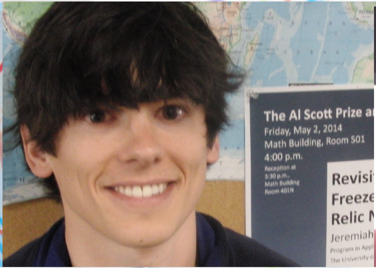
Quarks and Hadrons in the Primordial Universe

Johann Rafelski
The University of Arizona, Tucson
in collaboration with
Cheng Tao Yang and Jeremiah Birrell

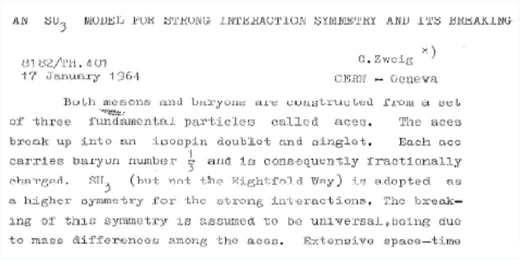
Long term objective (20y): use the know-how about the small bang (RHI collision) physics to extend our understanding of the Universe beyond the period of BBN, thus connecting the QGP Universe to the present era

Outline

1. Current understanding of the Universe: convergence of 1964-68 ideas
    - Quarks + Higgs → Standard Model of particle physics
    - CMB discovered → Big Bang
    - Statistical Bootstrap T_{H} → Quark-Gluon Plasma
2. QGP in the Universe, in laboratory
3. Antimatter disappears, neutrinos free-stream, (BBN) ...
4. Evolution of matter components in the Universe



1964: Quarks + Higgs → Standard Model

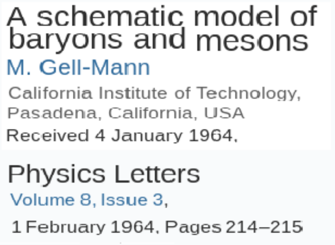


AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

8182/TH.401
17 January 1964

G. Zweig *)
CERN – Geneva

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



A schematic model of baryons and mesons

M. Gell-Mann

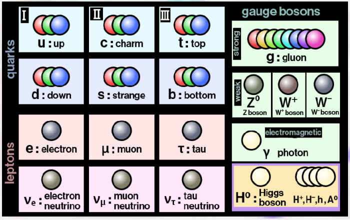
California Institute of Technology, Pasadena, California, USA

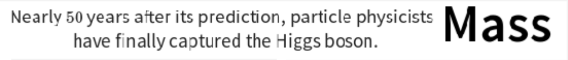
Received 4 January 1964.

Physics Letters

Volume 8, Issue 3,

1 February 1964, Pages 214–215

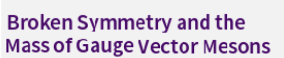




Nearly 50 years after its prediction, particle physicists have finally captured the Higgs boson.

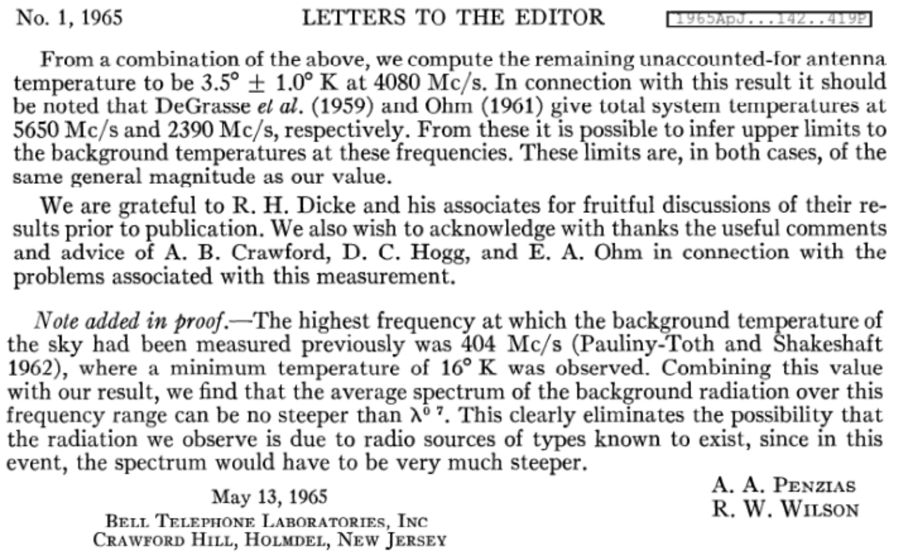
Mass

Broken Symmetries and the Masses of Gauge Bosons



Broken Symmetry and the Mass of Gauge Vector Mesons

1965: Microwave Background Penzias and Wilson



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

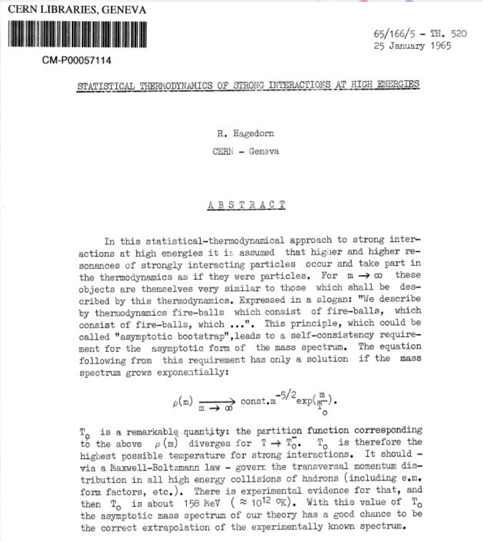
We are grateful to R. H. Dicke and his associates for fruitful discussions of their results prior to publication. We also wish to acknowledge with thanks the useful comments and advice of A. B. Crawford, D. C. Hogg, and E. A. Ohm in connection with the problems associated with this measurement.

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

A. A. Penzias
R. W. Wilson

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

Hagedorn Temperature October 1964 in press: Hagedorn Exponential Mass Spectrum 01/1965



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

STATISTICAL THERMODYNAMICS OF STRONG INTERACTIONS AT HIGH ENERGIES

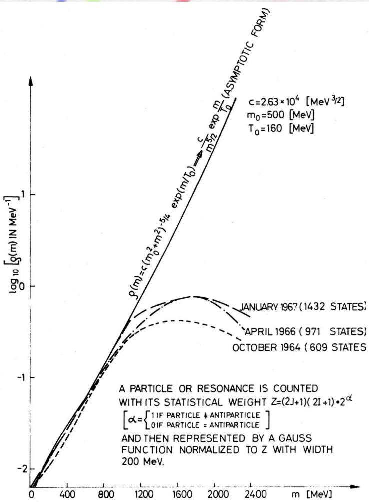
R. Hagedorn
CERN - Geneva

ABSTRACT

In this statistical-thermodynamical approach to strong interactions at high energies it is assumed that higher and higher resonances of strongly interacting particles occur and take part in the thermodynamics as if they were particles. For $m \rightarrow \infty$ these objects are themselves very similar to those which shall be described by this thermodynamics. Expressed in a slogan: "We describe by thermodynamics fire-balls which consist of fire-balls, which consist of fire-balls, which ...". This principle, which could be called "asymptotic bootstrap", leads to a self-consistency requirement for the asymptotic form of the mass spectrum. The equation following from this requirement has only a solution if the mass spectrum grows exponentially:

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

T_o is a remarkable quantity: the partition function corresponding to the above $\rho(m)$ diverges for $T \rightarrow T_o^-$. T_o is therefore the highest possible temperature for strong interactions. It should - via a Maxwell-Boltzmann law - govern the transversal momentum distribution in all high energy collisions of hadrons (including e.m. form factors, etc.). There is experimental evidence for that, and then T_o is about 158 MeV ($\approx 10^{12}$ °K). With this value of T_o the asymptotic mass spectrum of our theory has a good chance to be the correct extrapolation of the experimentally known spectrum.



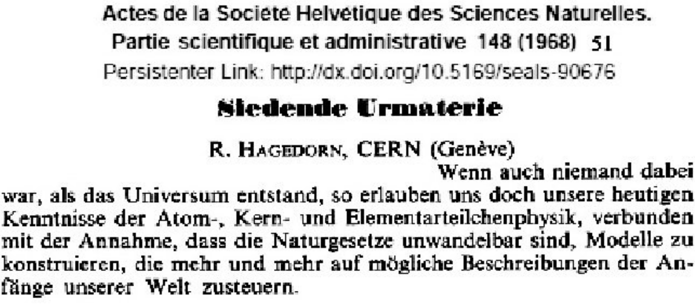
A PARTICLE OR RESONANCE IS COUNTED WITH ITS STATISTICAL WEIGHT $Z=(2J+1)(2I+1)\cdot 2^{\alpha}$

$$\left[\alpha=\begin{cases}1 \text{ IF PARTICLE} \neq \text{ANTIPARTICLE}\\ 0 \text{ IF PARTICLE} = \text{ANTIPARTICLE}\end{cases}\right]$$

AND THEN REPRESENTED BY A GAUSS FUNCTION NORMALIZED TO Z WITH WIDTH 200 MeV.

1965-7 – Hagedorn’s singular Statistical Bootstrap

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

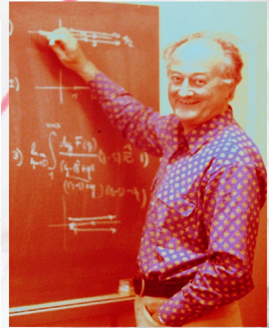


Actes de la Société Helvétique des Sciences Naturelles.
Partie scientifique et administrative 148 (1968) 51
Persistenter Link: http://dx.doi.org/10.5169/seals-90676

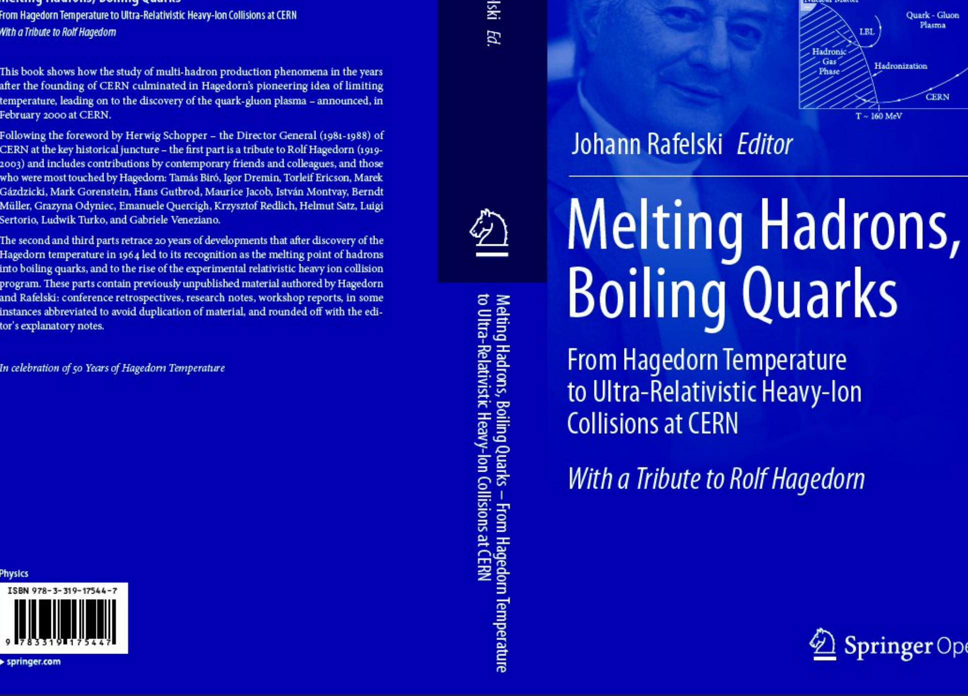
Siedende Urmaterie

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

Johann Rafelski *Editor*

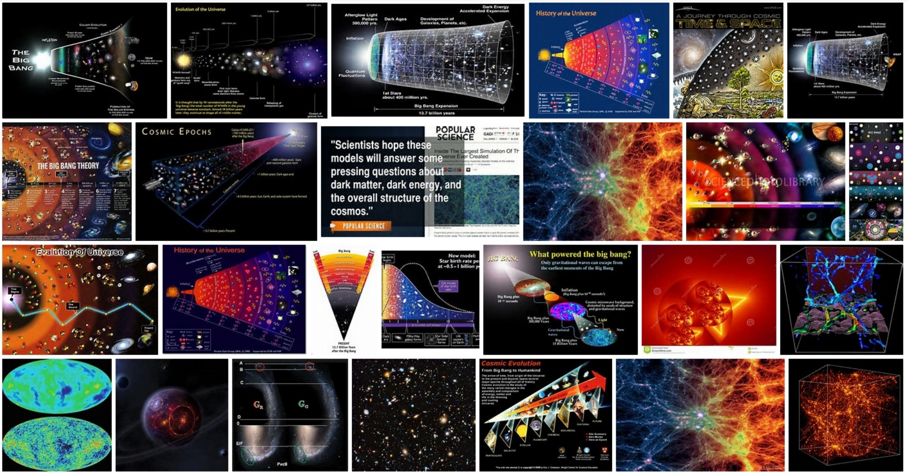
Melting Hadrons, Boiling Quarks

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

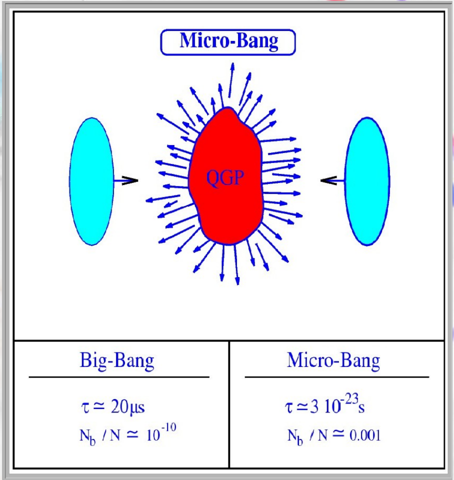
With a Tribute to Rolf Hagedorn

Springer Ope

Time travel forward 15 Years to 1980



CERN 1979: Can we recreate Big-Bang in the lab?



Big-Bang	Micro-Bang
$\tau \simeq 20\mu s$	$\tau \simeq 3\ 10^{-23} s$
$N_b\ /N \simeq 10^{-10}$	$N_b\ /N \simeq 0.001$

Relativistic Heavy Ion Collisions

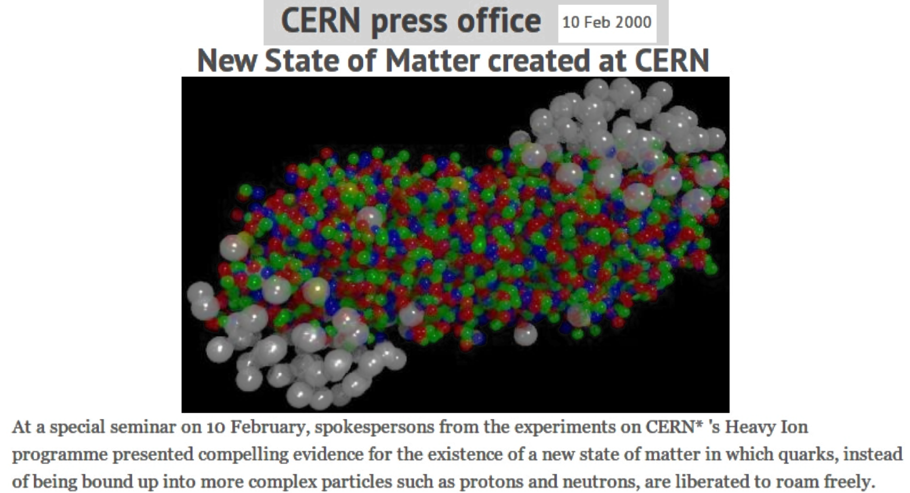
- Universe time scale 18 orders of magnitude longer, hence equilibrium of leptons & photons
- Baryon asymmetry six orders of magnitude larger in Laboratory, hence chemistry different
- Universe: dilution by scale expansion, Laboratory explosive expansion of a fireball

$\Longrightarrow$ Theory needed to connect RHI rapidly evolving collision hot matter experiments to the primordial Universe

Quark Gluon Plasma creation in RHI collisons:

1. RECREATES 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. OPENING TO 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. CHANCE to PROBE ORIGIN OF FLAVOR
   Normal matter made of first flavor family $(d, u, e, [\nu_e])$. Strangeness-rich QGP 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. PROBES 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 Magnetars; strongfields=strong force=strong acceleration
   $\to$ Acceleration Frontier

CERN in early 2000: QGP –A New State of Matter



CERN press office 10 Feb 2000

New State of Matter created at CERN

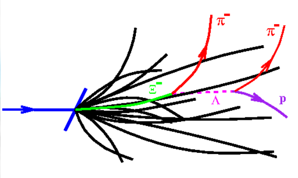
At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

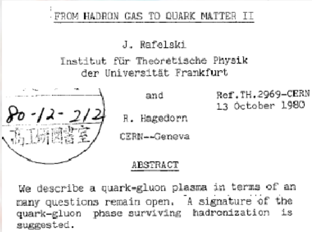
press.web.cern.ch/press-releases/2000/02/new-state-matter-created-cern

Preeminent signature: Strange antibaryon enhancement

About signatures of QGP discovery see discussion presented by **P Koch, B Müller, J Rafelski** in the review "From Strangeness Enhancement to Quark-Gluon Plasma Discovery" *Int. J. of Modern Physics A* **32** (2017) 1730024; DOI: 10.1142/S0217751X17300241; and arXiv 1708.0811

QGP signatures: 1980-81: Strangeness $s, \bar{s}$-many CERN experiments followed *Anti-strangeness in QGP: $\bar{s} > \bar{q}$ in SPS experiments*





FROM HADRON GAS TO QUARK MATTER II

J. Rafelski
Institut für Theoretische Physik
der Universität Frankfurt

and

R. Hagedorn
CERN--Geneva

Ref.TH.2969-CERN
13 October 1980

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.

Johann Rafelski 1980 Rolf Hagedorn

A: Strange hadrons are subject to a self analyzing decay

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

$$K(q\bar{s}), \quad \overline{K}(\bar{q}s), \quad K^*(890), \ldots$$
$$\Lambda(qqs), \quad \overline{\Lambda}(\bar{q}\bar{q}\bar{s}), \quad \Lambda(1520), \ldots$$
$$\phi(s\bar{s}), \quad \Xi(qss), \quad \overline{\Xi}(\bar{q}\bar{s}\bar{s}), \ldots$$
$$\Omega(sss), \quad \overline{\Omega}(\bar{s}\bar{s}\bar{s})$$

C: Production rates hence experimental statistical significance is high.

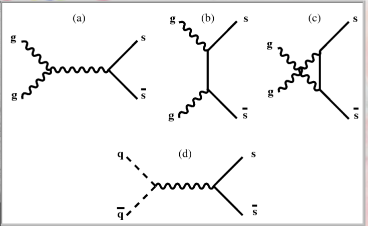
D: Strange Antibaryons produced like strange baryons hence greatly enhanced.

KINETIC THEORY FOR QCD

Chemical equilibrium abundance of strangness in QGP used in inital 1979-81 work. Following on a challenge from
Tamás Bíró and Jósef Zimányi PLB113 (1982) 678

A: 1982 JR-Berndt Müller PRL48 (1982) 1066 find kinetic production of strangeness dominated by gluon fusion $\boxed{GG \to s\bar{s}}$ Creation of connection: strangeness⇔gluons in QGP;

Berndt Müller in 1984 Johann Rafelski

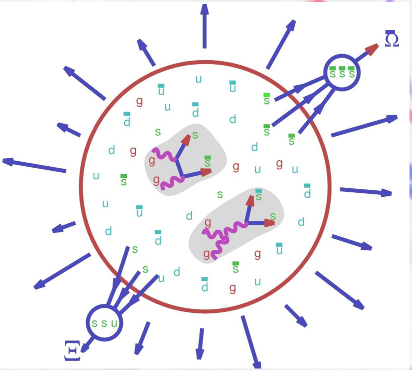


B: Show coincidence of scales:

$$\boxed{m_s \simeq T_c} \to \boxed{\tau_s \simeq \tau_{\mathrm{QGP}}} \to$$

strangeness yield can grow gradually - make s-yield time/size dep.

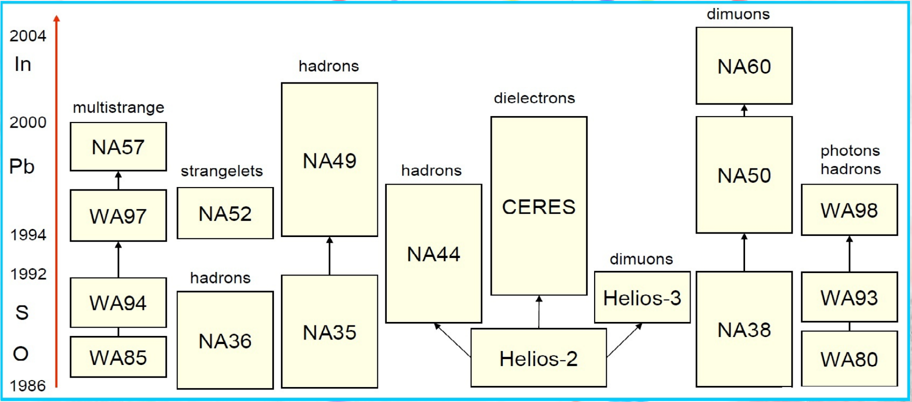
Strange hadrons from QGP: two-step formation mechanism



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

RHI experimental program is born 1980-86



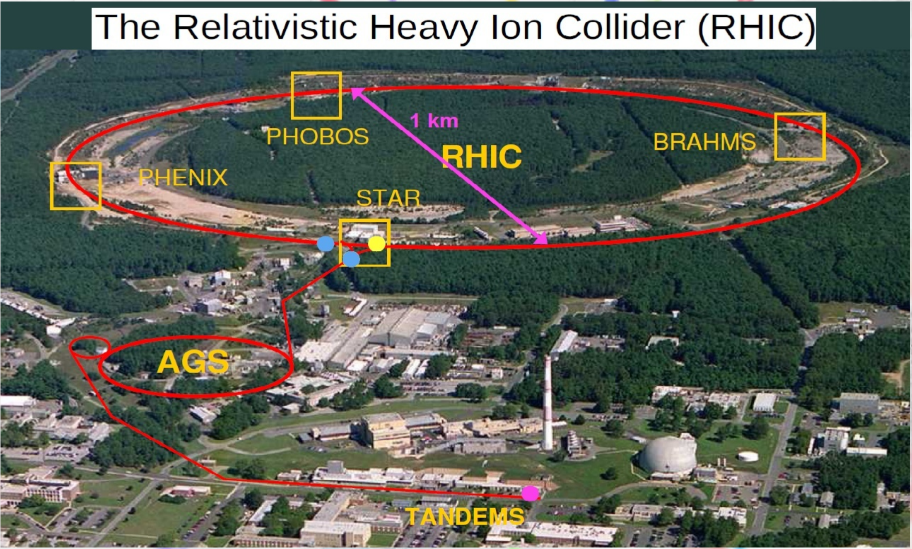
Lines of experiments approved to run at the high energy (at the time) CERN SPS particle accelerator:

particle and nuclear physics united for RHI in Europe

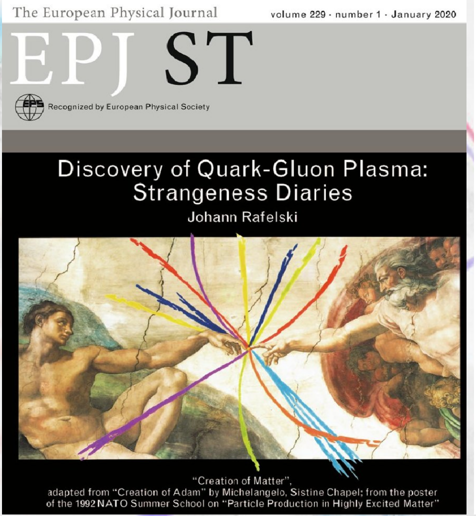
62 months after CERN: 9AM, 18 April 2005 BNL/DOE announce QGP at APS Spring Meeting

A new feature studied at BNL: matter explosive flow

A new collider was build at BNL-NY: 1984-2001/operating today



Multi-discovery background in ”Strangeness Diaries”



The European Physical Journal volume 229 · number 1 · January 2020

EPJ ST

Recognized by European Physical Society

Discovery of Quark-Gluon Plasma:
Strangeness Diaries
Johann Rafelski

“Creation of Matter”,
adapted from “Creation of Adam” by Michelangelo, Sistine Chapel; from the poster of the 1992 NATO Summer School on “Particle Production in Highly Excited Matter”

Eur. Phys. J. Special Topics **229**, 1–140 (2020)

https://doi.org/10.1140/epjst/e2019-900263-x

THE EUROPEAN PHYSICAL JOURNAL
SPECIAL TOPICS

Review

Discovery of Quark-Gluon Plasma: Strangeness Diaries

Johann Rafelski[1,2,a]

[1] CERN-TH, 1211 Geneva 23, Switzerland
[2] Department of Physics, The University of Arizona, Tucson, AZ, 85721, USA

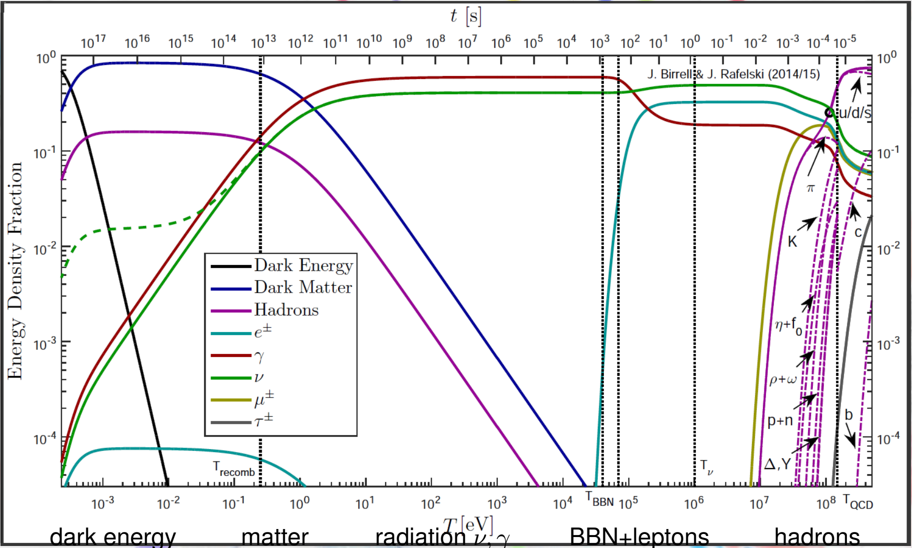
Received 4 November 2019
Published online 24 January 2020

Abstract. We look from a theoretical perspective at the new phase of matter, quark-gluon plasma (QGP), the new form of nuclear matter created at high temperature and pressure. Here I retrace the path to QGP discovery and its exploration in terms of strangeness production and strange particle signatures. We will see the theoretical arguments that have been advanced to create interest in this determining signature of QGP. We explore the procedure used by several experimental groups making strangeness production an important tool in the search and discovery of this primordial state of matter present in the Universe before matter in its present form was formed. We close by looking at both the ongoing research that increases the reach of this observable to LHC energy scale *pp* collisions, and propose an interpretation of these unexpected results.

> *It is very appropriate that you did reconstruct your version of the QGP discovery. Your quotations concerning me are correct and reproduce well my opinion, which I have not changed. CERN found good evidence for deconfinement, and it was at all appropriate to say that in public, independently from the status of RHIC at the time.*
> **Luciano Maiani** CERN Director General 1 January 1999–31 December 2003.

20y after: Connect to hot Quark-Hadron ‘Hagedorn’ Universe

TODAY **The Universe Composition in Single View** **QGP**



Different dominance eras: Temperature grows to → right

First step: Chemical equilibrium 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.

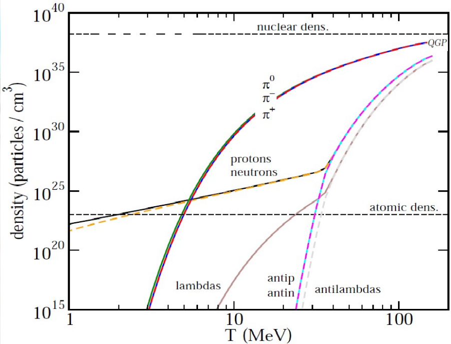
ii. Net lepton number equals(?) net baryon number
B/L-asymmetry can hide in neutrino-antineutrino imbalance

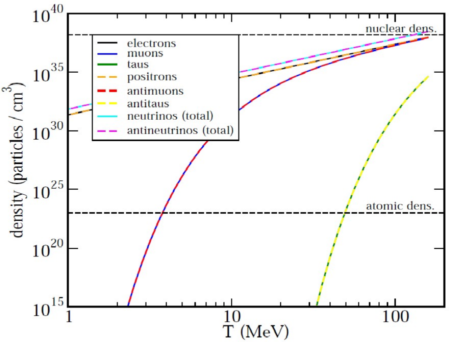
iii. Prescribed value of entropy-per-baryon $\equiv n_B/n_\gamma$

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

$S/B \simeq 3$–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

Towards kinetic theory: Connecting Universe temperature to time

Friedmann−Lemaitre−Robertson−Walker (FRW) cosmology

- Einstein Universe:

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

where $T^{\mu}_{\nu} = \mathrm{diag}(\rho, -P, -P, -P)$, $R = g_{\mu\nu}R^{\mu\nu}$, and

- • Homogeneous and • Isotropic metric

$$ds^2 = g_{\mu\nu}dx^{\mu}dx^{\nu} = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2(\theta)d\phi^2)\right].$$

$a(t)$ determines the distance between objects comoving in the Universe frame. Skipping $g^{\mu\nu} \rightarrow R^{\mu\nu}$
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

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

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

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

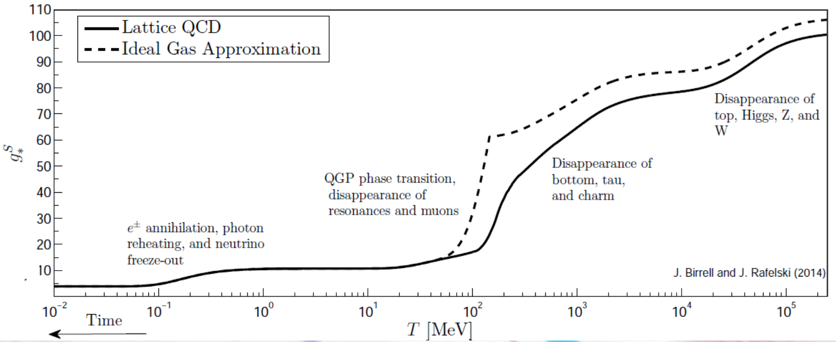
In flat $k = 0$ Universe: ρ fixes H; with P also q fixed, and thus also $\dot{H}$ fixed so also $\dot{\rho}$ fixed, and therefore also for $\rho = \rho(T(t))$ and also $\dot{T}$ fixed.

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

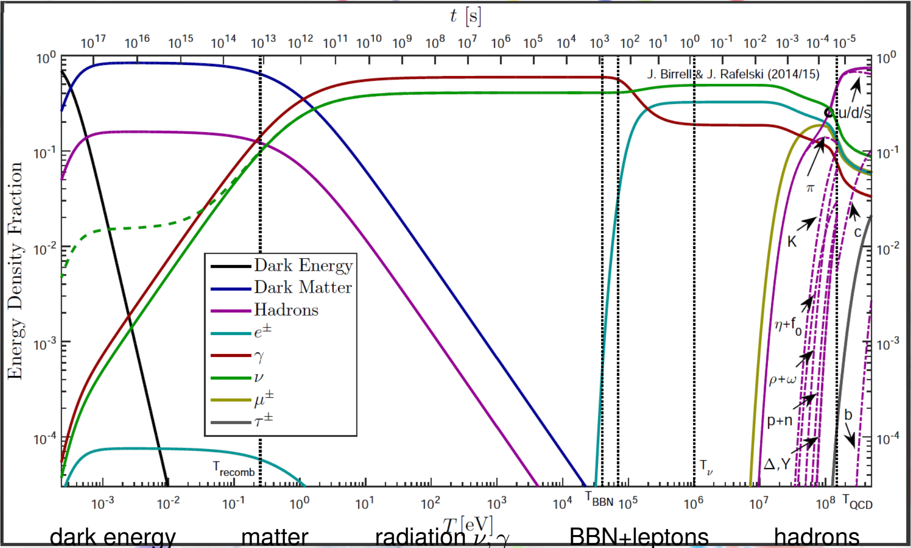


Distinct Composition Eras visible. Equation of state from lattice-QCD, and at high T thermal-QCD must be used [1,2].

[1] *S. Borsanyi, Nucl. Phys. A904-905, 270c (2013)*
[2] *Mike Strickland (private communication of results and review of thermal SM).*

20y after: Connect to hot Quark-Hadron ‘Hagedorn’ Universe

TODAY **The Universe Composition in Single View** **QGP**



dark energy matter radiation ν, γ BBN+leptons hadrons

Different dominance eras: Temperature grows to → right

Mechanism assuring hadrons in kinetic/thermal equilibrium

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

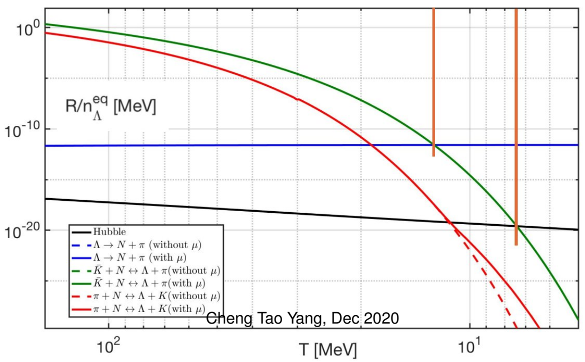
$$\pi^0 \leftrightarrow \gamma + \gamma$$

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 $T = \mathcal{O}$(2-4)MeV
Photons freeze-out at $T = 0.235$ eV
But is the early Universe beyond $T = 1$ MeV really made of hadrons only?

Kinetic strangeness in thermal Universe 2020



Cheng Tao Yang, Dec 2020

- We mark in cosmic medium at $T = 13$ MeV where strangeness exchange reactions $K + n \Leftrightarrow \Lambda + \pi$ become slower compared to WI $\Lambda \Leftrightarrow N + \pi$. At yet lower temperature $s \neq \bar{s}$. At lower T strangeness contents needs to follow kinetic theory.

- At $T = 7.3$ MeV we mark the point where the Hubble expansion becomes faster $\Lambda \Leftrightarrow N + \pi$. Now Λ disappear and latest here strangeness must disappear completly from the inventroy of the Universe: At a lower T Λ are out of detailed balance.

Are Kaons still in equilibrium abundance?

JR & Cheng Tao Yang “Reactions Governing Strangeness Abundance in Primordial Universe” arXiv:2009.05661

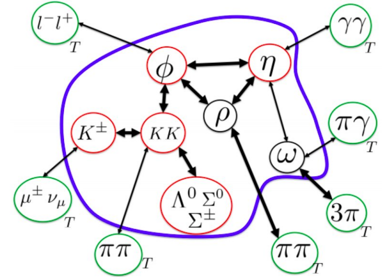


Figure 1. Principal strangeness abundance changing processes in the hadronic Universe $T < T_H = 150$ MeV. The blue boundary is drawn around hadronic particles expected to fall out of abundance equilibrium. The red circles within this domain represent strangeness-carrying mesons, black non-strange mesons of importance in creation of strangeness. The equilibrium (index T) heat bath of particles in green circles outside the blue domain contribute to meson forming reactions we study seen in the blue dynamical particle ‘pot’.

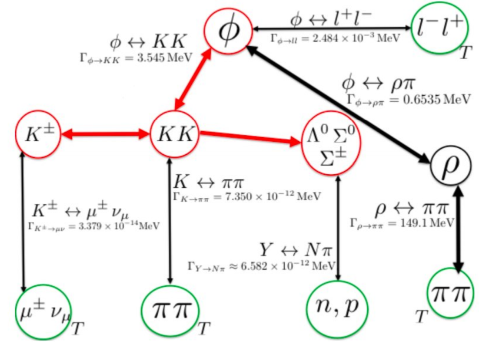


Figure 2. The strangeness abundances changing reactions in primordial Universe. The red circles show strangeness carrying hadronic particles; red thick lines denote effectively instantaneous reaction. Black thick lines show relatively strong hadronic reactions before strangeness is produced.

Key rates

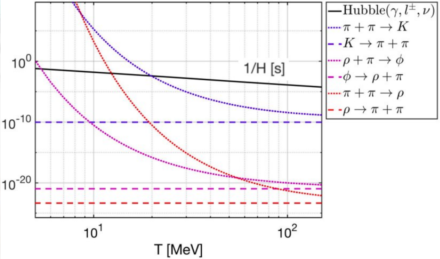


Figure 3. Hubble time $1/H$ (black line) as a function of temperature is compared to hadronic relaxation reaction times, see Eq. (19), for reactions $\pi + \pi \leftrightarrow K$(blue), $\pi + \pi \leftrightarrow \rho$ (red), $\rho\pi \leftrightarrow \phi$(purple). The horizontal dashed lines are the natural decay lifespans.

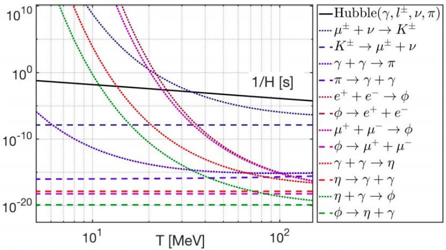
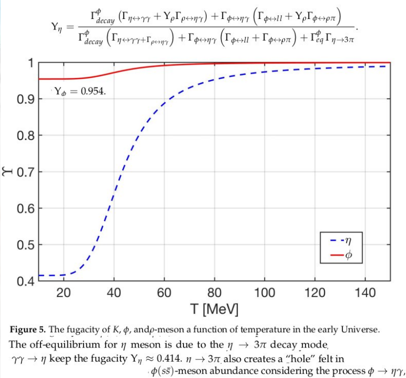


Figure 4. Hubble time $1/H$ (black line) as a function of temperature is compared to leptonic and photonic relaxation reaction times, see Eq. (19), for $\gamma + \gamma \leftrightarrow \pi$ (blue), $\gamma + \gamma \leftrightarrow \eta$ (red), $\eta + \gamma \leftrightarrow \phi$ (green), $l^{+} + l^{-} \leftrightarrow \phi$ (brown and purple), and $\mu^{\pm} + \nu_{\mu} \longrightarrow K^{\pm}$(dark blue line). The horizontal dashed lines are the natural decay lifespans.

Consequences



$$Y_\eta = \frac{\Gamma^{\phi}_{decay}\left(\Gamma_{\eta\leftrightarrow\gamma\gamma} + Y_\rho\Gamma_{\rho\leftrightarrow\eta\gamma}\right) + \Gamma_{\phi\leftrightarrow\eta\gamma}\left(\Gamma_{\phi\leftrightarrow ll} + Y_\rho\Gamma_{\phi\leftrightarrow\rho\pi}\right)}{\Gamma^{\phi}_{decay}\left(\Gamma_{\eta\leftrightarrow\gamma\gamma+\Gamma_{\rho\leftrightarrow\eta\gamma}}\right) + \Gamma_{\phi\leftrightarrow\eta\gamma}\left(\Gamma_{\phi\leftrightarrow ll} + \Gamma_{\phi\leftrightarrow\rho\pi}\right) + \Gamma^{\phi}_{eq}\Gamma_{\eta\to 3\pi}}.$$

Figure 5. The fugacity of K, ϕ, andρ-meson a function of temperature in the early Universe. The off-equilibrium for η meson is due to the $\eta \to 3\pi$ decay mode, $\gamma\gamma \to \eta$ keep the fugacity $Y_\eta \approx 0.414$. $\eta \to 3\pi$ also creates a "hole" felt in $\phi(s\bar{s})$-meson abundance considering the process $\phi \to \eta\gamma$,

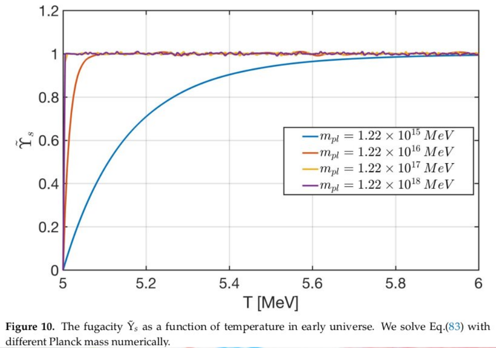


Figure 10. The fugacity $\tilde{\Upsilon}_s$ as a function of temperature in early universe. We solve Eq.(83) with different Planck mass numerically.

Sideline: muons like pions in thermal equilibrium

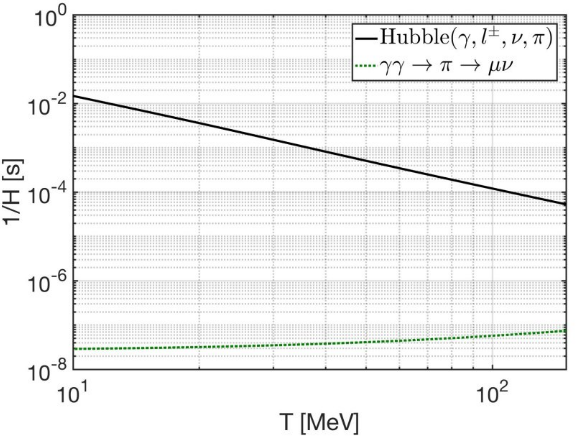


Figure A1. The reaction time for $\gamma + \gamma \longrightarrow [\pi^0 \leftrightarrow \pi^\pm] \longrightarrow \mu^\pm + \nu_\mu$ and Hubble time $1/H$ as a function of temperature in the early Universe.

Noteworthy: the continous replentishment of muons at EM rate and their WI decay rate generated added 'hot' neutrino component in primordial Universe.

Last Words: Dominant content of the Universe and Origin of baryon asymmetry remain a mystery

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

1. Visible (baryonic) matter: mainly hydrogen, helium
   (less 5% of present day total energy inventory)
   A mere 10^{-9} remnant of post QGP baryon annihilation period
2. Free-streaming matter
   i.e particles that do not interact – have ‘frozen’ out:
   - Photons: since $T = 0.235$eV *(insignificant in today’s inventory)*
   - Neutrinos: since $T = 1.5$–3.5 MeV
   - Mystery dark matter *(25% in energy inventory)*
     1. Massive ColdDarkMatter free from way before QGP hadronization
     2. Warm dark matter: e.g. neutrinos of suitable mass
     3. Unknown massless dark matter: darkness: maybe ‘needed’, origin precedes neutrino decoupling
3. Dark energy = vacuum energy *(70% of energy inventory)*