How Energy Becomes Matter: $E \Rightarrow mc^2$: Probing QGP with Strangeness

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Seminar at IFJ, Kraków July 3, 2018

How is matter produced in the form we are familiar with? This question and the answer were formulated more than half a century ago when Big-Bang model became the new paradigm. The entire relativistic heavy ion collision research program was build to experimentally confirm theory. ALICE is the experiment at the CERN LHC build predominantly to study how energy turns into matter in ultra relativistic nuclear (AA) collisions. In contemporary experiments key information is derived in study of multistrange hadrons which carry information both, about the process of matter production (hadronization) $E \Rightarrow mc^2$*, as well as about earlier stages when entropy and strangeness are produced. Very recent results show that even a relatively small pp and pA collisions at the LHC energy-scale are creating the new quark-gluon plasma (QGP) phase of matter.*

Background: 1992 NATO School Il Ciocco Poster

1965-7 – Hagedorn’s singular Statistical Bootstrap

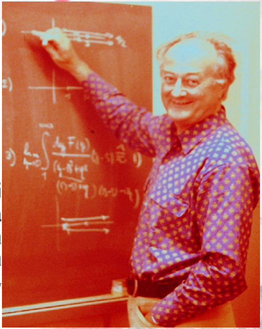
accepted as ‘the’ initial singular hot Big-Bang theory

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

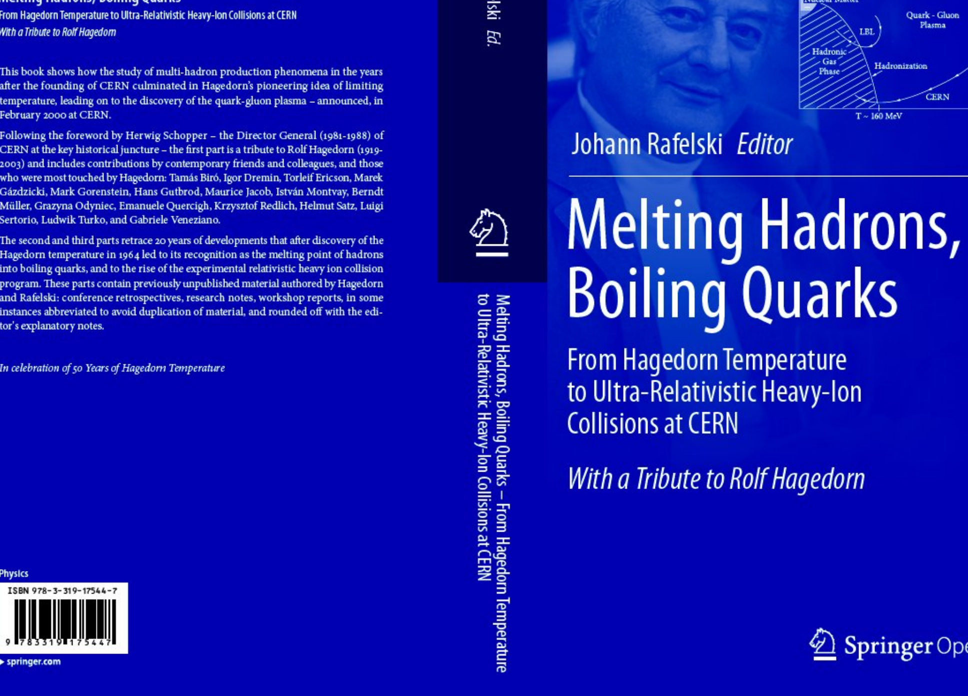
Siedende Urmaterie

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. . . We would have never understood these things if we had not advanced on Earth the fields of atomic and nuclear physics. To understand the great, we must descend into the very small.*


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
lski Ed.
Melting Hadrons, Boiling Quarks – From Hagedorn Temperature to Ultra-Relativistic Heavy-Ion Collisions at CERN
Quark - Gluon Plasma
LBL
Hadronic Gas Phase
Hadronization
CERN
T ~ 160 MeV
Johann Rafelski Editor
Melting Hadrons, Boiling Quarks
From Hagedorn Temperature to Ultra-Relativistic Heavy-Ion Collisions at CERN
With a Tribute to Rolf Hagedorn
Springer Ope

1966-1968: SBM Hot Big-Bang via Hagedorn becomes conventional wisdom

1965 (Bootstrap year): Penzias and Wilson discover CMB

1966-1968: Hot Big-Bang becoming conventional wisdom

physicstoday

The early universe

Edward R. Harrison

June 1968, page 31

IN RECENT YEARS the active frontiers of cosmology have widened stimulated by discovery of the universal black-body radiation 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 erasto its present state of comparative darkness and emptiness.

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

nature

article

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

Comments on the Big-bang

F. 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?

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1. Harrison, E. R., *Nature*, **215**, 151 (1967).

14. Hagedorn, R., *Suppl. Nuovo Cim.*, **3**, 147 (1965); *ibid.*, **6**, 311 (1968); *Nuovo Cim.*, **52A**, 1336 (1967); *ibid.*, **56A**, 1027 (1968); *Astron. Astrophys.*, **5**, 184 (1970).

15. Hagedorn, R., and Ranft, J., *Suppl. Nuovo Cimento*, **6**, 169 (1968).

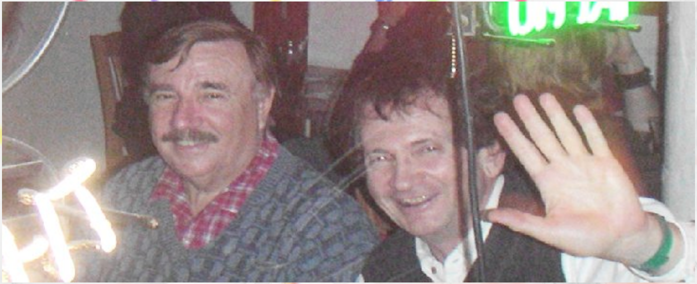
"We did NOT know what was there at the 'Beginning'

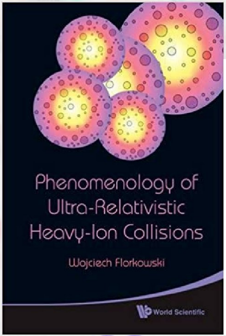
how matter was created."

I will (mostly) talk about these itmes

- 50+ years ago particle production in pp reactions prompted introduction of Hagedorn Temperature $T_{\rm H}$ along with singular energy density – both linked to the Big-Bang.
- By 1980 $T_{\rm H}$ reinterpreted as the critical temperature at which vacuum 'melts', matter surrounding us dissolves; This prompts CERN and BNL experimental relativistic heavy ion collision program to recreate quark-gluon-plasma (QGP) pre-matter in laboratory.
- We developed laboratory observables of this quark-gluon phase of matter: cooking strange quark flavor.
- 18-13 years ago we witnessed both CERN and BNL announcing the discovery of QGP prompting models of the properties of the baby Universe 10 ns – 18μs.
- We develope detailed understanding how matter in Universe emerges from energy $E \Rightarrow mc^2$: statistical hadronization model (SHM).
- Understanding of early Universe allows consistency studies: we set limits on variation of natural constants in early Universe, constrain any new radiance (darkness); characterize cosmic microwave neutrinos. Interface to vacuum bi-stability issue.

For many details I recommend reading the text books





Hadrons and Quark–Gluon Plasma

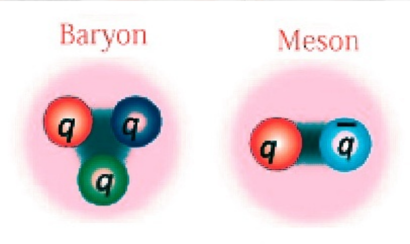
Series: Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology (No. 18)

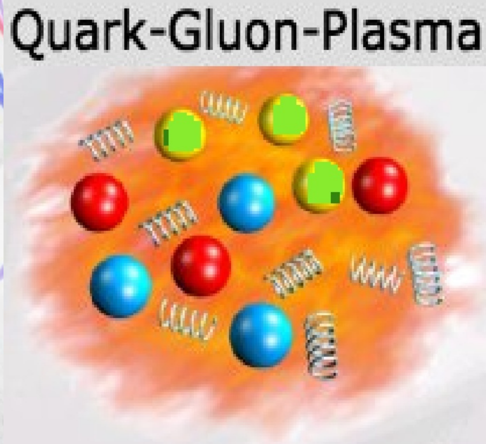
Jean Letessier
Université de Paris VII (Denis Diderot)

Johann Rafelski
University of Arizona

Hardback (ISBN-13: 9780521385367 | ISBN-10: 0521385369) Also available in Paperback | Adobe eBook

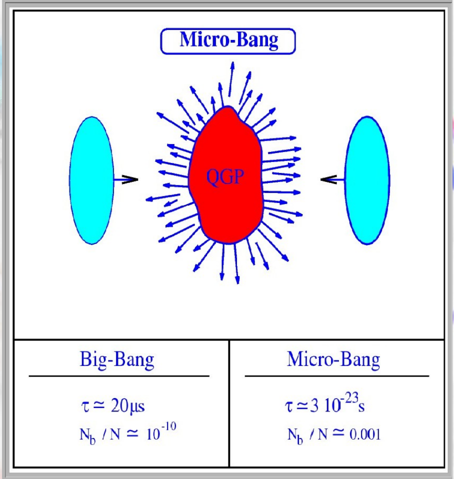
Quarks make pions (mesons); squeeze many together





In the early Universe the building blocks of baryons and mesons were liberated: Universe was made from a new type of matter: QGP

Can we recreate Big-Bang in lab?



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

First question; is there really a fireball of matter?
Two extreme views on stopping in RHI collisions

Fly-through

PHYSICAL REVIEW D VOLUME 22, NUMBER 11 1 DECEMBER 1980

Central collisions between heavy nuclei at extremely high energies: The fragmentation region

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(Received 11 August 1980)

We discuss central collisions between heavy nuclei of equal baryon number at extremely high energies. We make a crude estimation of the energy deposited in the fragmentation regions of the nuclei. We argue that the fragmentation-region fragments thermalize, and two hot fireballs are formed. These fireballs would have rapidities close to the rapidities of the original nuclei. We discuss the possible formation of hot, dense quark plasmas in the fireballs.

The collisions of very-high-energy nuclei are likely to be the subject of intense experimental investigation in the next few years.

We shall discuss the theory of such collisions in this paper. We shall concentrate on describing central collisions between nuclei of equal baryon number.

The fragmentation regions of the nuclei represent an area of phase space where new phenomena might occur. "Fragmentation region" refers to the region of phase space of particles where the particles have longitudinal momentum close to that of the original nucleus projectile or target. In the fragmentation region, the nucleus fragments and inelastically produced particles might form a hot, dense fireball. We shall soon see that this forma-

full stopping

Volume 97B, number 1 PHYSICS LETTERS 17 November 1980

HOT HADRONIC MATTER AND NUCLEAR COLLISIONS ☆

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and

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Received 22 August 1980

we develop a description of hadronic matter with particular emphasis on hot nuclear matter as created in relativistic heavy ion collisions. We apply our theory to calculate temperatures and of hadronic fireballs.

Transparency ⇐Two opposite views⇒ SPS-RHIC large stopping

LHC a nice fireball in all cases

Citations favor wrong paper: 272 vs 239 today

My views about importance of RHI collisions & Quark Gluon Plasma?

1. RECREATE THE EARLY UNIVERSE IN LABORATORY
   Recreate and understand the high energy density conditions prevailing in the Universe when matter formed from elementary degrees of freedom (quarks, gluons) at about 20 μs after the Big-Bang.
2. PROBING OVER A 'LARGE' DISTANCE THE (DE)CONFINING QUANTUM VACUUM STRUCTURE
   The quantum vacuum, the present day relativistic æther, determines prevailing form of matter and laws of nature.
3. STUDY OF THE ORIGIN OF MATTER & OF MASS
   Matter and antimatter created when QGP 'hadronizes'. Mass of matter originates in the confining vacuum structure
4. PROBE ORIGIN OF FLAVOR
   Normal matter made of first flavor family $(d, u, e, [\nu_e])$. Strangeness-rich quark-gluon plasma the sole laboratory environment filled 'to the rim' with 2nd family matter $(s, c, [\mu, \nu_\mu]))$. and considerable abundance of b and even t.
5. PROBE STRONGEST FORCES IN THE UNIVERSE
   For a short time the relativistic approach and separation of large charges $Ze \leftrightarrow Ze$ generates EM fields 1000's time stronger than those in

I argued 1980-81 that anti-strangeness in QGP can be more abundant than anti-light quarks. Many experiments followed.

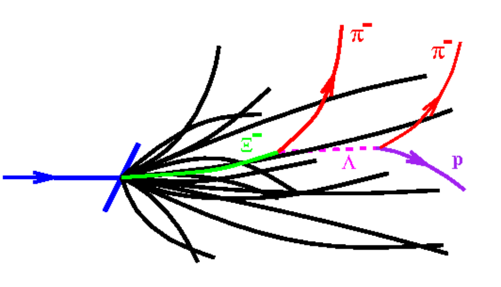
A: There are many strange particles allowing to study different physics questions $(q = u, d)$:

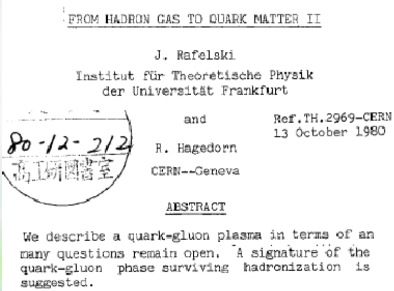
$$K(q\bar{s}),\quad \overline{K}(\bar{q}s),\quad K^*(890),\quad \Lambda(qqs),\quad \overline{\Lambda}(\bar{q}\bar{q}\bar{s}),\quad \Lambda(1520)$$

$$\phi(s\bar{s}),\quad \Xi(qss),\quad \overline{\Xi}(\bar{q}\bar{s}\bar{s}),\quad \Omega(sss),\quad \overline{\Omega}(\bar{s}\bar{s}\bar{s})$$

B: Production rates hence statistical significance is high.

C: Strange hadrons are subject to a self analyzing decay





FROM HADRON GAS TO QUARK MATTER II

J. Rafelski
Institut für Theoretische Physik
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CERN--Geneva

Ref.TH.2969-CERN
13 October 1980

ABSTRACT

We describe a quark-gluon plasma in terms of an many questions remain open. A signature of the quark-gluon phase surviving hadronization is suggested.

The idea of 1980 in detail:CERN-TH-2969 of October 1980; Published in “Statistical Mechanics of Quarks and Hadrons”, H. Satz, editor, Elsevier 1981; Also other conferences 1980 incl Quark Matter I

-17-

In order to observe properties of quark-gluon plasma we must design a thermometer, an isolated degree of freedom weakly coupled to the hadronic matter. Nature has, in principle (but not in praxis) provided several such thermometers: leptons and heavy flavours of quarks. We would like to point here to a particular phenomenon perhaps quite uniquely characteristic of quark matter; first we note that, at a given temperature, the quark-gluon plasma will contain an equal number of strange (s) quarks and antistrange ($\bar{s}$) quarks, naturally assuming that the hadronic collision time is much too short to allow for light flavour weak interaction conversion to strangeness. Thus, assuming equilibrium in the quark plasma, we find the density of the strange quarks to be (two spins and three colours):

$$\frac{s}{V} = \frac{\bar{s}}{V} = 6\int\frac{d^3p}{(2\pi)^3}\, e^{-\sqrt{p^2+m_s^2}/T} = 3\,\frac{T m_s^2}{\pi^2}\, K_2\!\left(\frac{m_s}{T}\right) \qquad (26)$$

(neglecting, for the time being, the perturbative corrections and, of course, ignoring weak decays). As the mass of the strange quarks, m_s, in the perturbative vacuum is believed to be of the order of 280-300 MeV, the assumption of equilibrium for $m_s/T \sim 2$ may indeed be correct. In Eq. (26) we were able to use the Boltzmann distribution again, as the density of strangeness is relatively low. Similarly, there is a certain light antiquark density ($\bar{q}$ stands for either $\bar{u}$ or $\bar{d}$):

$$\frac{\bar{q}}{V} \simeq 6\int\frac{d^3p}{(2\pi)^3}\, e^{-|p|/T-\mu_q/T} = e^{-\mu_q/T}\cdot T^3\,\frac{6}{\pi^2} \qquad (27)$$

-18-

where the quark chemical potential is, as given by Eq. (3), $\mu_q = \mu/3$. This exponent suppresses the $q\bar{q}$ pair production as only for energies higher than μ_q is there a large number of empty states available for the q.

What we intend to show is that there are many more $\bar{s}$ quarks than antiquarks of each light flavour. Indeed:

$$\frac{\bar{s}}{\bar{q}} = \frac{1}{2}\left(\frac{m_s}{T}\right)^2 K_2\!\left(\frac{m_s}{T}\right) e^{\mu/3T} \qquad (28)$$

The function $x^2K^2(x)$ is, for example, tabulated in Ref. 15). For $x = m_s/T$ between 1.5 and 2, it varies between 1.3 and 1. Thus, we almost always have more $\bar{s}$ than $\bar{q}$ quarks and, in many cases of interest, $\bar{s}/\bar{q} \sim 5$. As $\mu \to 0$ there are about as many $\bar{u}$ and $\bar{q}$ quarks as there are $\bar{s}$ quarks.

When the quark matter dissociates into hadrons, some of the numerous $\bar{s}$ may, instead of being bound in a $q\bar{s}$ Kaon, enter into a $(\bar{q}\bar{q}\bar{s})$ antibaryon and, in particular, a $\bar{\Lambda}$ or $\bar{\Sigma}^0$. The probability for this process seems to be comparable to the similar one for the production of antinucleons by the antiquarks present in the plasma. What is particularly noteworthy about the $\bar{s}$ carrying antibaryons is that they can only be produced in direct pair production reactions. Up to about $E_{k,lab}/A = 3.5$ GeV this process is strongly suppressed by the energy-momentum conservation and because for free p-p collisions the threshold is at about 7 GeV. We thus would like to argue that a study of the $\bar{\Lambda}$, $\bar{\Sigma}^0$ in nuclear collisions for $2 < E_{k,lab}/A < 4$ GeV could shed light on the early stages of the nuclear collisions in which quark matter may be formed.

Who says there is chemical equilibrium in QGP? (Biro-Zimanyi)

....till today we live with some consequences

Fulbright Flex researcher Johann Rafelski at Wigner Centre for Physics

Johann Rafelski from *The University of Arizona* in Tucson, USA, was awarded a Senior Flex Fulbright Fellowship to visit in Summer 2019 and 2020 the Wigner Research Centre for Physics in Budapest. Eugene Paul Wigner was a Hungarian-American theoretical physicist, engineer and mathematician who won Noble prize in 1963. The Wigner Institute is the largest Hungarian fundamental science research center where the research legacy of Prof. Wigner continues. Rafelski will be given the title "Distingusihed Wigner Professor" by this institute.

Rafelski's primary host is Prof. Tamás Biró, vice-director of the Institute for Particle and Nuclear Physics, incorporating half of the Wigner Centre. Prof. Rafelski is well known to the Hungarian Physics community, and this relation has roots that go back nearly 40 years, when the young Dr. Rafelski proposed "Strangeness Signature" of the primordial phase of matter, the quark-gluon plasma. At that time a bit younger graduate student Tamas Biro was charged by his supervisor Prof. Dr. Joseph Zimanyi to review Rafelski's ideas and to improve the mathematical-theoretical description. The effort of Biro and Zimanyi helped Rafelski to refine his proposal further which became one of the corner stones of the research field where, since then, a few thousand scientists perform experiments at largest particle colliders simulating the Big-Bang conditions in the laboratory.

A low level connection of Rafelski with Budapest continued for the following decades. For example after Rafelski started the new conference series "Strangeness in Quark Matter", within a few years in late '90s the meeting took place in Budapest. However, a direct collaborative research effort of Rafelski and Biro did not occur even though both work in parallel to this day in several research fields. This possibility has been opened now by the Fulbright Flex Program.

Both researchers seen in the picture came to visit the Fulbright office in Budapest during a preparatory visit June 19, 2018 (Rafelski on right). They are looking forward to a fruitful and rewarding joint effort addressing the most intriguing current questions in the area of fundamental theoretical physics.

Instant success of strangeness signature proposal

CPOD, WROCLAW, June 2, 2016

First strangeness signature 1980: ratio of $\bar{s}/\bar{q}$ in $\overline{\Lambda}/\bar{p}$ triggers Marek's strange interest!

What we intend to show is that there are many more $\bar{s}$ quarks than antiquarks of each light flavour. Indeed:

$$\frac{\bar{s}}{\bar{q}} = \frac{1}{2}\left(\frac{m_s}{T}\right)^2 K_2\left(\frac{m_s}{T}\right) e^{\mu/3T} \qquad (23)$$

The function $x^2K^2(x)$ is, for example, tabulated in Ref. 15). For $x = m_s/T$ between 1.5 and 2, it varies between 1.3 and 1. Thus, we almost always have more $\bar{s}$ than $\bar{q}$ quarks and, in many cases of interest, $\bar{s}/\bar{q} \sim 5$. As $\mu \to 0$ there are about as many $\bar{u}$ and $\bar{q}$ quarks as there are $\bar{s}$ quarks.

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In *Statistical mechanics of quarks and hadrons* proceedings Bielefeld, August 24-31, 1980

picked up by Marek in Dubna . . .

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Received by Publishing Department
on July, 20, 1983.

4

Anikina M. et al. E1-83-521

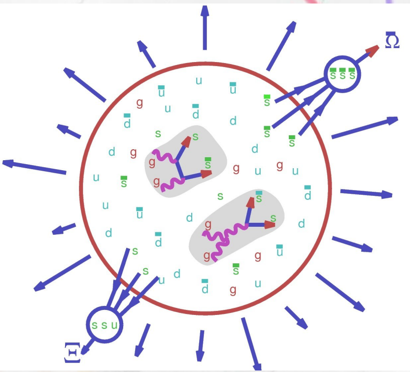
A Study of Λ-Production in Central Nucleus-Nucleus Interactions at a Momentum of 4.5 GeV/c Per Incident Nucleon

Transverse momenta and rapidities of Λ's produc
leus-nucleus collisions at 4.5 GeV/c per nucleon /CC ,
CZr , CPb , OPb / have been studied and compared with t
He-Li interactions at the same incident momentum. Pola
hyperons was found to be consistent /within the errors/
(αP_Λ -0.06 ±0.11) for 224 Λ's from central collis
of $\bar{\Lambda}/\Lambda$ production ratio was estimated to be less than
confidence level.
The analyzed experimental data were obtained usin
2 m streamer spectrometer SKM-200.

The investigation has been performed at the Labora
Energies, JINR.

Communication of the Joint Institute for Nuclear Resear

Strange hadrons from QGP: two-step formation mechanism

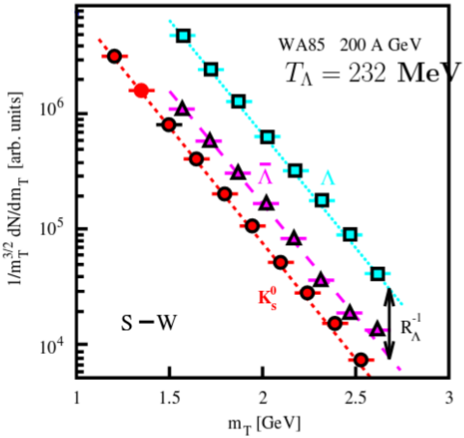


1. $GG \to s\bar{s}$ (thermal gluons collide)
   $GG \to c\bar{c}$ (initial parton collision)
   gluon dominated reactions
2. hadronization of pre-formed $s, \bar{s}, c, \bar{c}, b, \bar{b}$ quarks

Evaporation-recombination formation of complex rarely produced (multi)exotic flavor (anti)particles from QGP is signature of quark mobility thus of deconfinement. Enhancement of flavored (strange, charm,. . .) antibaryons progressing with 'exotic' flavor content. J. Rafelski, *Formation and Observables of the Quark-Gluon Plasma* Phys.Rept. **88** (1982) p331; P. Koch, B. Muller, and J. Rafelski; *Strangeness in Relativistic Heavy Ion Collisions*, Phys.Rept. **142** (1986) p167

Anticipated: Sudden hadronization of QGP
Proposed evidence: matter-antimatter symmetry

High $m_\perp$ slope universality



SUDDEN hadronization without rescattering.

Discovered in S-Pb collisions by WA85, very pronounced in Pb-Pb Interactions.

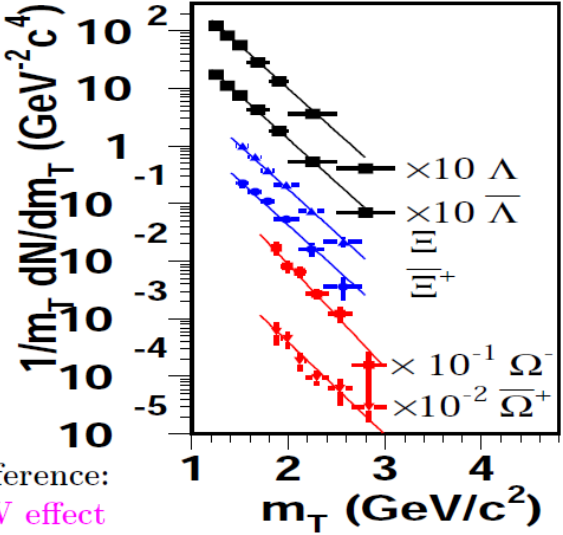
Emanuele Quercigh

Why is the slope of baryons and antibaryons the same?

Pb-Pb SPS collisions also show matter-antimatter symmetry

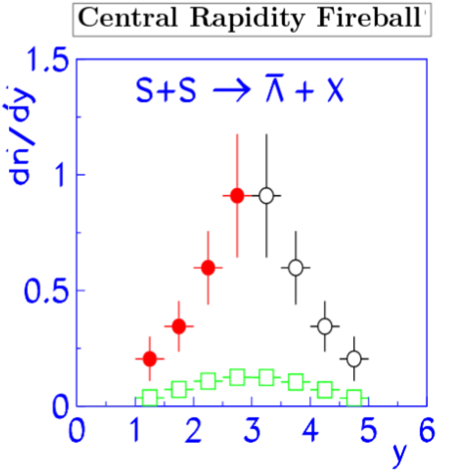
WA97	$T_\perp^{\mathrm{Pb}}$ [MeV]
T^{K^0}	230 ± 2
T^{Λ}	289 ± 3
$T^{\overline{\Lambda}}$	287 ± 4
T^{Ξ}	286 ± 9
$T^{\overline{\Xi}}$	284 ± 17
$T^{\Omega+\overline{\Omega}}$	251 ± 19

Λ within 1% of $\overline{\Lambda}$



Kaon – hyperon difference:
EXPLOSIVE FLOW effect

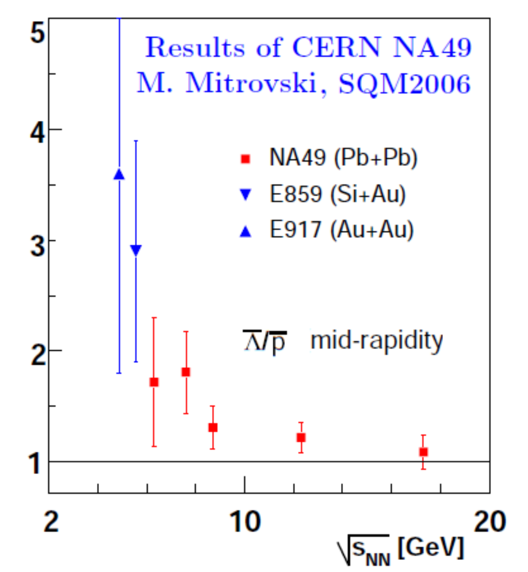
Anticipated: Central QGP fireball
Proposed evidence: (Strange)Antimatter

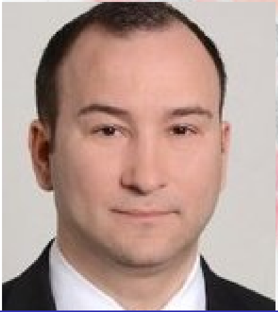


First antibaryon enhancement result, 1990-94, SPS-NA35II EXCESS $\bar{\Lambda}$ emitted from a central well localized source. Background (squares) from multiplicity scaled NN reactions. From Yiota Foka, PhD Thesis, Geneva University 1994.

Conclusion: by early 1990's we have convincing evidence of QGP formation at SPS energy heavy ion collisions in-

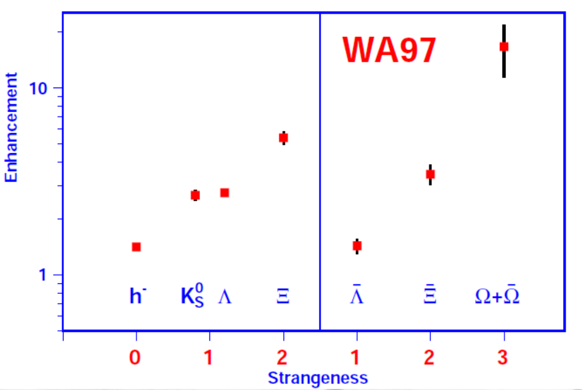
NA49 Pb-Pb SPS confirmation $\overline{\Lambda}/\bar{p} > 1$ (1980 prediction)





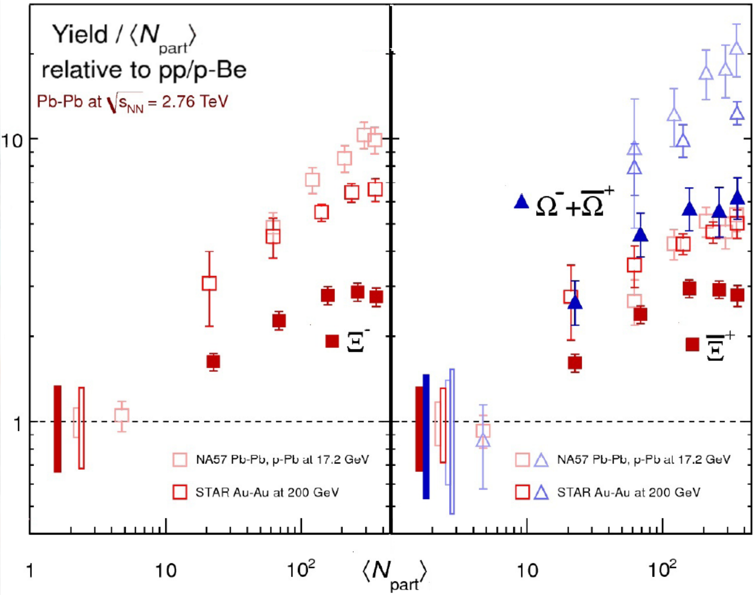
Predicted: Strange antibaryons enhanced

WA97 SPS Antihyperons: The largest observed QGP medium effect



Enhancement GROWS with a) strangeness b) antiquark content as we predicted. Enhancement with respect to yield in p–Be collisions, scaled up with the number of 'wounded' nucleons. Result → CERN QGP discovery announcement in 2000. All other CERN strangeness experimental results agree.

Today: Effect remains largest medium effect in RHI collisions

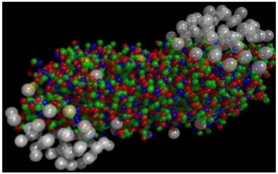


Reminder: When and how did we discover QGP?

CERN press office

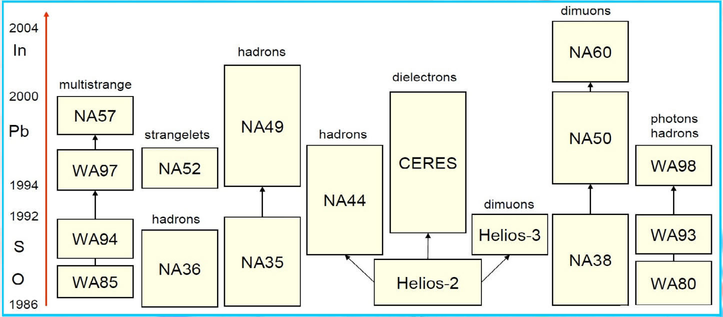
New State of Matter created at CERN

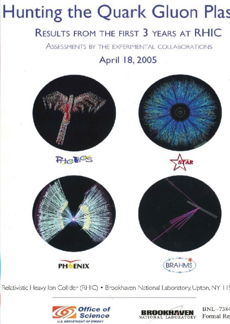
10 Feb 2000



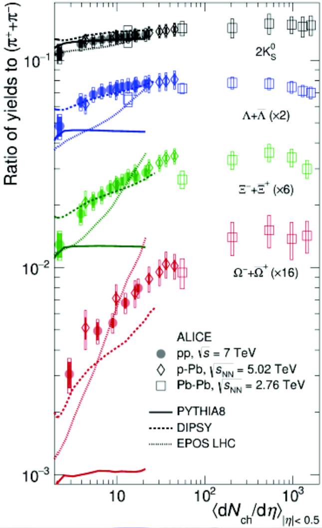
At the April 2005 meeting of the American Physical Society, held in Tampa, Florida a press conference took place on Monday, April 18, 9:00 local time. The public announcement of this event was made April 4, 2005:

EVIDENCE FOR A NEW TYPE OF NUCLEAR MATTER At the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab (BNL), two beams of gold atoms are smashed together, the goal being to recreate the conditions thought to have prevailed in the universe only a few microseconds after the big bang, so that novel forms of nuclear matter can be studied. At this press conference, RHIC scientists will sum up all they have learned from several years of observing the worlds most energetic collisions of atomic nuclei. The four experimental groups operating at RHIC will present a consolidated, surprising, exciting new interpretation of their data. Speakers will include: Dennis Kovar, Associate Director, Office of Nuclear Physics, U.S. Department of Energy's Office of Science; Sam Aronson, Associate Laboratory Director for High Energy and Nuclear Physics, Brookhaven National Laboratory. Also on hand to discuss RHIC results and implications will be: Praveen Chaudhari, Director, Brookhaven National Laboratory; representatives of the four experimental collaborations at the Relativistic Heavy Ion Collider; and several theoretical physicists.





Current interest in small systems: Strange antibaryon enhancement smoothly rising with entropy of fireball



Nature Physics 2017; doi:10.1038/nphys4111 ALICE

Significant enhancement of strangeness with multiplicity in high multiplicity pp events

pp behavior resamble p-Pb : both in term of value of the ratio and shape

No evident dependence on cms energy: strangeness production apparently driven by final state rather than collision system or energy

At high mult. pp ratio reaches values similar to the one in Pb-Pb (when ratio saturates)

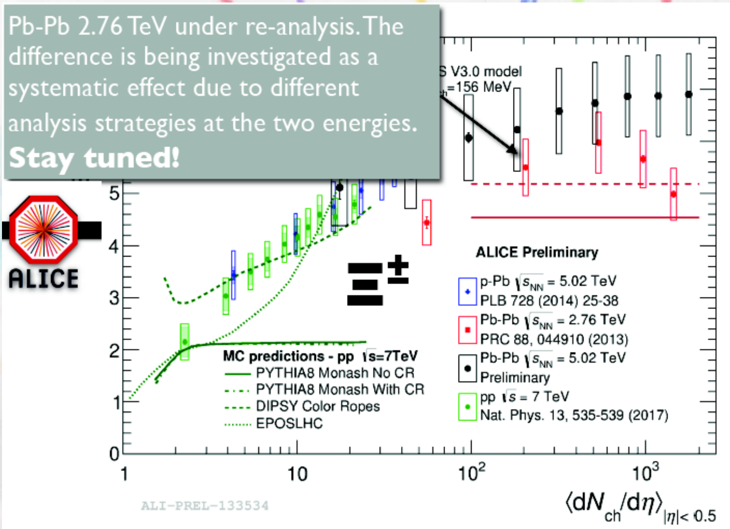
Models fail to riproduce data. Only DIPSY gives a qualitative description.

Alessandro Grelli **10/7/2017**

Small systems: $\Xi(ssq)$ Alice 2014 needs minor attention

Pb-Pb 2.76 TeV under re-analysis. The difference is being investigated as a systematic effect due to different analysis strategies at the two energies.

Stay tuned!



Ratio of p_T-integrated yield to pions show compatibility

No evident energy dependence. Smooth trend among systems

Small system: particle yield constrained by conservation law: Canonical phase space required

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

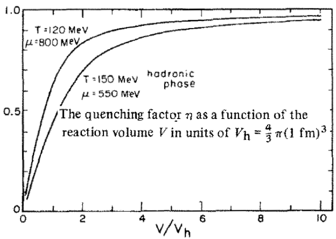
and

Michael DANOS
National Bureau of Standards, Washington, DC 20234

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



The quenching factor η as a function of the reaction volume V in units of $V_h = \frac{4}{3}\pi(1\text{ fm})^3$

PHYSICAL REVIEW C VOLUME 31, NUMBER 4 APRIL 1985

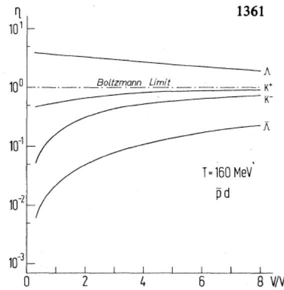
Strangeness abundances in p̄-nucleus annihilations

C. Derreth and W. Greiner
Institut für Theoretische Physik der Universität Frankfurt, 6000 Frankfurt, Federal Republic of Germany

H.-Th. Elze* and Johann Rafelski
Institute of Theoretical Physics and Astrophysics, University of Cape Town, Rondebosch 7700, Cape Town, South Africa

(Received 27 September 1984)

Strange particle abundances in small volumes of hot hadronic gas are determined in the canonical ensemble with exact strangeness and baryon number conservation. Substantial density and baryon number dependence is found. A p̄d experiment is examined and applications to p̄-nucleus annihilations are considered.



Small system: An elegant nonabelian group theory approach

Ref.TH.3053-CERN
26 March 1981

Ref.TH.3053-CERN

PHASE TRANSITION IN HADRONIC MATTER WITH INTERNAL SYMMETRY *)

K. Redlich **) and L. Turko **)
CERN -- Geneva

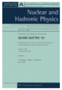
ABSTRACT

A general formalism for the description of a thermodynamical system with internal symmetry is introduced. Results are applied to the statistical bootstrap model describing hadronic clusters with isospin conservation taken into account and equations of state are obtained. It is shown that at the sufficiently high energy density, a phase transition occurs. A new phase is an intermediate one between hadronic matter and a quark-gluon plasma phase.

.... and the strangeness part is REDISCOVERED decade later

Nuclear Physics A

Volume 638, Issues 1–2, 10 August 1998, Pages 399c-402c



Canonical strangeness enhancement

J. Sollfrank [a], F. Becattini [b], K. Redlich [c], H. Satz [d]

https://doi.org/10.1016/S0375-9474(98)00395-9 Get rights and content

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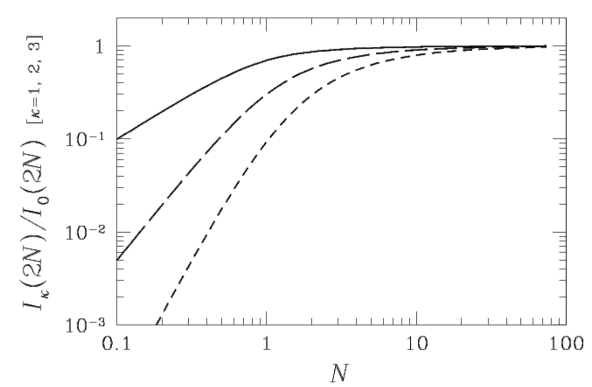
12. K. Redlich, H. Satz and J. Sollfrank, University Regensburg preprint TPR-98-04.

Strangeness conservation alone: in QGP book JL/JR; p225-232:

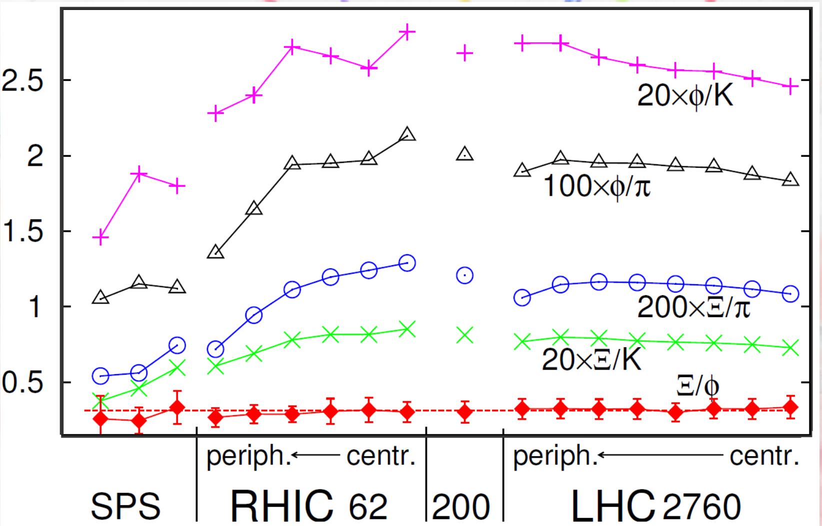
1-2-3-strange flavored particle suppression factors



$$\langle N_\kappa^{\rm CE}\rangle = N_\kappa^{\rm GC}\,\frac{I_\kappa(2N_{\rm pair}^{\rm GC})}{I_0(2N_{\rm pair}^{\rm GC})}.$$

Canonical yield-suppression factors I_κ/I_0 as function of the grand-canonical pair yield N. Short-dashed line: the suppression of triply-strange-flavored hadrons; long-dashed line: the suppression of doubly-strange-flavored hadrons; and solid line, the suppression of singly-strange-flavored hadrons.

$\Xi(ssq)/\phi(s\bar{s})$ (nearly) constant: same production mechanism



M. Petran, J. Rafelski, *Multistrange Particle Production and the Statistical Hadronization Model* Phys.Rev. C **82** (2010) 011901

The chemical hadronization analysis from (re)invention to generalization

Physics Letters B
Volume 262, Issues 2–3, 20 June 1991, Pages 333-340
open access

Strange anti-baryons from quark-gluon plasma

Johann Rafelski Department of Physics, University of Arizona, Tuczon, AZ 85721

Received 5 April 1991, Available online 17 October 2002.
https://doi.org/10.1016/0370-2693(91)91576-H

Abstract

Experimental results on strange anti-baryon production in nuclear S→W collisions at 200 *A* GeV are described in terms of a simple model of an explosively disintegrating quark-lepton plasma (QGP). The importance of the strange anti-baryon signal for the identification of the QGP state and for the diagnosis of its properties is demonstrated.

Chemical nonequilibrium and deconfinement in 200*A* GeV sulphur induced reactions

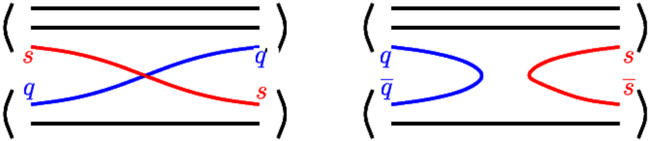
Jean Letessier and Johann Rafelski
Phys. Rev. C **59**, 947 – Published 1 February 1999 Received 17 June 1998
DOI: https://doi.org/10.1103/PhysRevC.59.947
PHYSICAL REVIEW C
covering nuclear physics

We interpret hadronic particle abundances produced in S-Au/W/Pb $200A$ GeV reactions in terms of the final state hadronic phase space model and determine by a data fit of the chemical hadron freeze-out parameters. Allowing for the flavor abundance nonequilibrium a highly significant fit to experimental particle abundance data emerges, which supports the possibility of strangeness distillation. We find under different strategies stable values for freeze-out temperature $T_f = 143 \pm 3$ MeV, baryochemical potential $\mu_B = 173 \pm 6$ MeV, ratio of strangeness (γ_s) and light quark (γ_q) phase space occupancies $\gamma_s/\gamma_q = 0.60 \pm 0.02$, and $\gamma_q = 1.22 \pm 0.05$ without accounting for collective expansion (radial flow). When introducing flow effects which allow a consistent description of the transverse mass particle spectra, yielding $|v_c| = 0.49 \pm 0.01\ c$, we find $\gamma_s/\gamma_q = 0.69 \pm 0.03$, $\gamma_q = 1.41 \pm 0.08$. The strange quark fugacity is fitted at $\lambda_s = 1.00 \pm 0.02$ suggesting chemical freeze-out directly from the deconfined phase.

Magic coincidence: while we battled our referee for 6 months Krzysztof Redlich enters this field with the 2 page preprint in August 1998: *Unified description of freezeout parameters in relativistic heavy ion collisions*, Phys.Rev.Lett. 81 (1998) 5284-5286

EXAMPLE: Strangeness in HG:

Relative chemical equilibrium | **Absolute** chemical equilibrium



EXCHANGE REACTION | **PRODUCTION REACTION**

Absolute equilibrium $\gamma \to 1$ require more rarely occurring truly inelastic collisions with creation of new particles.

γ_i controls overall abundance of quark 'i' pairs	Absolute chemical equilibrium
λ_i controls difference between strange and non-strange quarks 'i'	Relative chemical equilibrium

a) Confinement: $\Longrightarrow$ breakup into free quarks not possible;
b) Strong interaction: $\Longrightarrow$ equal hadron production strength irrespective of produced hadron type
$\Longrightarrow$ 'elementary' hadron yields depend only on the available phase space
Historical approaches:

- Fermi: Micro-canonical phase space
  sharp energy and sharp number of particles
  E. Fermi, Prog.Theor.Phys. 5 (1950) 570: HOWEVER
  Experiments report event-average rapidity particle abundances, model should describe an average event
- Canonical phase space: sharp number of particles
  ensemble average energy $E \rightarrow T$ temperature
  T could be, but needs not to be, a kinetic process temperature
- Grand-canonical – ensemble average energy and number of particles:
  $N \rightarrow \mu \Leftrightarrow \Upsilon = e^{(\mu/T)}$

Our interest: bulk QGP fireball properties of hadron source evaluated independent of complex explosion dynamics $\Longrightarrow$ analyze integrated hadron spectra.

SHARE Idea/Team: US-Polish NATO collaboration 2002/04

Statistical HAadronization with REsonances

2000-06 Golden age of scientific collaboration Kraków-Arizona

ELSEVIER Computer Physics Communications 167 (2005) 229–251

SHARE: Statistical hadronization with resonances

G. Torrieri [a], S. Steinke [a], W. Broniowski [b], W. Florkowski [b,c], J. Letessier [a], J. Rafelski [a]

[a] Department of Physics, University of Arizona, Tucson, AZ 85721, USA
[b] The H. Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, PL-31342 Kraków, Poland
[c] Institute of Physics, Świętokrzyska Academy, PL-25406 Kielce, Poland

Received 27 July 2004; received in revised form 9 November 2004; Available online 19 March 2005

Abstract

SHARE is a collection of programs designed for the statistical analysis of particle production in relativistic heavy-ion collisions. With the physical input of intensive statistical parameters, it generates the ratios of particle abundances. The program includes cascade decays of all confirmed resonances from the Particle Data Tables. The complete treatment of these resonances has been known to be a crucial factor behind the success of the statistical approach. An optional feature implemented is the Breit–Wigner distribution for strong resonances. An interface for fitting the parameters of the model to the experimental data is provided.

ELSEVIER Physics Letters B 633 (2006) 488–491

Balance of baryon number in the quark coalescence model

A. Bialas [a,*], J. Rafelski [b]

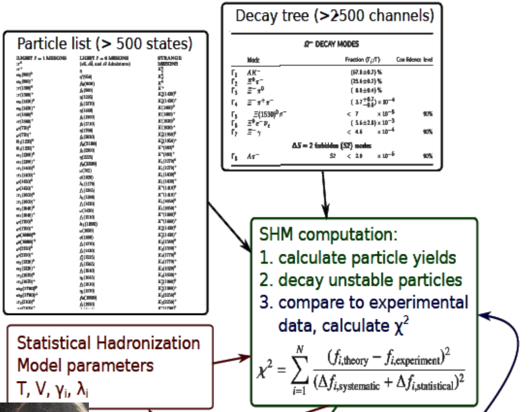
[a] M. Smoluchowski Institute of Physics Jagellonian University, Reymonta 4, 30-059 Cracow, Poland
[b] Department of Physics, University of Arizona, 1118 E. 4th Street, Tucson, AZ 85721, USA

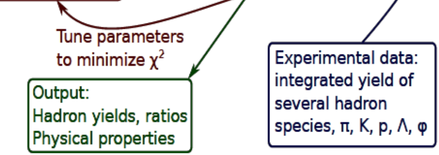
Received 29 August 2005; received in revised form 7 November 2005; Available online 7 December 2005

The charge and baryon balance functions are studied in the coalescence hadronization mechanism of quark–gluon plasma. Assuming that in the plasma phase the $q\bar{q}$ pairs form uncorrelated clusters whose decay is also uncorrelated, one can understand the observed small width of the charge balance function in the Gaussian approximation. The coalescence model predicts even smaller width of the baryon–antibaryon balance function: $\sigma_{B\bar{B}}/\sigma_{+-} = \sqrt{2/3}$

PROCEDURE – FITTING SHM PARAMETERS TO DATA

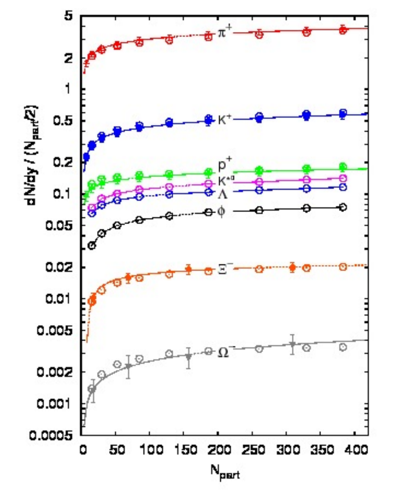
1. Input: T, V, γ_q, γ_s, λ_q, $\lambda_s.\lambda_3$
2. Compute yields of all hadrons
3. Decay feeds – particles experiment observes
4. Compare to exp. data (χ^2)
5. Including bulk properties, constraints
6. Tune parameters to match data (minimize χ^2)





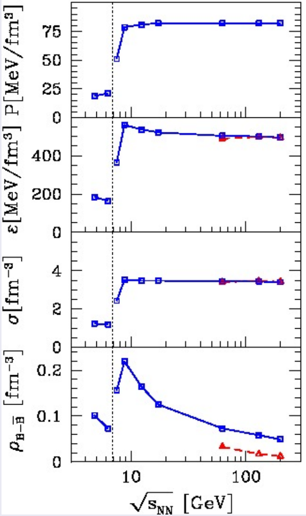
Examples SHM Analysis (Chemical Nonequilibrium)

Particle Yield Example:LHC



M. Petran, J.Letessier, V. Petracek, J. Rafelski Phys.Rev. C **88** (2013) no.3, 034907

Bulk properties from SHM yields



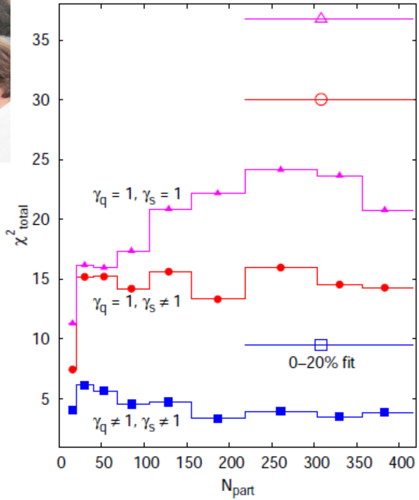
J. Letessier, J. Rafelski, Eur.Phys.J. A **35** (2008) 221-242

SHM fit Quality LHC Pb-Pb 2.76 TeV data

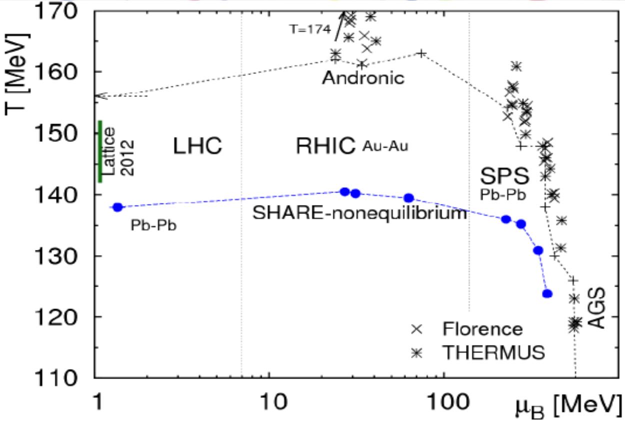
Chemical non-equilibrium SHM works at all centralities

Non-equilibrium

- $\chi^2/\text{ndf} \simeq 4.5/9 = 0.5$,
- constant across centrality
- improvement by factor of 3 resp. 5 comparing to $\gamma_q = 1$
- Only in peripheral collisions $\gamma_q \simeq 1$ maybe possible



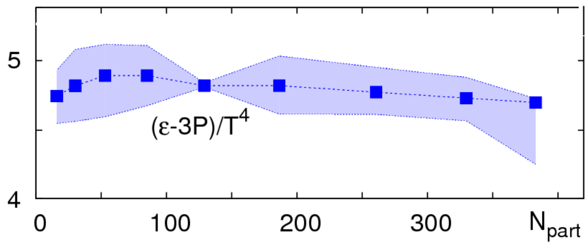
SHARE consistent with lattice QCD
Chemical nonequilibrium + supercooling
= sudden fireball breakup



Chemical freeze-out MUST be below lattice results. For direct free-streaming hadron emission from QGP, T-SHM is the QGP source temperature, there cannot be full chemical equilibrium.

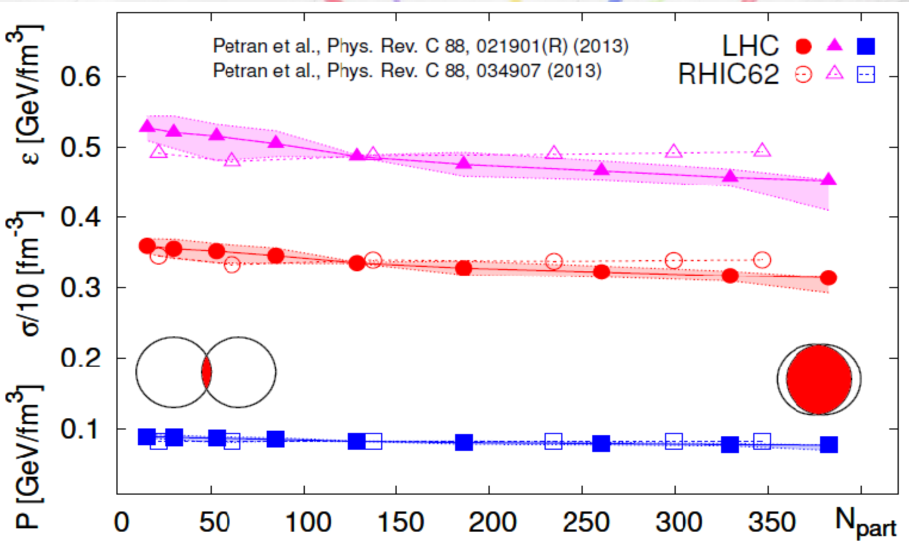
SPS, RHIC, LHC *AA* SHM Digest

- Strange antibaryon signature of QGP leads to discovery of universal properties of QGP at hadronization; differences in: Volume size, Strangeness saturation.
- Universality of fireball bulk properties across the entire reaction energy domain we express in terms of the invariant measure



- At SPS, RHIC: Baryon number deposition varies strongly as function of collision energy. This is the chemical potential dependence on collision energy. WHY? – To clarify question: why there is no McLerran-Bjorken transparency?

Smaller systems hadronize earlier (more dense fireball)

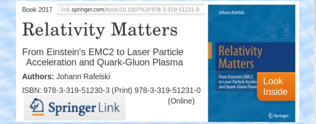


A few first look at small ALICE systems remarks

- ALICE small system results shows growth γ_s of strangeness yield with size of the system.
- Hadronization condition T a few MeV higher compared to large systems: conclusion there is less/no supercooling in less explosive expansion.
- Corresponding bulk matter properties are higher. No test of universal hadronization / conformal anomaly was as yet performed.
- Small system net flavor content universally zero (and it seems we are sensitive due to small system): there is no electric charge, etc.
- **There is no doubt that after 38 years of waiting the $pp \rightarrow AA$ ALICE results demonstrate that there are 10-20-30% canonical phase space effects: when strange pairs are few and baryon number is rare, strange antibaryons are slightly suppressed as the correct theory predicts. Dominant effect still from strangeness chemical non-equilibrium γ_s . No publication forthcoming as lack of resources prevents appropriate analysis effort.**

Summary: In last 100 years (variant of A Bialas fest slide)

- Particle accelerators barely started 100 years ago, particle production study begins in earnest 75 years ago; leading us to understand origin of mass of matter, the early Universe, the Æther = quantum vacuum, and how energy becomes matter in primordial Universe $E \to mc^2$.
- Much 'naive' and 'profound ' mystery remains: Why colliding hadrons make lots of entropy – what else is in quantum vacuum? . . .
- Kraków coffee houses, Zakopane mountains: These are essential tools assuring future progress and continued success for the large Krakow group that rose to World prominence in the past 50 years.
- **Big riddles: In my view the new physics we are looking for is associated with 'FORCES' and the biggest hammer is a relativistic heavy ion, side perhaps of some laser stuff**


Book 2017 link.springer.com/book/10.1007%2F978-3-319-51231-0

Relativity Matters

From Einstein's EMC2 to Laser Particle Acceleration and Quark-Gluon Plasma

Authors: Johann Rafelski

ISBN: 978-3-319-51230-3 (Print) 978-3-319-51231-0 (Online)

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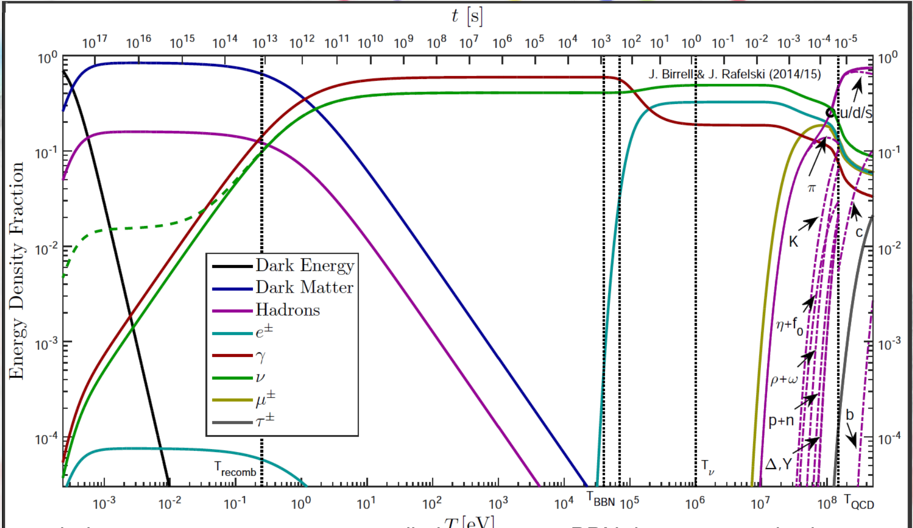
The Universe Composition in Single View



dark energy matter radiation ν, γ BBN+leptons hadrons

Different dominance eras: Temperature grows to right

Objective: connect the hot Hagedorn Universe with present day

The contents of the Universe today
(fractions change 'rapidly' in expanding Universe)

1. Visible (baryonic) matter
   (less 5% of total energy inventory)
2. Free-streaming matter
   i.e particles that do not interact – have 'frozen' out:
   - photons: since $T = 0.25$eV *(insignificant in inventory)*
   - neutrinos: since $T = 1.5$–3.5 MeV *(insignificant)*
   - dark matter *(25% in energy inventory)*
     1. Massive ColdDarkMatter from way before QGP hadronization
     2. massless dark matter: darkness: maybe 'needed', origin precedes neutrino decoupling
3. Dark energy = vacuum energy *(70% of energy inventory)*

darkness: quasi-massless particles influence early Universe dynamics

Particle composition in thermal Universe

The chemistry of particle reactions in the Universe has three 'chemical' potentials needing to be constrained. There are also three physics constraints Michael J. Fromerth, JR etal e-Print: astro-ph /0211346; arXiv:1211.4297 → Acta Phys.Polon. B43 (2012), 2261

i. Electrical charge neutrality

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

Q_i and n_i charge and number density of species i.

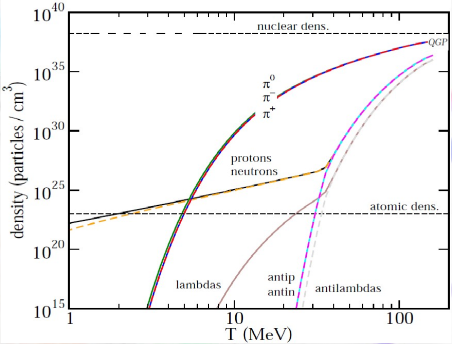
ii. Net lepton number equals(?) net baryon number
B/L-asymmetry can hide in neutrino-antineutrino imbalance

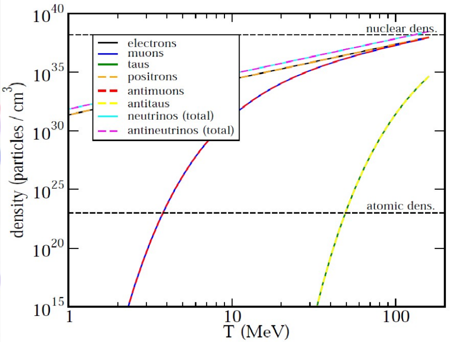
iii. Prescribed value of entropy-per-baryon $\equiv n_B/n_\gamma$

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

$S/B \simeq 3$–5×10^{10}, results shown for 4.5×10^{10}

Particle composition: balancing ‘chemical’ reactions





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

Mechanisms assuring hadrons in thermal equilibrium

The key doorway reaction to 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 at $T = \mathcal{O}$2-4MeV, more discussion follows

Photons freeze-out at $T = 0.25$ eV

But is the early Universe really made of hadrons?

Free streaming matter not same as thermal matter

Free-streaming matter in the Universe: 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). For CDM (cold dark matter) $m_{\rm CDM} >> T_k$; for neutrinos $m_\nu << T_k$.

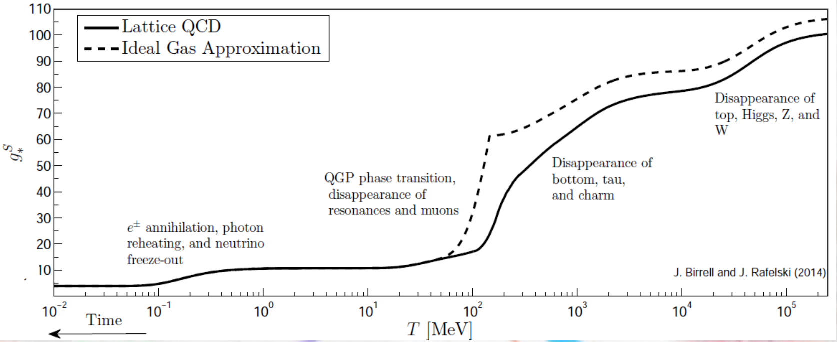
C. Cercignani, and G. Kremer. The Relativistic Boltzmann Equation: Basel, (2000).
H. Andreasson, "The Einstein-Vlasov System"Living Rev. Rel. **14**, *4 (2011) Y. Choquet-Bruhat. General Relativity and the Einstein Equations, Oxford (2009).*

Distinct Composition Eras in the Universe

Composition of the Universe changes as function of T:

- From Higgs freezing to freezing of QGP
- QGP hadronization
- Hadronic antimatter annihilation
- Onset of neutrino free-streaming just before and when
- e^+e^- annihilate; overlapping with begin of
- Big-Bang nucleosynthesis within a remnant e^+e^- plasma
- Radiation 'Desert'(ν, γ)
- emergence of free streaming dark matter
- Photon Free-streaming (CMB) – Composition Cross-Point
- emergence of Dark energy = vacuum energy

Count of Degrees of Freedom



Distinct Composition Eras visible. 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

- 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]].

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. Knowing the Universe composition in present era we can integrate back IF we know what is the contents.

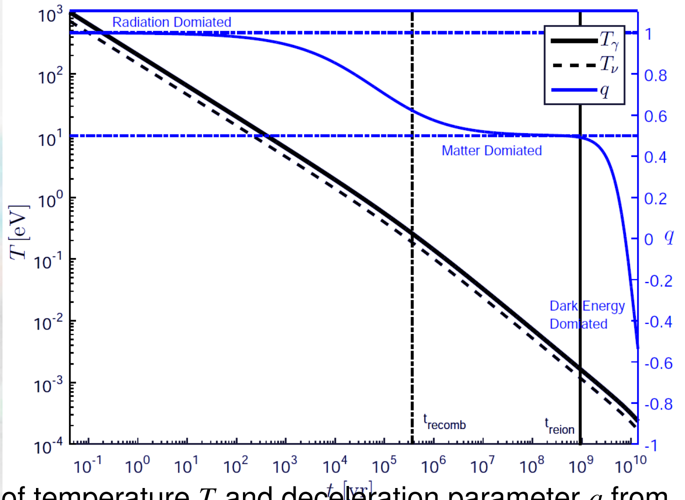
Evolution Eras and Deceleration Parameter q

Using Einsteins equations solving for $G_N = G_N$

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

- Radiation dominated universe: $P = \rho/3 \implies q = 1$.
- Matter dominated universe: $P \ll \rho \implies q = 1/2$.
- Dark energy (Λ) dominated universe: $P = -\rho \implies q = -1$.
  Accelerating Universe

'Recent' evolution

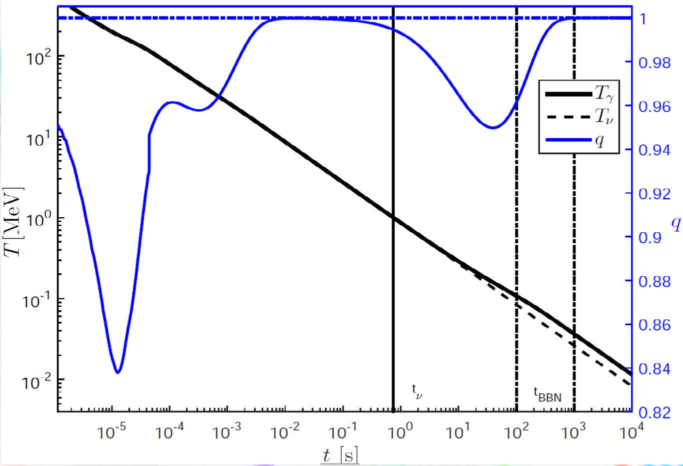


Evolution of temperature T and deceleration parameter q from near/after BBN to the present day: time grows to right

Long ago: Hadron and QGP Era

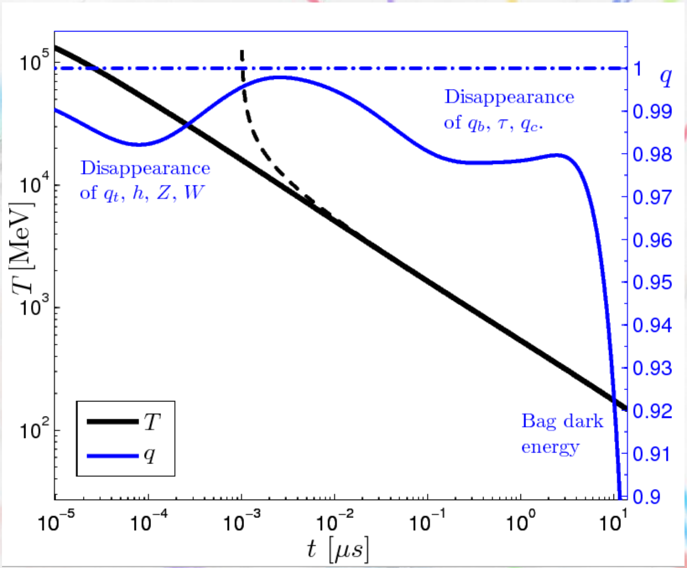
- QGP era down to phase transition at $T \approx 150$MeV. Energy density dominated by photons, neutrinos, $e^{\pm}$, $\mu^{\pm}$ along with u, d, s quarks.
- $2+1$-flavor lattice QCD equation of state used
- u, d, s, G lattice energy density is matched by ideal gas of hadrons to sub percent-level at $T = 115$MeV.
- Hadrons included: pions, kaons, eta, rho, omega, nucleons, delta, hyperons
- Pressure between QGP/Hadrons is discontinuous (need mixed phase) hard to notice discontinuity in q (slopes match). A first study, better EOS can be used.

From QGP across BBN



Temperature T and deceleration parameter q from QGP era until near BBN. Time grows to right

EW and QGP Eras



Temperature T and deceleration parameter q from Electro-Weak symmetric era to near QGP hadronization. Time grows to right

What is this all good for? A few examples

'Darkness' in the Universe enters laboratory experiments

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

doi:10.1016/j.physletb.2014.12.033

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

Abstract

The effective number of neutrinos, $N_{\rm eff}$, 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 $N_{\rm eff}$ 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

What is this all good for? A few examples

Time independence of natural constants

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Nuclear Physics B 890 (2015) 481–517

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Relic neutrino freeze-out: Dependence on natural constants

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Received 9 June 2014; received in revised form 2 November 2014; accepted 22 November 2014

Available online 27 November 2014

Editor: Tommy Ohlsson

Abstract

Analysis of cosmic microwave background radiation fluctuations favors an effective number of neutrinos, $N_\nu > 3$. This motivates a reinvestigation of the neutrino freeze-out process. Here we characterize the dependence of N_ν on the Standard Model (SM) parameters that govern neutrino freeze-out. We show that N_ν depends on a combination η of several natural constants characterizing the relative strength of weak interaction processes in the early Universe and on the Weinberg angle $\sin^2\theta_W$. We determine numerically the dependence $N_\nu(\eta, \sin^2\theta_W)$ and discuss these results. The extensive numerical computations are made possible by two novel numerical procedures: a spectral method Boltzmann equation solver adapted to allow for strong reheating and emergent chemical non-equilibrium, and a method to evaluate Boltzmann equation collision integrals that generates a smooth integrand.

What is this all good for? A few examples

Knowing neutrino microwave background – look for them

Eur. Phys. J. C (2015) 75:91
DOI 10.1140/epjc/s10052-015-3310-3

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Proposal for resonant detection of relic massive neutrinos

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Received: 24 November 2014 / Accepted: 8 February 2015 / Published online: 24 February 2015

Abstract We present a novel method for detecting the relic neutrino background that takes advantage of structured quantum degeneracy to amplify the drag force from neutrinos scattering off a detector. Developing this idea, we present a characterization of the present day relic neutrino distribution in an arbitrary frame, including the influence of neutrino mass and neutrino reheating by e^+e^- annihilation. We present explicitly the neutrino velocity and de Broglie wavelength distributions for the case of an Earthbound observer. Considering that relic neutrinos could exhibit quantum liquid features at the present day temperature and density, we discuss the impact of neutrino fluid correlations on the possibility of resonant detection.

tering there are also inelastic processes–we note the development of the PTOLEMY experiment [16] aiming to observe relic electron neutrino capture by tritium, as originally proposed by Weinberg [17].

In this paper we will first characterize the free-streaming distribution from the perspective of an observer in relative motion under the usual Boltzmann dilute gas assumption, utilizing the physically consistent equation of state from [18]. We will then argue that high degree of degeneracy of the non-equilibrium relic neutrino distribution, together with their temperature $T_\nu \ll m_\nu$, implies the inadequacy of the dilute gas assumption, resulting in a correlated background. This leads us to explore the possibility of the detection of relic neutrinos by resonant amplification of the neutrino–detector interaction.

What is this all good for? A few examples

Attempts to understand Universe bi-stability

1NPBNeutri... 15_02NeutrinoD... 15JHEP_FAlseVa...

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Dynamical emergence of the Universe into the false vacuum

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Received October 20, 2015 Published November 23, 2015

Abstract. We study how the hot Universe evolves and acquires the prevailing vacuum state, demonstrating that in specific conditions which are believed to apply, the Universe becomes frozen into the state with the smallest value of Higgs vacuum field $v = \langle h \rangle$, even if this is not the state of lowest energy. This supports the false vacuum dark energy Λ-model. Under several likely hypotheses we determine the temperature in the evolution of the Universe at which two vacuua v_1, v_2 can swap between being true and false. We evaluate the dynamical surface pressure on domain walls between low and high mass vaccua due to the presence of matter and show that the low mass state remains the preferred vacuum of the Universe.

JCAP11(2015)035

What is this all good for? A few examples

EOS with free-streaming massive neutrinos

PHYSICAL REVIEW D **89,** 023008 (2014)

Relic neutrinos: Physically consistent treatment of effective number of neutrinos and neutrino mass

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(Received 10 December 2013; published 24 January 2014)

We perform a model independent study of the neutrino momentum distribution at freeze-out, treating the freeze-out temperature as a free parameter. Our results imply that measurement of neutrino reheating, as characterized by the measurement of the effective number of neutrinos N_ν, amounts to the determination of the neutrino kinetic freeze-out temperature within the context of the standard model of particle physics where the number of neutrino flavors is fixed and no other massless (fractional) particles arise. At temperatures on the order of the neutrino mass, we show how cosmic background neutrino properties, i.e., energy density, pressure, and particle density, are modified in a physically consistent way as a function of neutrino mass and N_ν.

DOI: 10.1103/PhysRevD.89.023008 PACS numbers: 51.10.+y, 95.30.Cq, 14.60.Pq, 26.35.+c

Summary Cosmo

- 50 years ago particle production in pp reactions prompted introduction of Hagedorn Temperature $T_{\rm H}$ along with singular energy density – linked to the Big-Bang;
- By 1980 $T_{\rm H}$ critical temperature at which vacuum 'melts', matter surrounding us dissolves; This prompts CERN and BNL experimental program to recreate pre-matter in laboratory.
- Today: In laboratory: We explore the phase diagram of QGP; In cosmology: we study the evolution of the Quark-Universe across many domains to the present day.
- We have detailed understanding how Hot Hagedorn Universe evolves and the matter in Universe arises
- Comprehensive view allows diverse consistency studies: we set limits on variation of natural constants in early Universe, constrain any new radiance (darkness); characterize cosmic microwave neutrinos. Interface to vacuum bi-stability issue.