TIME: 3:45-4:35 pm, Thursday, September 22, 2016

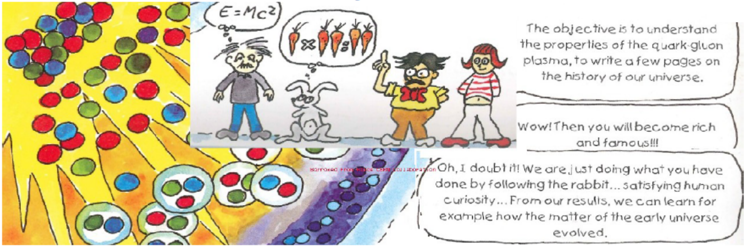
THE GEORGE WASHINGTON UNIVERSITY

Department of Physics Colloquium

QGP in the Universe and in the Laboratory

Johann Rafelski

University of Arizona



We celebrated last year 50 years of Hagedorn temperature, the pivotal idea that opened to study high energy density matter defining our Universe in primordial times. Today we are able to connect the present day visible Universe with prior invisible eras, leading on to the primordial period above Hagedorn temperature before the emergence of matter as we know it. This was the quark-gluon plasma, a new phase of matter discovered in recent experimental laboratory work at CERN-SPS, at BNL-RHIC and studied at LHC. We understand and can track the energy content of the Universe in time and connect the physics from nano-second scale to present day.

Vocabulary: BNL; RHIC; CERN; SPS; LHC;

QGP: Quark-Gluon Plasma;

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

Graduate Students at 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 the modern scientific epoch

- Quarks + Higgs $\rightarrow$ Standard Model of Particle Physics
- CMB discovered (GWU's Gamov prediction) $\rightarrow$ Big Bang
- Hagedorn Temperature, Statistical Bootstrap
  $\rightarrow$ QGP: A new elementary state of matter

Topics today:

1. Convergence of 1964/65 ideas and discoveries:
   understanding back to 10 ns of our Universe
2. Roots of QGP: from Hagedorn $T_{\rm H}$ $\rightarrow$ Big Bang; to
3. QGP Laboratory Discovery
4. QGP in the Universe
5. History of the Universe

1964: 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

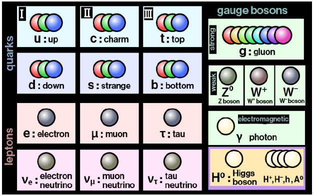
California Institute of Technology, Pasadena, California, USA

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 (Pauling-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.

May 13, 1965
BELL TELEPHONE LABORATORIES, INC
CRAWFORD HILL, HOLMDEL, NEW JERSEY

A. A. PENZIAS
R. W. WILSON

physicstoday

The early universe

Edward R. Harrison

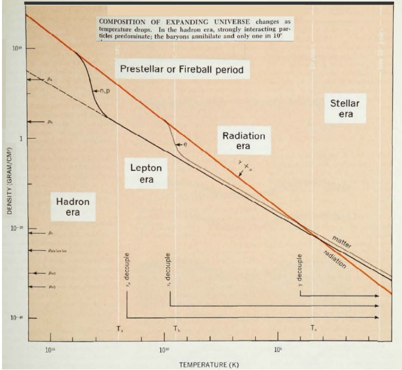
June 1968, page 31

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

G. Gamov GWU prediction
1966-1968: Hot Big-Bang
⇒ conventional wisdom



Hagedorn Temperature October 1964 in press:
Hagedorn Spectrum January 1965 ⇒ March 1966

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

STATISTICAL THERMODYNAMICS OF STRONG INTERACTIONS AT HIGH ENERGIES

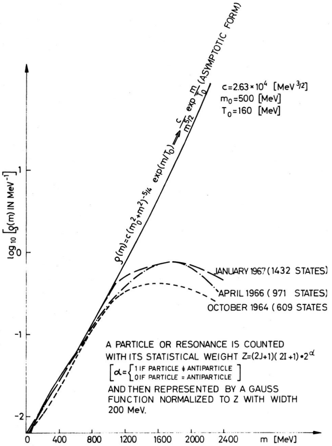
R. Hagedorn
CERN - Geneva

A B S T R A C T

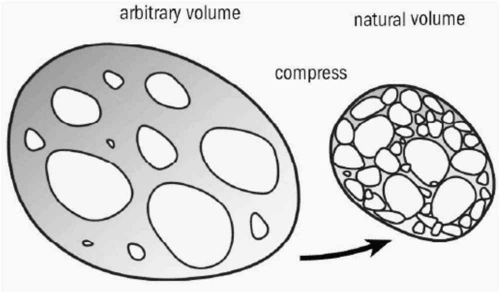
In this statistical-thermodynamical approach to strong interactions at high energies it is assumed that higher and higher resonances of strongly interacting particles occur and take part in the thermodynamics as if they were particles. For $m \to \infty$ these objects are themselves very similar to those 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:

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

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.



What is the Statistical Bootstrap Model (SBM)?



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

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

Exponential Mass Spectrum
We search and discover new particle checking this extreme idea

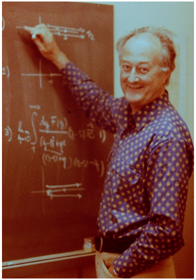
by 1967 – Hagedorn’s SBM: Statistical Bootstrap Model ‘the’ initial singular Hot Big-Bang theory

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.*

By 1980: SBM ⇒ Quark-Gluon Plasma
HI collisions+strangeness

JR & Michael Danos of NIST

JR & Rolf Hagedorn of CERN

Volume 97B, number 2 PHYSICS LETTERS 1 December 1980

THE IMPORTANCE OF THE REACTION VOLUME IN HADRONIC COLLISIONS

Johann RAFELSKI [1,2]
Institut für Theoretische Physik der Universität, D-6000 Frankfurt/Main, West Germany

and

Michael DANOS
National Bureau of Standards, Washington, DC 20234, USA

Received 10 October 1980

The pair production in the thermodynamic model is shown to depend sensitively on the (hadronic) reaction volume. Strangeness production in nucleus–nucleus collisions is treated as an example.

We consider particle production in the frame of the thermodynamic description [1] and explore the physical consequences arising from the conservation of quantum numbers which are conserved exactly during the strong interaction. An example treated here is the direct and associated production of strange particles.

The motivation for this study is the recent interest in high energy nucleus–nucleus (N–N) collisions. The main difference from the p–p scattering arises from the possibility of large reaction volumina. We will show that particle multiplicities can depend sensitively on the size of the reaction volume. Specifically, the production of heavy flavors (strangeness, etc.) is significantly enhanced.

[1] Guestworker, National Bureau of Standards.
[2] Supported in part by Deutsche Forschungsgemeinschaft.

PLB **97** pp.279-282 (1980)

FROM HADRON GAS TO QUARK MATTER II *)

J. Rafelski
Institut für Theoretische Physik
der Universität Frankfurt

and

R. Hagedorn
CERN--Geneva

Ref.TH.2969-CERN
13 October 1980

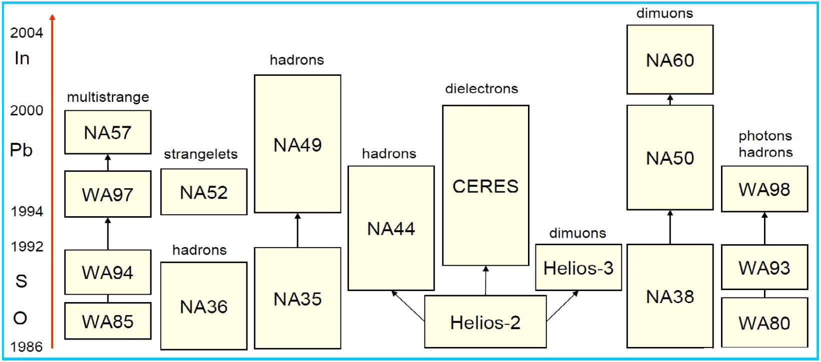
We describe a quark-gluon plasma coincident with the bootstrap critical curve found in the first lecture. We therefore argue that these possibly coinciding critical curves separate two phases in which strongly interacting matter can exist: a hadronic phase and a quark-gluon plasma phase. There is a finite region of coexistence between these two phases, which is determined by the usual Maxwell construction. Having thus joined the two models along their possibly common critical curves, we try to confront our model with experiments on relativistic heavy ion collisions. A signature of the quark-gluon phase surviving hadronization is suggested.

*) Invited lecture presented by J.R. at the "International Symposium on Statistical Mechanics of Quarks and Hadrons" University of Bielefeld, Germany, August 1980.

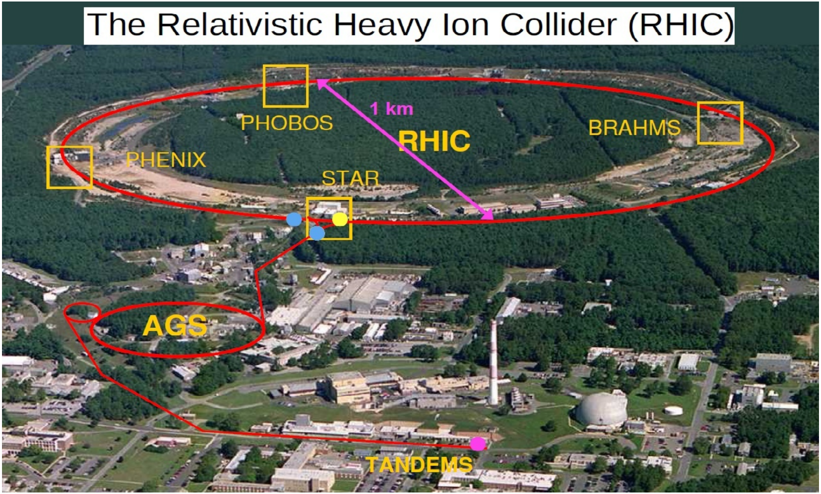
Research time-line: Quarks → QGP formation in RHICollision

- Cold quark matter in diverse formats from day 1: 1965
  D.D. Ivanenko and D.F. Kurdgelaidze, *Astrophysics* **1**, 147 (1965)
  Hypothesis concerning quark stars
- Interacting QCD quark-plasma: 1974
  P. Carruthers, *Collect. Phenomena* **1**, 147 (1974)
  Quarkium: a bizarre Fermi liquid
- Formation of quark matter in RHI collisions: 1978
  conference talks by Rafelski-Hagedorn (CERN)
  unpublished document (MIT web page) Chapline-Kerman
- Hot interacting QCD QGP: 1979 (first complete eval!)
  J. Kapusta, *Nucl. Phys. B* **148**, 461 (1979)*QCD at high temperature*
- Formation of QGP in RHI collisions 1979-80
  CERN Theory Division talks etc Hagedorn, Kapusta, Rafelski, Shuryak
- Experimental signature:
  Strangeness and Strange antibaryons 1980
  Rafelski (with Danos, Hagedorn, Koch (grad student), Müller
- Statistical materialization model (SHM) of QGP: 1982
  Rafelski (with Hagedorn, Koch(grad student), Müller

CERN RHI experimental SPS program is born 1980-86



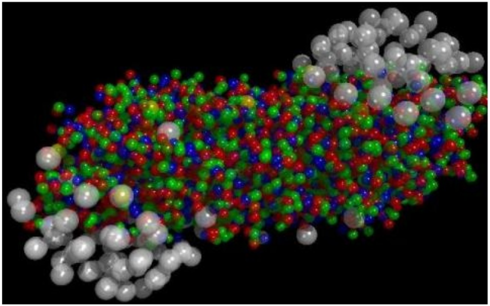
A new ‘large’collider is build at BNL: 1984-2001/operating today



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.

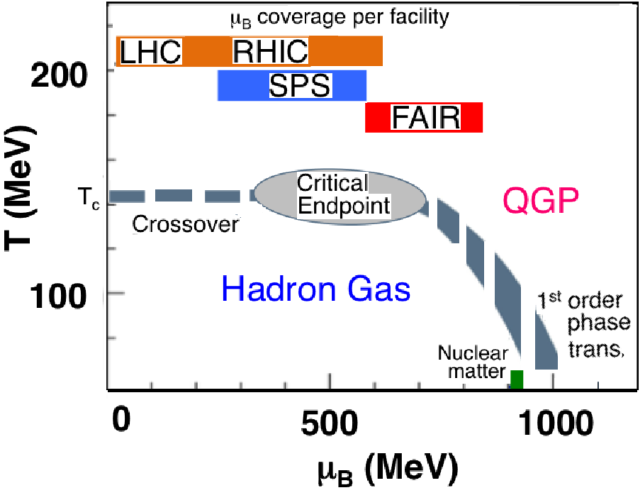
Preeminent signature: Strange antibaryon enhancement

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

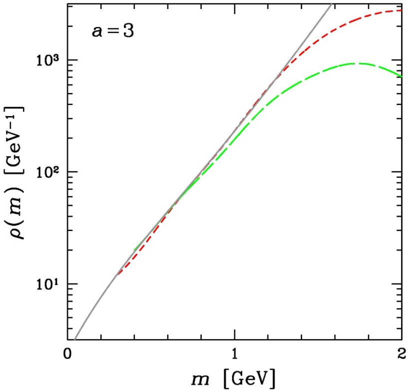
9AM, 18 April 2005; US – RHIC announces QGP Press conference APS Spring Meeting

Preeminent property: non-viscous flow

Current interest: Exploration of the QGP phase diagram



Current interest: Exploration of exponential mass spectrum

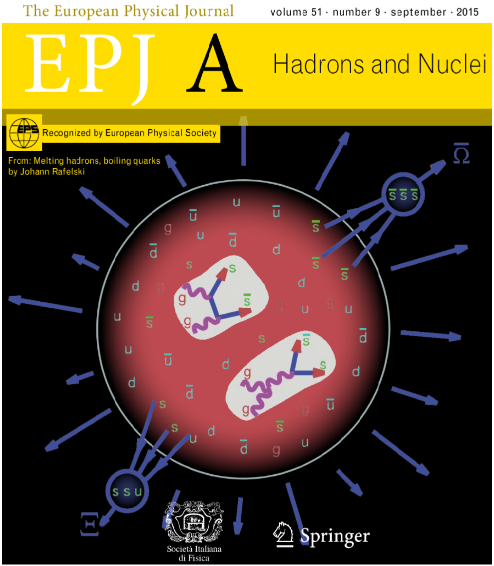


Slope for prescribed pre-exponential shape is the Hagedorn Temperature: another way to determine critical properties of deconfinement phase change

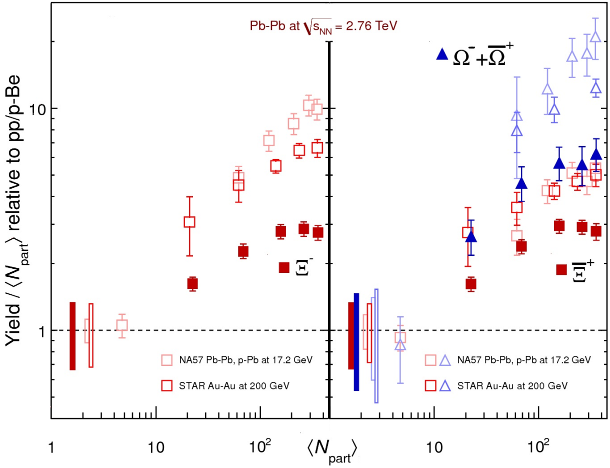
My expertise:

Cooking strange quarks $\longrightarrow$ strange antibaryons

APS car sticker from period



Prediction: 1980-86 confirmed by experimental results: Particle yields=integrated spectra

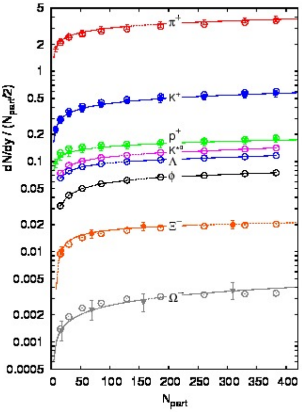


Statistical Hadronization Model Interpretation (SHM)

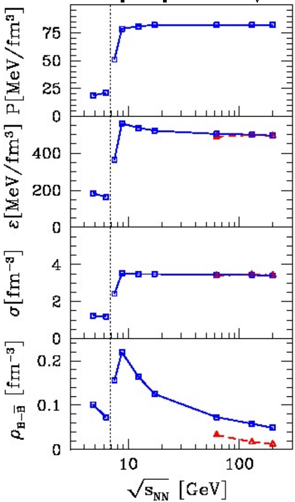
equal hadron production strength

yield depending on available phase space

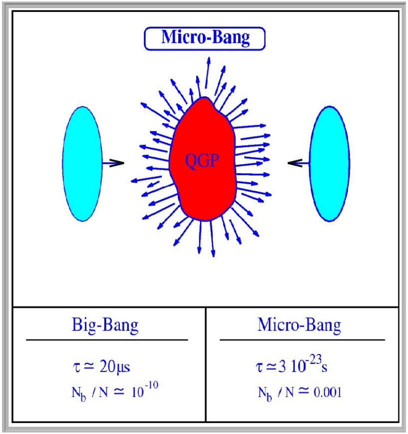
Example data from LHC⇓



Bulk properties⇓



Relativistic Heavy Ion Collisions and the Big-Bang



- 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

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).

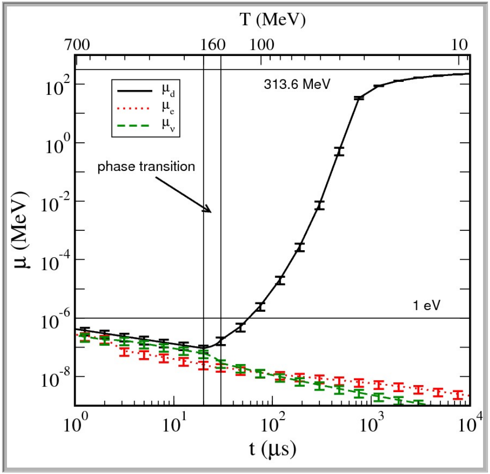
Equilibrium abundance of π^0 assures equilibrium of charged pions due to charge exchange reactions; heavier mesons and thus nucleons, and nucleon resonances follow:

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

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

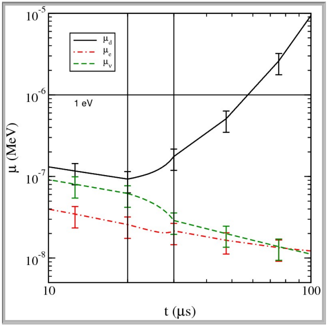
Chemical Potential in the Universe



M. Fromerth and JR astro-ph/0211346

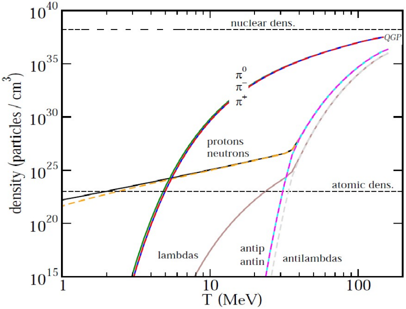
Minimum:

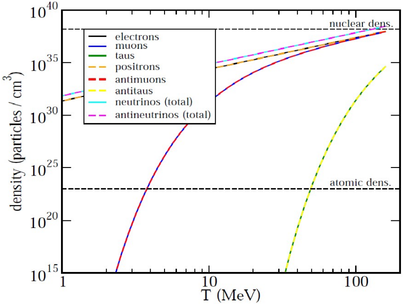
$\mu_B = 0.33^{+0.11}_{-0.08}$eV



$\Longrightarrow$ μ_B defines remainder of matter after annihilation

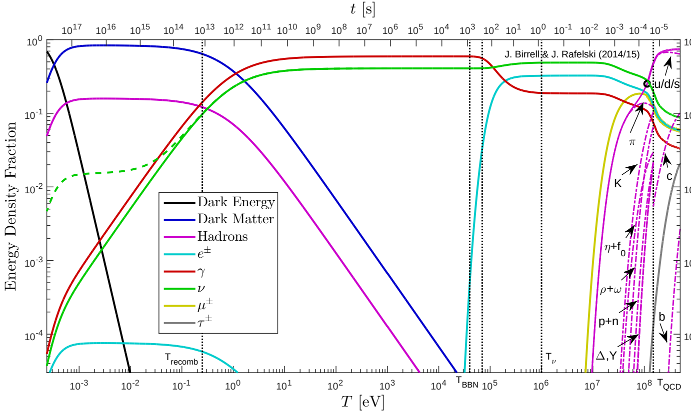
Particle Composition after QGP Hadronization





$\Longrightarrow$ 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

The Universe Composition Changes



dark energy matter radiation ν, γ leptons hadrons

$\Longrightarrow$ Different dominance eras

The contents of the Universe today

1. All visible matter
2. Free-streaming matter
   particles that do not interact – have ‘frozen’ out:
   - dark matter:from way before QGP hadronization
   - massless dark matter: darkness: maybe needed
   - neutrinos: since $T = 1$–3 MeV
   - photons: since $T = 0.25$eV
3. Dark energy = vacuum energy

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 $m \rightarrow mT(t)/T_k$ *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).*

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

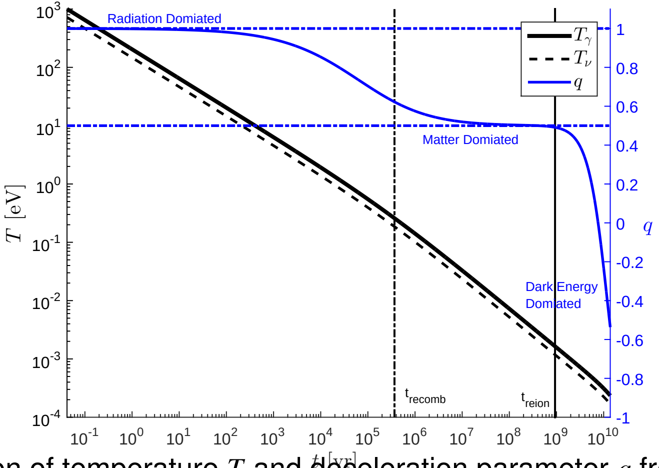
Evolution Eras and Deceleration Parameter q

Using Einsteins equations exact expression in terms of energy, pressure content (a is the scale of the Universe, flat $k = 0$ Universe favored)

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

- 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(!)

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, hyperons
- 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

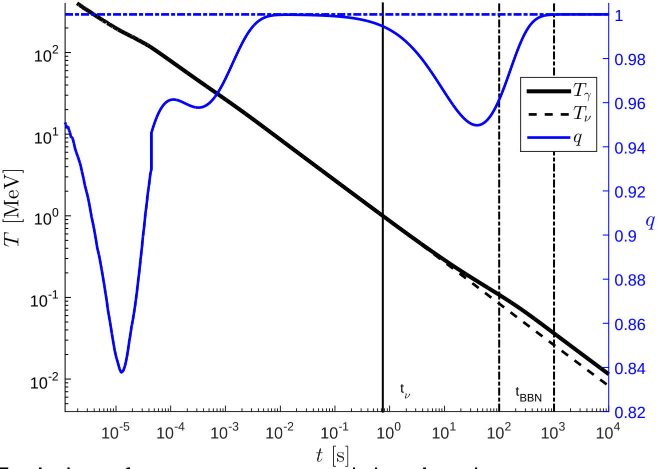


Figure: Evolution of temperature T and deceleration parameter q from QGP era until near BBN.

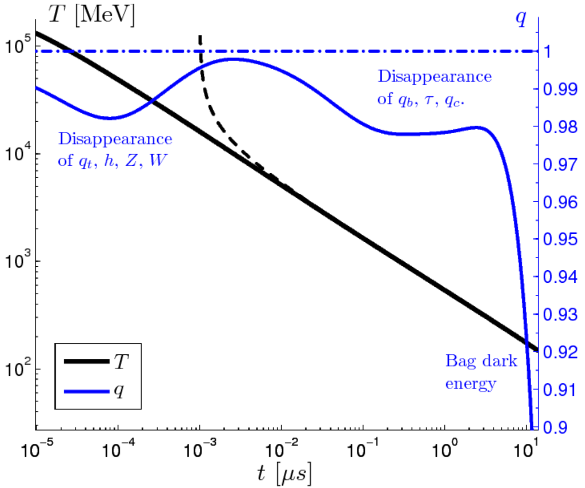


Figure: Evolution of temperature T and deceleration parameter q from Electro-Weak symmetric era to near QGP hadronization.

Summary

- 50 years ago particle production in pp reactions prompted introduction of Hagedorn Temperature T_{H}; soon after recognized as the critical temperature at which matter surrounding us dissolves into primordial new phase of matter made of quarks and gluons – QGP.
- 35 years ago we realized the opportunity to recreate a new phase of matter smashing heaviest nuclei
- We developed laboratory observables of this quark-gluon phase of matter: cooking strange quark flavor.
- 15 years ago we witnessed two international Laboratories announcing the discovery of QGP leading to models of the properties of the baby Universe 10 ns – 18μs.
- Today: We explore the phase diagram of QGP; we describe the evolution of the Quark-Universe across the neutrino desert into the era of Big-Bang nucleosynthesis (BBN) and on to CMB freeze-out