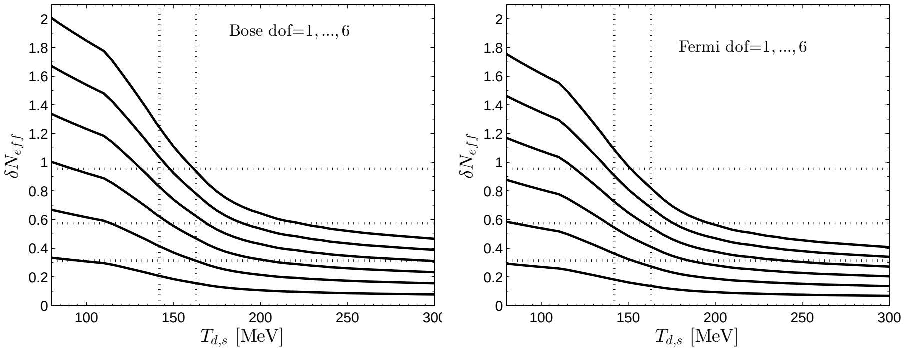
Abstract

The effective number of neutrinos, N_{eff}, obtained from CMB fluctuations accounts for all effectively massless degrees of freedom present in the Universe, including but not limited to the three known neutrinos. Using a lattice-QCD derived QGP equation of state, we constrain the observed range of N_{eff} in terms of the freeze-out of unknown degrees of freedom near to quark–gluon hadronization. We explore limits on the coupling of these particles, applying methods of kinetic theory, and discuss the implications of a connection between N_{eff} and the QGP transformation for laboratory studies of QGP.

Hadron and QGP Era

- QGP: from electro-weak mass emergence down to phase transition at $T \approx 150$MeV Energy density dominated by QCD (quarks and gluons) but photons, neutrinos, $e^{\pm}$, $\mu^{\pm}$ need to be remembered
- $2+1$-flavor lattice QCD equation of state must be used [1]
- u,d,s lattice energy density is matched by ideal gas of hadrons to sub percent-level at $T = 115$MeV
- Hadrons included: pions, kaons, eta, rho, omega, nucleons, delta, Y
- Hadron pressure matching lattice-QGP and a few resonances is discontinuous but hard to notice.

[1] *S. Borsanyi, Nucl. Phys. A904-905, 270c (2013)*



Left pane: Increase in δN_{eff} due to the effect of $1, \ldots, 6$ light Goldstone boson DoF ($g_s = 1, \ldots, 6$, bottom to top curves) as a function of freeze-out temperature $T_{d,s}$. Right pane: Increase in δN_{eff} due to the effect of $1, \ldots, 6$ light sterile fermion DoF ($g_s = 7/8 \times 1, \ldots, 7/8 \times 6$, bottom to top curves) as a function of freeze-out temperature $T_{d,s}$. The horizontal dotted lines: $\delta N_{\text{eff}} + 0.046 = 0.36, 0.62, 1$. Vertical dotted lines: $T_c = 142 - 163$ MeV.

Limits on Couplings:
Goldstone Boson limit in laboratory

Laboratory setting: Chemical equilibrium abundance of Darkness is achieved in the short lifespan of QGP formed in laboratory heavy ion collisions if

$$G_{\text{Darkness}}^{-1/2} \simeq 170\,\text{MeV} \quad \text{compare} \quad G_{\text{WI}}^{-1/2} = 300\ \text{GeV}. \tag{1}$$

The appearance of a coupling on the order of the QCD scale is consistent with the intuition about the interaction strength that is required for particles to reach chemical equilibrium in laboratory QGP experiments. However, could such particles be excluded already by experiment?

HOWEVER: Activation of QCD Scale Interactions by T

QGP activation: Missing Energy in RHI Collisions

- Breakup: Counting degrees of freedom and presuming Darkness equilibration before hadronization, approximately $12 \pm 8\%$ of all entropy content of the QGP is in Darkness.
- Continuous emission: Darkness stops interacting at the QGP surface – escapes freely during the entire lifespan of the QGP. This Dark-radiation loss proportionally largest for long-lived QGP $\rightarrow$ Does energy in/out balance in large AA collision systems beyond threshold of QGP formation?
- Experiment: A systematic exploration of the energy balance as function of $\sqrt{s}$ and A at energies near to QGP formation threshold: = NA61 experiment..

QGP Phase Transition Accentuated?

- We recall that lattice-QCD results show a gradual transformation of the QGP into hadrons consistent with the absence of a phase transition.
- However, Darkness as above introduced contributes to the pressure internal to QGP, yet not in the external region – free streaming. This should sharpen the QGP phase boundary surface.
- This impacts model of QGP flow and formation azimuthal asphericity [1,2] (particle v_2). Darkness thus has indirect, dynamical effect on the flow of QCD matter.

[1] *Y.J. Ollitrault, Phys.Rev. D46, 229 (1992)*
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Summary

- 50 years ago particle production in pp reactions prompted introduction of Hagedorn Temperature $T_{\rm H}$; soon after recognized as the critical temperature at which matter surrounding us dissolves into its different fundamental phase of quarks and gluons – QGP.
- Laboratory work confirms QGP and leads the way to an understanding of the properties of the Universe below the age of 18μs.
- A first links between observational cosmology and hadronization stage of the Quark Universe is found: Released Darkness could be a new component pushing the Universe apart.
- Laboratory effort: a search for missing energy in connection to dynamics of hadronization near to phase boundary as function of $\sqrt{s}$ with energy imbalance increasing with A.