QGP in the Universe and in the Laboratory

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 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, hadronic matter – QGP theory
2. 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
Hagedorn and the Universe

QGP Discovery

QGP in the Universe

Particles in the Universe

FRW Cosmology and Λ-CDM

View

Hagedorn Temperature October 1964

Hagedorn Spectrum January 1965 ⇒ March 1966

Johann Rafelski, May 11, 2016, Seattle

QGP Universe 4/46
SBM only model providing ‘the’ initial singular condition
1967 many regard SBM as the Hot Big-Bang theory

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 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.

$$\tau(m^2)dm^2 = \rho(m)dm, \quad \rho(m) \propto m^{-\alpha}\exp(m/T_H).$$
By 1980: SBM ⇒ Quark-Gluon Plasma
HI collisions+strangeness

The importance of the reaction volume in hadronic collisions

Joachim 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 13 October 1980

The pair production in the thermodynamic model is shown to depend sensitively on the hadronic reaction volume. Strangeness production in n-d sector reactions 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 volumes. 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.

PLB 97 pp.279-282 (1980)
Birth of QGP/RHI formation: CERN theory division 1977-80

- **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**
  *Quarkium: a bizarre Fermi liquid*

- **Formation of quark matter in RHI collisions: 1978**
  conference talks by Rafelski-Hagedorn
  unpublished document (MIT web page) Chapline-Kerman

- **Hot interacting QCD QGP: 1979 (without errors!)**
  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 help of Danos, Hagedorn, Koch (grad student), Muller

- **Statistical materialization model (SHM) of QGP: 1982**
  Rafelski (with help of Hagedorn, Koch(grad student), Muller
and Antiproton Annihilation
Hotspot in a Nucleus $\Rightarrow$ QGP Formation

QUARK–GLUON PLASMA IN 4 GeV/c ANTIPROTON ANNIHILATIONS ON NUCLEI

Johann RAFELSKI

Department of Physics, University of Arizona, Tucson, AZ 85721, USA

Received 8 February 1988, revised manuscript received 19 April 1988

Recent data on strange particle production in 4 GeV/c antiproton annihilations on Ta can be successfully interpreted if quark–gluon plasma formation is assumed along with a simple reaction model in which antiprotons deposit energy in the forward cone of nuclear matter within the target nucleus. The observed spectra and total abundances of lambdas and kaons are consistent with the hypothesis that (super cooled) quark matter phase has been formed at a rather modest temperature $T \leq 60$ MeV. The spectra can then be successfully interpreted both with reference to their form and relative abundance.

In the annihilation reaction of antiprotons on nuclei it is possible to deposit in the target nucleus most of the annihilation energy. In such a possibly rare reaction very excited forms of nuclear matter may be created [1,2] #1 We will here present an interpretation of the strange particle production experiment [3] in which 4 GeV/c antiproton-annihilation on heavy nuclei (Ta) was studied. It will be shown that an understanding of the experimental results can be arrived at with a great economy of effort employing as reaction mechanism the excitation of the quark matter (quark–gluon plasma QGP) state of nuclear matter [4]. It should be noted that previous attempts to describe these data in terms of individual hadronic reactions have not been successful [5].

© Elsevier Science Publishers B V 371
**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.
Cooking strange quarks $\rightarrow$ strange antibaryons

APS sticker from period

PHYSICISTS have STRANGE QUARKS
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

\[ \rho_{H^{-}} \text{ [fm}^{-3}\text{]} \]

Bulk properties
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 property: non-viscous flow
LHC-Alice: Exploration of QGP

The objective is to understand the properties of the quark-gluon plasma, to write a few pages on the history of our universe.

Wow! Then you will become rich and famous!!

Oh, I doubt it! We are just doing what you have done by following the rabbit... satisfying human curiosity... From our results, we can learn for example how the matter of the early universe evolved.

‘We’? But who is ‘we’?

We are about 1000 researchers, engineers, technicians and students from all over the world. For years, we have been working hard to design and build the ALICE experiment. This is an exciting period; but even more exciting will be when we cook the soup... speaking of soup, would you like to join our party? I can introduce you to my colleagues.
QGP in Universe and Laboratory

“Scientists hope these models will answer some pressing questions about dark matter, dark energy, and the overall structure of the cosmos.”
Experiments Probe the Universe

Visible Matter Density [g cm⁻³]

- LHC
- RHIC
- SPS
- quarks combine
- antimatter disappears
- neutrinos decouple

- nuclear reactions: light nuclei formed
- atoms form
- photons decouple
- era of galaxies and stars

Time [s]:
- 10⁻¹²
- 10⁻⁵
- 1
- 10⁵
- 10¹²
- 10¹⁵
- 10¹⁸

Temperature [K]:
- 10⁴
- 10⁷
- 10¹⁶

Particle energy:
- 1 PeV
- 1 GeV
- 1 MeV
- 1 keV
- 1 eV

Johann Rafelski, May 11, 2016, Seattle
The Universe Composition Changes

J. Birrell & J. Rafelski (2014/15)

dark energy matter radiation $\nu, \gamma$ leptons hadrons

$\Rightarrow$ Different dominance eras

Johann Rafelski, May 11, 2016, Seattle  QGP Universe  19/46
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

⇒ Theory connects RHI collision experiments to Universe

<table>
<thead>
<tr>
<th>Big-Bang</th>
<th>Alice Micro-Bang</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \approx 20\mu s$</td>
<td>$\tau \approx 3 \times 10^{-23} s$</td>
</tr>
<tr>
<td>$N_b / N \approx 10^{-10}$</td>
<td>$N_b / N \approx 0.001$</td>
</tr>
</tbody>
</table>
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 \( \pi^0 \) 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 \( \pi^0 \) remains always in chemical equilibrium All charged leptons always in chemical equilibrium – with photons Neutrinos freeze-out (like photons later) at \( T = 0 \) MeV
Particle Content and Chemical Potentials

Chemical potentials control particle/antiparticle abundances:

\[ \frac{f_p}{a} = \frac{1}{e^{\beta(\varepsilon \pm \mu)} + 1}, \quad \varepsilon = \sqrt{p^2 + m^2} \]

- **Quark side:** $d \leftrightarrow s \leftrightarrow b_{\text{bottom}}$ oscillation means $\mu_d = \mu_s = \mu_{\text{bottom}}$ 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. $\Sigma^0 (uds)$ has chemical potential $\mu_{\Sigma^0} = \mu_u + \mu_d + \mu_s$. The baryochemical potential $\mu_B$ 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 $\mu_B$. 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 $4.5 \times 10^{10}$
Chemical Potential in the Universe

Minimum:
\[ \mu_B = 0.33^{+0.11}_{-0.08} \text{ eV} \]

\[ \mu_B \] defines remainder of matter after annihilation
Particle Composition after QGP Hadronization

\[ \rightarrow \text{Antimatter annihilates to below matter abundance before } T = 30 \text{ MeV, universe dominated by photons, neutrinos, leptons for } T < 30 \text{ MeV} \]

Next: distribution normalized to unity
The effective number of entropy degrees of freedom, $g^S_*$, defined by

$$S = \frac{2\pi^2}{45} g^S_* T^3 \gamma a^3.$$ 

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, $f^\pm_i$ 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].

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

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

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 \( T^\mu_\nu = \text{diag}(\rho, -P, -P, -P) \), \( R = g_{\mu\nu}R^{\mu\nu} \), 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** \( g^{\mu\nu} \rightarrow R^{\mu\nu} \)

Flat \((k = 0)\) metric favored in the \( \Lambda \)CDM 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 $\Lambda$-term) into the energy $\rho$ and pressure $P$

$$\rho \rightarrow \rho + \rho_\Lambda, \quad P \rightarrow P + P_\Lambda$$

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

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

The pressure $P_\Lambda$ has a) opposite sign from all matter contributions and b) $\rho_\Lambda/P_\Lambda = -1$. The independent measurement of $\rho$ 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: $\rho$ 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 $T = \text{a few MeV}$
   - photons: since $T = 0.25\text{eV}$

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)

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

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

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).


Evolution Eras and Deceleration Parameter $q$

Using Einstein's equations exact expression in terms of energy, pressure content

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

- **Radiation dominated universe:** $P = \rho/3 \implies q = 1$.
- **Matter dominated universe:** $P \ll \rho \implies q = 1/2$.
- **Dark energy ($\Lambda$) 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 $T \approx 150\text{MeV}$. 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 $T = 115\text{MeV}$.
- 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

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 $m > \mathcal{O}(\text{eV})$ sterile $\nu$ 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

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

Jeremiah Birrell, Johann Rafelski

Abstract

The effective number of neutrinos, $\nu_{\text{eff}}$, 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 $\nu_{\text{eff}}$ 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

→ 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 $T_H$; 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.
- Laboratory discovery of QGP leading to models of properties of the Universe below the age of 18µs.
- Universe expansion before CMB freeze-out a rich domain bridging QGP era to BBN and BBN to CMB
- Speed of Universe expansion expressed by unseen ‘neutrino’ effective degrees of freedom offer a connection between observational cosmology and hadronization stage of the Quark Universe: Released Darkness could be a new component pushing the Universe apart. Experimental precision to improve and constrain the theoretical discussion in next generation CMB experiments.
References


