QGP in the Universe and in the Laboratory

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

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

From a combination of the above, we compute the remaining unaccounted-for antenna temperature to be $3.5^\circ \pm 1.0^\circ$ 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 $16^\circ$ 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 $\alpha^2$. 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

The early universe
Edward H. 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.

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1966-1968: Hot Big-Bang ➞ conventional wisdom
Hagedorn Temperature October 1964
Hagedorn Spectrum January 1965

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 elegant: "We describe by thermodynamics fireballs 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:

\[
\rho(m) \sim \text{const.} \frac{m^3}{\pi^2} \exp\left(-\frac{m}{T_0}\right).
\]

\( T_0 \) 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 Bessel-Boltzmann law - govern the transversal momentum distribution in all high energy collisions of nucleons (including e.g., from factors, etc.). There is experimental evidence for that, and then \( T_0 \) is about 198 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

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.

Johann Rafelski, December 4, 2015, AdW/SMI Vienna
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.

\[ \tau(m^2)dm^2 \equiv \rho(m)dm \quad \rho(m) \propto m^{-a} \exp(m/T_H). \]
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 2003 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 Biro, Igor Dremin, Torleif Ericsson, Marek Gaździcki, Mark Greenstein, Hans Gabathuler, Maurice Jacob, István Monnay, Berndt Müller, Grazyna Odrzyw, Emanuele Quevra, Krzysztof Redlich, Hélmut Sautz, Luigi Scorzetti, Ludwik Turko, and Gabriele Veneziano.

The second and third parts trace 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.
Antiproton Annihilation: Several GeV Hotspot in a Nucleus: QGP Formation

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 $T \lesssim 60$ 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]. 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].
Forward 50 Years to the Universe 2015

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

\[ t \, [s] \]

\[ T \, [\text{eV}] \]

- Dark Energy
- Dark Matter
- Hadrons
- \( e^\pm \)
- \( \gamma \)
- \( \nu \)
- \( \mu^\pm \)
- \( \tau^\pm \)

\( T_{\text{recomb}} \), \( T_{\nu} \), \( T_{\text{BBN}} \), \( T_{\text{QCD}} \)

\[ 10^{-3} \, 10^{-2} \, 10^{-1} \, 10^0 \, 10^1 \, 10^2 \, 10^3 \, 10^4 \, 10^5 \]

\[ 10^{-4} \, 10^{-3} \, 10^{-2} \, 10^{-1} \]

\[ 10^0 \, 10^1 \, 10^2 \, 10^3 \, 10^4 \, 10^5 \]

\[ \pi, K, p+n, \Delta, Y, \eta^+, c, \rho+\omega, \]

\[ \nu, \gamma, \text{leptons, hadrons} \]

\[ \Rightarrow \ \text{Different dominance eras} \]
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

⇒ Theory connects RHI collision experiments to Universe
Boiling quarks

THE ROOTS:

- Cold quark matter in diverse formats from day 1: 1965 →
- Hot interacting QCD quark-gluon plasma: 1979 →
- Formation of QGP in relativistic nuclear (heavy ion collisions) 1979 →
- Experimental signatures: Strange antibaryons 1980 →
- Materialization of QGP: 1982 →
  Statistical Hadronization Model (SHM)
Cooking strange quarks → strange antibaryons

APS sticker from period

PHYSICISTS have STRANGE QUARKS

Johann Rafelski, December 4, 2015, AdW/SMI Vienna

QGP Universe 16/46
**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

Johann Rafelski, December 4, 2015, AdW/SMI Vienna QGP Universe 19/46
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.
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 \( T = \mathcal{O} \text{MeV} \)
Particle Content and Chemical Potentials

Chemical potentials control particle/antiparticle abundances:

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

- **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. \( d \rightarrow u + e^- + \bar{\nu}_e \) 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: $\mu_B = 0.33^{+0.11}_{-0.08}$ eV

$\mu_B$ defines remainder of matter after annihilation
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
Particles in the Universe=Degrees of Freedom

The effective number of entropy degrees of freedom, $g^S_*$, defined by

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

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].

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

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

Solving both these equations for $8\pi G_N/3 \rightarrow$ 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 $T = a$ 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)

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

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

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

- **Radiation dominated universe:** $P = \rho/3 \Rightarrow q = 1$.

- **Matter dominated universe:** $P \ll \rho \Rightarrow q = 1/2$.

- **Dark energy ($\Lambda$) dominated universe:** $P = -\rho \Rightarrow q = -1$.

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 $T \approx 150\text{MeV}$. 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, $n_{\text{eff}}$, 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 $n_{\text{eff}}$ 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

Johann Rafelski, December 4, 2015, AdW/SMI Vienna
**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: $= \text{NA61 experiment..}$

Johann Rafelski, December 4, 2015, AdW/SMI Vienna  QGP Universe  44/46
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 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 18 $\mu$s.

- 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.