Near Beginning of Time . . . There Was QGP

Results obtained in collaboration with
Jeremiah Birrell, Michael Fromerth, Inga Kuznetsowa, Michal Petran

The University of Arizona

What is special with Quark Gluon Plasma?

1. RECREATE THE EARLY UNIVERSE IN LABORATORY:
   The topic of this talk
2. PROBING OVER A LARGE DISTANCE THE CONFINING VACUUM STRUCTURE
3. STUDY OF THE ORIGIN OF MASS OF MATTER
4. OPPORTUNITY TO PROBE ORIGIN OF FLAVOR?
   Normal matter made of first flavor family $(u, d, e, [\nu_e])$.
   Strangeness-rich quark-gluon plasma the sole laboratory environment filled with 2nd family matter (s, c).

50 years ago 1964/65: Beginning of a new scientific epoch

- Quarks, Higgs → Standard Model of Particle Physics
- CMB discovered
- Hagedorn Temperature, Statistical Bootstrap
  → QGP: A new elementary state of matter

Topics today:

1. Hagedorn, Big Bang and birth of hadronic matter theory
2. Introduction to QGP in Universe and Laboratory
3. Discovery of QGP
4. Quark-gluon plasma in the Universe
5. Particles in the evolving Universe
6. New Ideas? Darkness

Quarks, Higgs → Standard Model

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

8182/TH.401
17 January 1964

G. Zweig *)
CERN – Geneva

Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces break up into an isospin doublet and singlet. Each ace carries baryon number $\frac{1}{3}$ and is consequently fractionally charged. SU_3 (but not the Eightfold Way) is adopted as a higher symmetry for the strong interactions. The breaking of this symmetry is assumed to be universal, being due to mass differences among the aces. Extensive space-time

A schematic model of baryons and mesons

M. Gell-Mann

California Institute of Technology, Pasadena, California, USA

Received 4 January 1964,

Physics Letters

Volume 8, Issue 3,

1 February 1964, Pages 214–215

Nearly 50 years after its prediction, particle physicists have finally captured the Higgs boson.

Mass

Broken Symmetries and the Masses of Gauge Bosons

Peter W. Higgs

Phys. Rev. Lett. 13, 508 (1964)

Published October 19, 1964

Broken Symmetry and the Mass of Gauge Vector Mesons

F. Englert and R. Brout

Phys. Rev. Lett. 13, 321 (1964)

Published August 31, 1964

1965: Penzias and Wilson

No. 1, 1965 LETTERS TO THE EDITOR 1965ApJ...142..419P

From a combination of the above, we compute the remaining unaccounted-for antenna temperature to be 3.5° ± 1.0° K at 4080 Mc/s. In connection with this result it should be noted that DeGrasse *et al.* (1959) and Ohm (1961) give total system temperatures at 5650 Mc/s and 2390 Mc/s, respectively. From these it is possible to infer upper limits to the background temperatures at these frequencies. These limits are, in both cases, of the same general magnitude as our value.

We are grateful to R. H. Dicke and his associates for fruitful discussions of their results prior to publication. We also wish to acknowledge with thanks the useful comments and advice of A. B. Crawford, D. C. Hogg, and E. A. Ohm in connection with the problems associated with this measurement.

Note added in proof.—The highest frequency at which the background temperature of the sky had been measured previously was 404 Mc/s (Pauliny-Toth and Shakeshaft 1962), where a minimum temperature of 16° K was observed. Combining this value with our result, we find that the average spectrum of the background radiation over this frequency range can be no steeper than $\lambda^{0.7}$. This clearly eliminates the possibility that the radiation we observe is due to radio sources of types known to exist, since in this event, the spectrum would have to be very much steeper.

A. A. Penzias
R. W. Wilson

May 13, 1965
Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey

physicstoday

The early universe

Edward R. Harrison

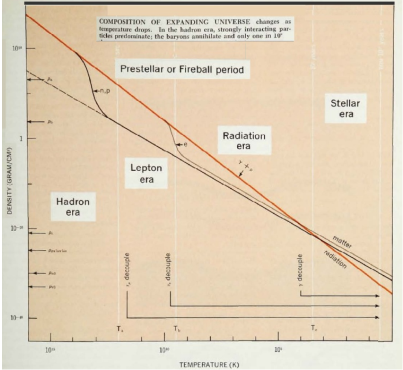
June 1968, page 31

IN RECENT YEARS the active frontiers of cosmology have widened and certain aspects of the subject are attracting more attention from physicists. Growing emphasis on physics has been stimulated by discovery of the universal black-body radiation and by growing realization that the composition of the universe was once extremely complex.

What was the universe like when it was very young? From a high-energy physicist's dream world it has evolved through many eras to its present state of comparative darkness and emptiness.

DOI: http://dx.doi.org/10.1063/1.3035005

1966-1968: Hot Big-Bang ⇒ conventional wisdom



Hagedorn Temperature October 1964
Hagedorn Spectrum January 1965

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

STATISTICAL THERMODYNAMICS OF STRONG INTERACTIONS AT HIGH ENERGIES

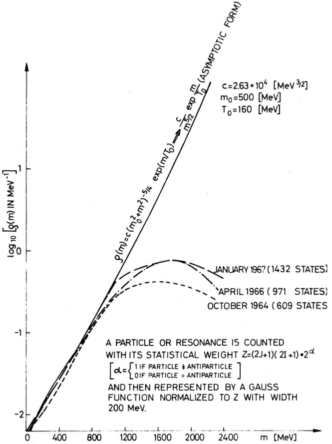
R. Hagedorn
CERN - Geneva

ABSTRACT

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:

$$\rho(m) \xrightarrow[m \to \infty]{} \text{const.}\, m^{-5/2} \exp\left(\frac{m}{T_0}\right).$$

T_0 is a remarkable quantity: the partition function corresponding to the above $\rho(m)$ diverges for $T \to T_0^-$. T_0 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_0 is about 158 MeV ($\approx 10^{12}$ °K). With this value of T_0 the asymptotic mass spectrum of our theory has a good chance to be the correct extrapolation of the experimentally known spectrum.



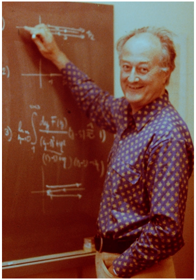
SBM the only model providing initial singular condition 1967 many regard SBM as the Hot Big-Bang theory

Actes de la Société Helvétique des Sciences Naturelles.
Partie scientifique et administrative 148 (1968) 51
Persistenter Link: http://dx.doi.org/10.5169/seals-90676

Siedende Urmaterie

R. Hagedorn, CERN (Genève)

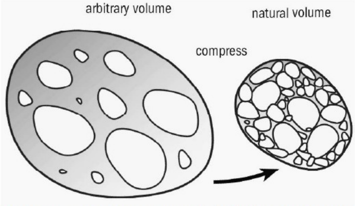
Wenn auch niemand dabei war, als das Universum entstand, so erlauben uns doch unsere heutigen Kenntnisse der Atom-, Kern- und Elementarteilchenphysik, verbunden mit der Annahme, dass die Naturgesetze unwandelbar sind, Modelle zu konstruieren, die mehr und mehr auf mögliche Beschreibungen der Anfänge unserer Welt zusteuern.



Boiling Primordial Matter *Even though no one was present when the Universe was born, our current understanding of atomic, nuclear and elementary particle physics, constrained by the assumption that the Laws of Nature are unchanging, allows us to construct models with ever better and more accurate descriptions of the beginning.*

1970: Statistical Bootstrap Model=Model of Hot Big Bang

What is the Statistical Bootstrap Model (SBM)?



A volume comprising a gas of fireballs compressed to natural volume is itself again a fireball.

$$\tau(m^2)\mathrm{d}m^2 \equiv \rho(m)\mathrm{d}m \quad \rho(m) \propto m^{-a}\exp(m/T_{\mathrm{H}}).$$

nature

article

Nature **228**, 258 - 260 (17 October 1970); doi:10.1038/228258a0

Comments on the Big-bang

E. R. HARRISON*

Institute of Theoretical Astronomy, University of Cambridge
*On leave from the Department of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01002.

Is the big-bang hot, warm or cold? And are galactic masses determined by the interplay of gravitational and strong interactions in the very early universe?

References

1. Harrison, E. R., *Nature*, **215**, 151 (1967).
2. Harrison, E. R., *Phys. Rev.* (in the press).
3. Harrison, E. R., *Mon. Not. Roy. Astro. Soc.*, **148**, 119 (1970).
4. Dicke, R. H., Peebles, P. J. E., Roll, P. G., and Wilkinson, D. T., *Astrophys. J.*, **142**, 414 (1965).
5. Wagoner, R. V., Fowler, W. A., and Hoyle, F., *Astrophys. J.*, **148**, 3 (1967).
6. Harrison, E. R., *Phys. Rev.*, **167**, 1170 (1968).
7. Misner, C. W., *Phys. Rev. Lett.*, **22**, 1071 (1969).Khalatnikov, I. M., and Lifshitz, E. M., *Phys. Rev. Lett.*, **24**, 76 (1970).
8. Harrison, E. R., *Astrophys. J.*, **142**, 1643 (1965).
9. Zel'dovich, Ya. B., *Sov. Phys., JETP*, **14**, 1143 (1962).
10. Harrison, E. R., *Mon. Not. Roy. Astro. Soc.*, **140**, 281 (1968).
11. Layzer, D., *Astrophys. Lett.*, **1**, 93 (1968).
12. Kaufman, M., *Astrophys. J.*, **160**, 459 (1970).
13. Rees, M. J., *Observatory*, **89**, 972 (1969).
14. Hagedorn, R., *Suppl. Nuovo Cim.*, **3**, 147 (1965); *ibid.*, **6**, 311 (1968); *Nuovo Cim.*, **52**A, 1336 (1967); *ibid.*, **56**A, 1027 (1968); *Astron. Astrophys.*, **5**, 184 (1970).
15. Hagedorn, R., and Ranft, J., *Suppl. Nuovo Cimento*, **6**, 169 (1968).

Hagedorn Temperature T_{H}
Singular point of partition function

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

Inserting $1 = \int \delta_0(m^2 - p^2)\mathrm{d}m^2$

I replacing $\tau(m^2)\mathrm{d}m^2$ by $\rho(m)\mathrm{d}m$

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

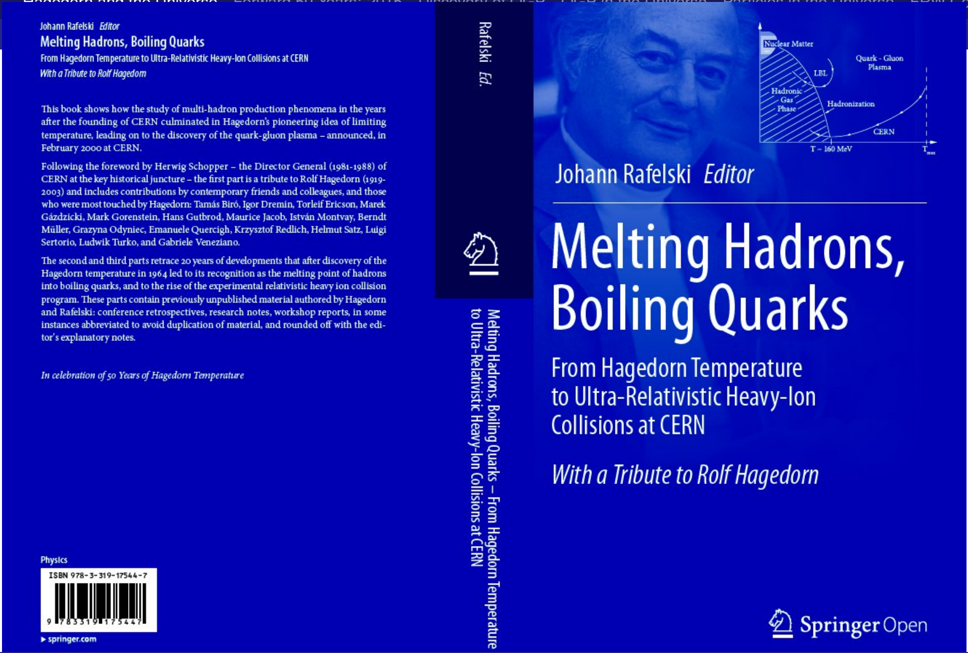
$$Z_1(\beta,V) \underset{T\to T_0}{\sim} C\int_M^\infty m^{3/2-a}\mathrm{e}^{-(\beta-\beta_0)m}\mathrm{d}m + C\,.$$

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

a	P	n	ε	$\delta\varepsilon/\varepsilon$	$C_V = \mathrm{d}\varepsilon/\mathrm{d}T$
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.



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

ISBN 978-3-319-17544-7

▸ springer.com

Rafelski *Ed.*

Melting Hadrons, Boiling Quarks – From Hagedorn Temperature to Ultra-Relativistic Heavy-Ion Collisions at CERN

Johann Rafelski *Editor*

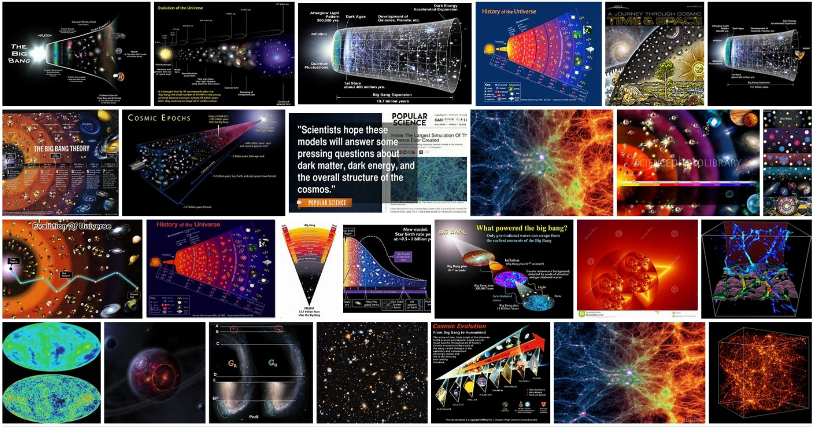
Melting Hadrons, Boiling Quarks

From Hagedorn Temperature to Ultra-Relativistic Heavy-Ion Collisions at CERN

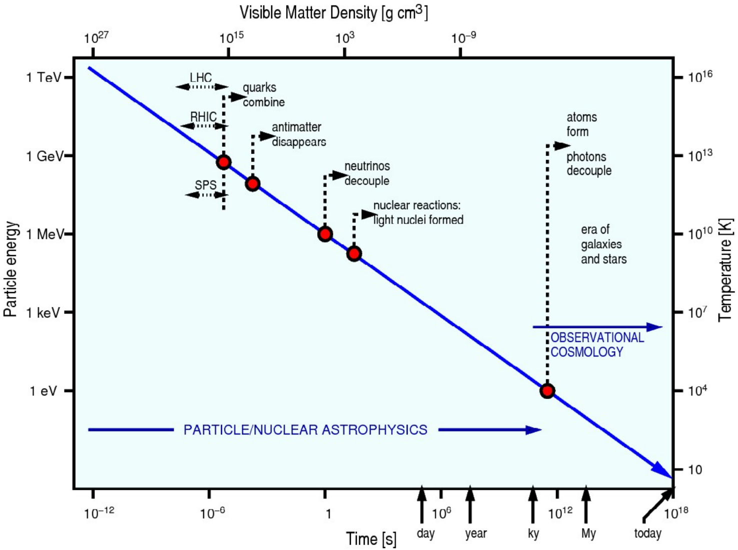
With a Tribute to Rolf Hagedorn

Springer Open

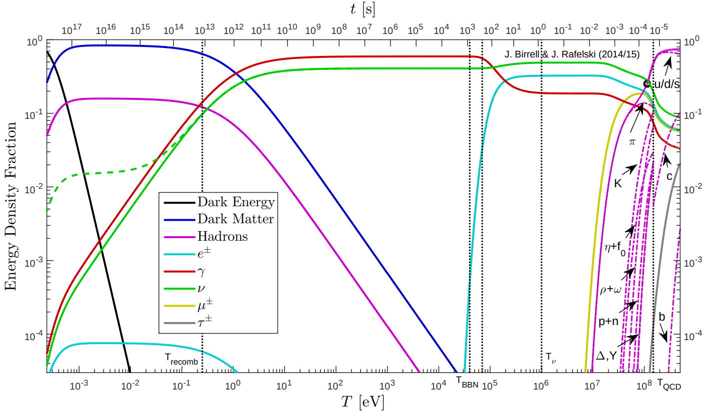
Forward 50 Years to the Universe 2015



Experiments Probe the Universe



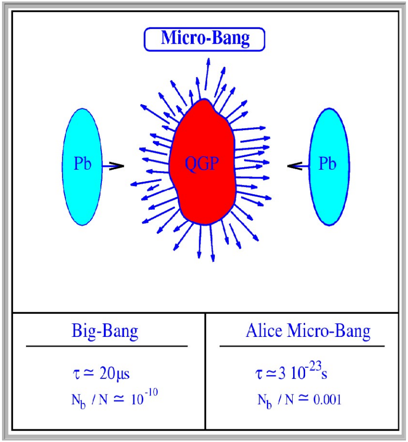
The Universe Composition Changes



dark energy matter radiation ν, γ leptons hadrons

$\Longrightarrow$ Different dominance eras

Connection to Relativistic Heavy Ion Collisions



- Universe time scale 18 orders of magnitude longer, hence equilibrium of leptons & photons
- Baryon asymmetry six orders of magnitude larger in Laboratory, hence chemistry different
- Universe: dilution by scale expansion, Laboratory explosive expansion of a fireball

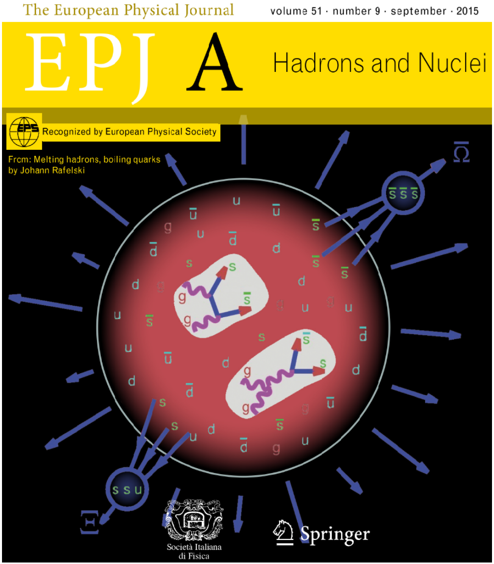
$\Longrightarrow$ Theory connects RHI collision experiments to Universe

Boiling quarks

THE ROOTS:

- Cold quark matter in diverse formats from day 1: 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)

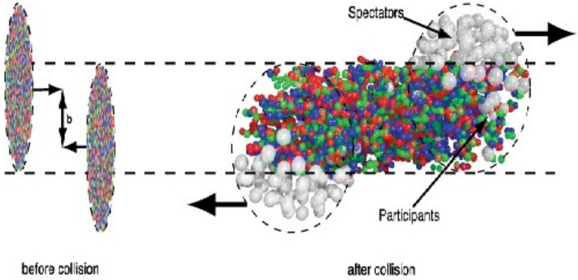
Cooking strange quarks → strange antibaryons



APS sticker from period

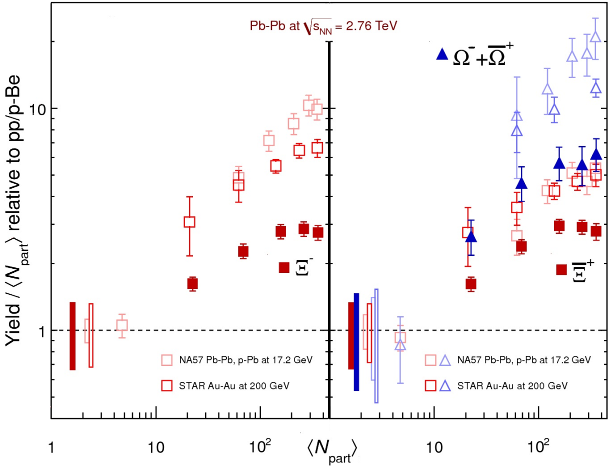
Particle yields: integrated spectra

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.

Prediction: 1980-86 confirmed by experimental results

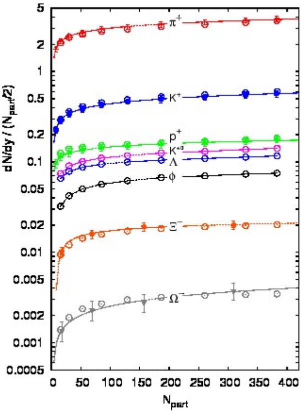


Statistical Hadronization Model Interpretation (SHM)

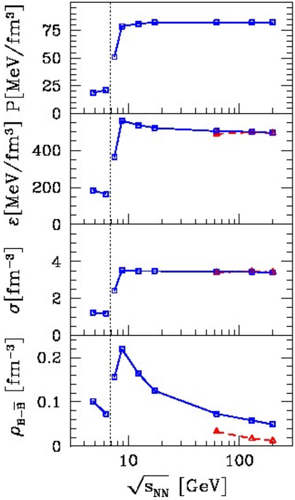
equal hadron production strength

yield depending on available phase space

Example data from LHC⇓



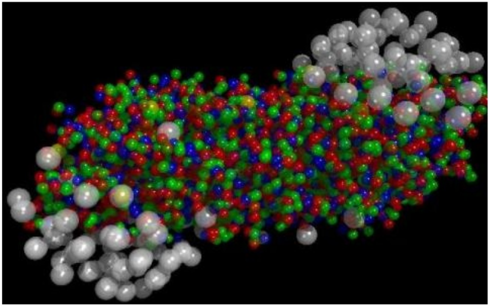
Bulk properties⇓



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.

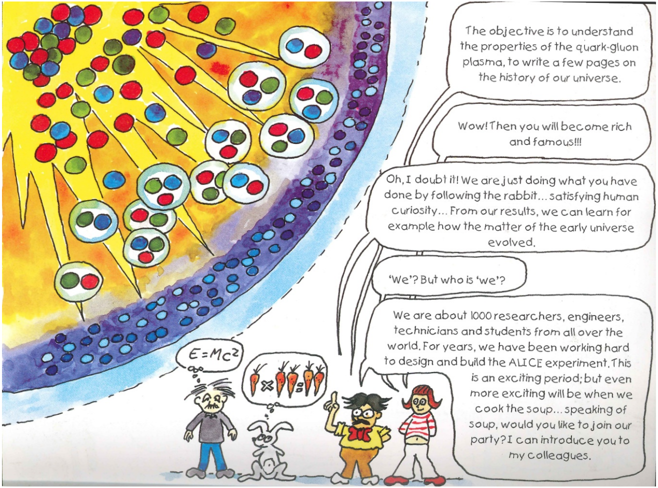
Preeminent signature: Strange antibaryon enhancement

press.web.cern.ch/press-releases/2000/02/new-state-matter-created-cern

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

Preeminent property: non-viscous flow

LHC-Alice: Exploration of QGP



Universe: QGP and Hadrons in full Equilibrium

The key doorway reaction too abundance (chemical) equilibrium of the fast diluting hadron gas in Universe:

$$\pi^0 \leftrightarrow \gamma + \gamma$$

The lifespan $\tau_{\pi^0} = 8.4 \times 10^{-17}$ sec defines the strength of interaction which beats the time constant of Hubble parameter of the epoch. Inga Kuznetsova and JR, Phys. Rev. C82, 035203 (2010) and D78, 014027 (2008) (arXiv:1002.0375 and 0803.1588).

Equilibrium abundance of π^0 assures equilibrium of charged pions due to charge exchange reactions; heavier mesons and thus nucleons, and nucleon resonances follow:

$$\pi^0 + \pi^0 \leftrightarrow \pi^+ + \pi^-. \quad \rho \leftrightarrow \pi + \pi, \quad \rho + \omega \leftrightarrow N + \bar{N}, \quad etc$$

The π^0 remains always in chemical equilibrium All charged leptons always in chemical equilibrium – with photons

Neutrinos freeze-out (like photons later) at $T = \mathcal{O}$MeV

Particle Content and Chemical Potentials

Chemical potentials control particle/antiparticle abundances:

$$f_{p/a} = \frac{1}{e^{\beta(\varepsilon \mp \mu)} \pm 1}, \qquad \varepsilon = \sqrt{p^2 + m^2}$$

• Quark side: $d \leftrightarrow s \leftrightarrow b_{\rm ottom}$ oscillation means $\mu_d = \mu_s = \mu_{\rm bottom}$ and similarly $\mu_{\nu_e} = \mu_{\nu_\mu} = \mu_{\nu_\tau}$. WI reaction e.g. $d \to u + e^- + \bar{\nu}_e$ imply $\mu_d - \mu_u = \Delta\mu_l$ with

$$\Delta\mu_l = \mu_e - \mu_{\nu_e} = \mu_\mu - \mu_{\nu_\mu} = \mu_\tau - \mu_{\nu_\tau}$$

• Hadron side: Quark chemical potentials control valence quarks and can be used in the hadron phase, e.g. Σ^0 (*uds*) has chemical potential $\mu_{\Sigma^0} = \mu_u + \mu_d + \mu_s$. The baryochemical potential μ_B is:

$$\mu_B = \frac{1}{2}(\mu_p + \mu_n) = \frac{3}{2}(\mu_d + \mu_u) = 3\mu_d - \frac{3}{2}\Delta\mu_l$$

Three Constraints

The chemistry of particle reaction and equilibration in the Universe has three chemical potentials 'free' i.e. not only baryochemical potential μ_B. We need three physics constraints Michael J. Fromerth , JR e-Print: astro-ph/0211346:

i. Charge neutrality eliminates Coulomb energy

$$n_Q \equiv \sum Q_i \, n_i(\mu_i, T) = 0,$$

Q_i and n_i charge and number density of species i.

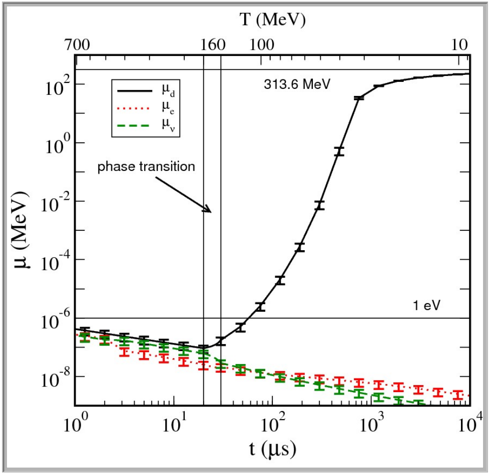
ii. Net lepton number equals net baryon number However, possible neutrino-antineutrino asymmetry can hide an imbalance

iii. Prescribed value of entropy-per-baryon

$$\frac{\sigma}{n_B} \equiv \frac{\sum_i \sigma_i(\mu_i, T)}{\sum_i B_i \, n_i(\mu_i, T)} = 3.2 \ldots 4.5 \times 10^{10}$$

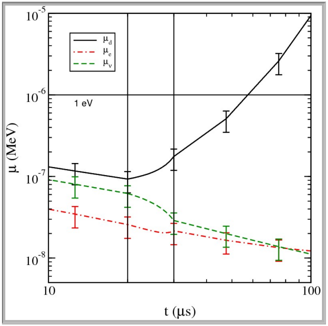
Today best est. $S/B = 3.5 \times 10^{10}$, results shown for 4.5×10^{10}

Chemical Potential in the Universe



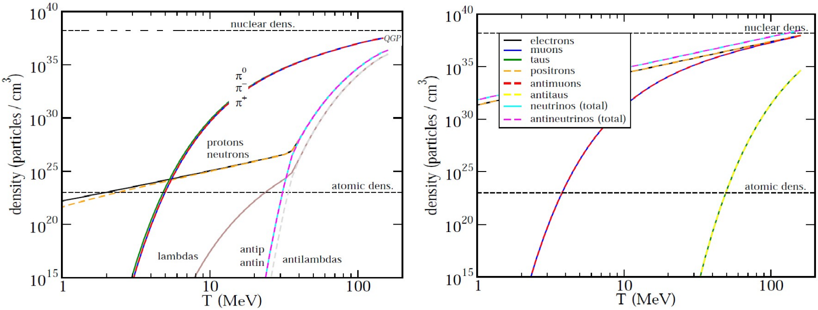
Minimum:

$\mu_B = 0.33^{+0.11}_{-0.08}$eV



$\Longrightarrow$ μ_B defines remainder of matter after annihilation

Particle Composition after QGP Hadronization



$\Longrightarrow$ Antimatter annihilates to below matter abundance before $T = 30$ MeV, universe dominated by photons, neutrinos, leptons for $T < 30$ MeV Next: distribution normalized to unity

Particles in the Universe=Degrees of Freedom

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 varying functions valued between 0 and 1 that turn off the various species as the temperature drops below their mass.

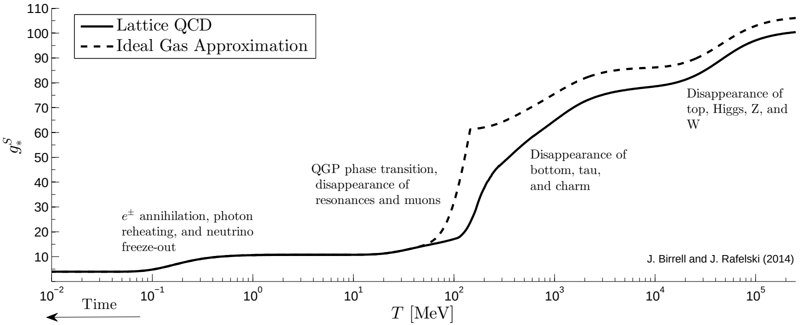
Speed of Universe expansion controlled by degrees of freedom thus g is an observable

Distinct Composition Eras

Composition of the Universe changes as function of T:

- From Higgs freezing to freezing of QGP
- QGP hadronization
- Antimatter annihilation
- Last leptons disappear just when
- Onset of neutrino free-streaming and begin of
- Big-Bang nucleosynthesis within a remnant lepton plasma
- Emergence of free streaming dark matter
- Photon Free-streaming – Composition Cross-Point
- Dark Energy Emerges – vacuum energy

Count of Degrees of Freedom



Distinct Composition Eras visible. In PDG ideal gas approximation (dashed) is not valid in QGP domain, equation of state from lattice-QCD, and at high T thermal-QCD must be used [1,2].

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

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

Reheating

Once a family ‘i’ of particles decouples at a photon temperature of T_i, a difference in its temperature from that of photons will build up during subsequent reheating periods as other particles feed their entropy into photons. This leads to a temperature ratio at $T_\gamma < T_i$ of

$$R \equiv T_i/T_\gamma = \left(\frac{g_*^S(T_\gamma)}{g_*^S(T_i)}\right)^{1/3}.$$

This determines the present day reheating ratio as a function of decoupling temperature T_i throughout the Universe history.
Example: neutrinos colder compared to photons.
Reheating ‘hides’ early freezing particles: darkness

Reheating History

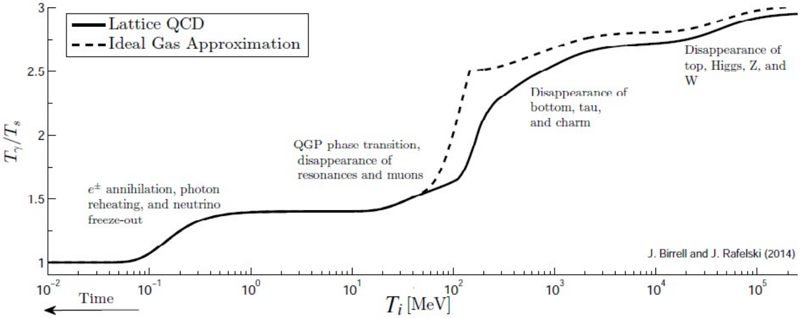


Figure: The reheating ratio reflects the disappearance of degrees of freedom from the Universe as function of T_i. These results are for adiabatic evolution of the Universe. Primordial dark matter colder by factor 3. Particles decouple at QGP hadronization colder by factor 2.

Connecting time to temperature

Friedmann–Lemaitre–Robertson–Walker (FRW) cosmology

- Einstein Universe:

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

  where $T^{\mu}_{\nu} = \mathrm{diag}(\rho, -P, -P, -P)$, $R = g_{\mu\nu}R^{\mu\nu}$, and
- • Homogeneous and • Isotropic 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 comoving in the Universe frame. Skipping $g^{\mu\nu} \to R^{\mu\nu}$
  Flat ($k = 0$) metric favored in the ΛCDM analysis, see e.g. Planck Collaboration, Astron. Astrophys. **571**, A16 (2014) [arXiv:1303.5076] and arXiv:1502.01589 [astro-ph.CO]].

We absorb the vacuum energy (Einstein Λ-term) into the energy ρ and pressure P

$$\rho \to \rho + \rho_\Lambda, \qquad P \to P + P_\Lambda$$

which contain other components in the Universe including CDM: cold dark matter; this is ΛCDM model.

$$\rho_\Lambda \equiv \Lambda/(8\pi G_N) = 25.6\ \mathrm{meV}^4, \qquad P_\Lambda = -\rho_\Lambda$$

The pressure P_Λ has a) opposite sign from all matter contributions and b) $\rho_\Lambda/P_\Lambda = -1$. The independent measurement of ρ and P or, equivalently, expansion speed (next slide) allows to disentangle matter from dark energy

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

$$\frac{8\pi G_N}{3}\rho = \frac{\dot a^2 + k}{a^2} = H^2\left(1+\frac{k}{\dot a^2}\right), \quad \frac{4\pi G_N}{3}(\rho+3P) = -\frac{\ddot a}{a} = qH^2.$$

solving both these equations for $8\pi G_N/3 \to$ we find for the deceleration parameter:

$$q = \frac{1}{2}\left(1+3\frac{P}{\rho}\right)\left(1+\frac{k}{\dot a^2}\right); \quad k=0$$

In flat $k=0$ Universe: ρ fixes H; with P also q fixed, and thus also $\dot H$ fixed so also $\dot\rho$ fixed, and therefore also for $\rho = \rho(T(t))$ and also $\dot T$ fixed.

The contents of the Universe today and yesterday:

1. Photons and all matter coupled to photons:
   thermal matter = ideal Bose-Fermi gases
2. Free-streaming matter (particles that have ‘frozen’ out):
   - dark matter:from before QGP hadronization
   - darkness: at QGP hadronization
   - neutrinos: since $T =$ a few MeV
   - photons: since $T = 0.25$eV
3. Dark energy = vacuum energy

darkness: quasi-massless particles, like neutrinos but due to earlier decoupling small impact on Universe dynamics; includes recent speculations on dark photons for dark matter

Free-streaming matter contributions: solution of kinetic equations with decoupling boundary conditions at T_k (kinetic freeze-out)

$$\rho = \frac{g}{2\pi^2}\int_0^\infty \frac{\left(m^2+p^2\right)^{1/2} p^2 dp}{\Upsilon^{-1} e^{\sqrt{p^2/T^2+m^2/T_k^2}}+1}, \quad P = \frac{g}{6\pi^2}\int_0^\infty \frac{\left(m^2+p^2\right)^{-1/2} p^4 dp}{\Upsilon^{-1} e^{\sqrt{p^2/T^2+m^2/T_k^2}}+1},$$

$$n = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\Upsilon^{-1} e^{\sqrt{p^2/T^2+m^2/T_k^2}}+1}.$$

These differ from the corresponding expressions for an equilibrium distribution by the replacement $m \to mT(t)/T_k$ *only* in the exponential. Only for massless photons free-streaming = thermal distributions (absence of mass-energy scale).

C. Cercignani, and G. Kremer. The Relativistic Boltzmann Equation: Basel, (2000).
H. Andreasson, "The Einstein-Vlasov System"Living Rev. Rel. **14***, 4 (2011) Y. Choquet-Bruhat. General Relativity and the Einstein Equations, Oxford (2009).*

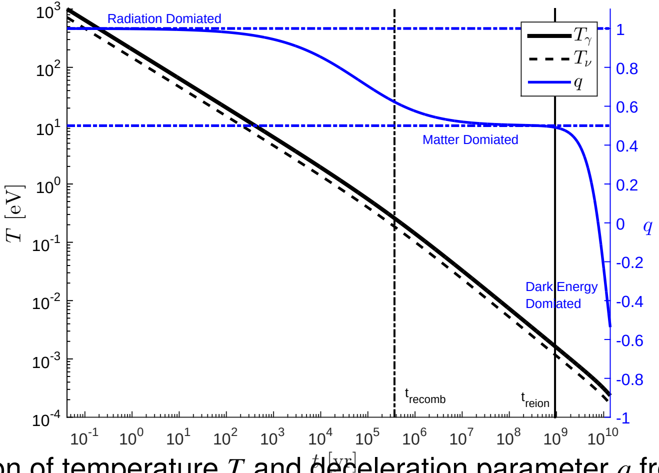
Evolution Eras and Deceleration Parameter q

Using Einsteins equations exact expression in terms of energy, pressure content

$$q \equiv -\frac{\ddot{a}a}{\dot{a}^2} = \frac{1}{2}\left(1+3\frac{P}{\rho}\right)\left(1+\frac{k}{\dot{a}^2}\right) \qquad k=0 \text{ favored}$$

- Radiation dominated universe: $P = \rho/3 \implies q = 1$.
- Matter dominated universe: $P \ll \rho \implies q = 1/2$.
- Dark energy (Λ) dominated universe: $P = -\rho \implies q = -1$.
  Accelerating Universe TODAY(!):
  Saul Perlmutter, Brian Schmidt and Adam Riess

Today and recent evolution



Evolution of temperature T and deceleration parameter q from soon after BBN to the present day

Long ago: Hadron and QGP Era

- QGP era down to phase transition at $T \approx 150$MeV. Energy density dominated by photons, neutrinos, $e^{\pm}$, $\mu^{\pm}$ along with u,d,s.
- $2+1$-flavor lattice QCD equation of state used
- 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
- Pressure between QGP/Hadrons is discontinuous at up to 10% level. Causes hard to notice discontinuity in q (slopes match). Need more detailed hadron and quark-quark interactions input

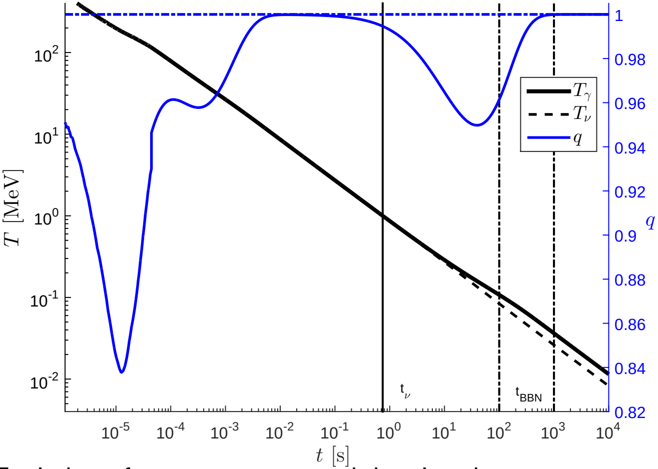


Figure: Evolution of temperature T and deceleration parameter q from QGP era until near BBN.

Are there additional dark degrees of freedom

<u>Darkness Candidates</u>

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).

How understanding the Universe enters laboratory experiments: Example

ELSEVIER

Physics Letters B

Volume 741, 4 February 2015, Pages 77–81

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

Jeremiah Birrell, Johann Rafelski

Show more

doi:10.1016/j.physletb.2014.12.033

Get rights and content

Open Access funded by SCOAP³ - Sponsoring Consortium for Open Access Publishing in Particle Physics

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

Activation of QCD Scale Interactions

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..

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 possible link between observational cosmology and hadronization stage of the Quark Universe: 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.

In Conclusion – and outlook

- We connected the hot melted quark Universe, to the boiling hadron Universe, on to lepton Universe, and the ensuing matter emergence, and dark energy emergence.
- We studied/set limits on effects due to modifications of natural constants, and on any new radiance from the deconfined Universe
- CMB fluctuations (PLANCK, WMAP data) have been connected to the QGP work in the laboratory.