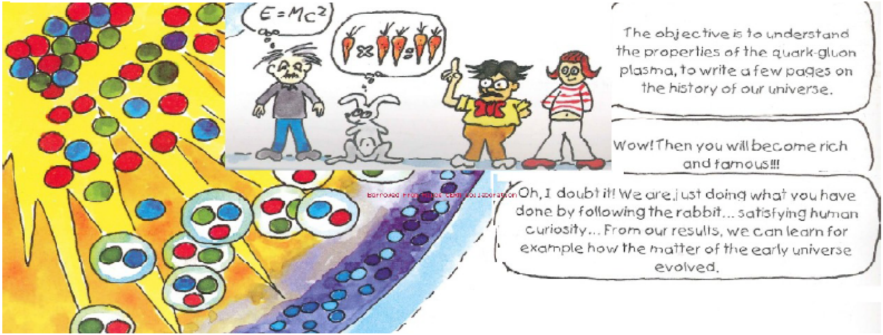
Wroclaw: [Seminarium Zakładu Teorii Cząstek Elementarnych]

Time Evolution of Hot Hagedorn Universe

Jan Rafelski, Department of Physics, *University of Arizona*



The task: connect the present day visible Universe with prior eras, back to primordial conditions at and above Hagedorn temperature, the point of creation of matter as we know it. Matter and antimatter emerged from Quark_Gluon Plasma when the Universe was 13 microseconds old. A nano-fraction surplus of matter survives the ensuing annihilation process. A dense electron positron- photon-neutrino plasma evolves. Electrons and positrons annihilate while neutrinos decouple. All this takes less than a second, this creates the context for the big-bang nucleo-synthesis and ultimately leads to the visible Universe around us. The continuous evolution across many evolutionary eras will be discussed and the Universe energy composition across cosmological history illustrated.

Outline

1. Convergence of 1964-68 ideas
   - Quarks + Higgs → Standard Model of particle physics
   - CMB discovered → Big Bang
   - Hagedorn Temperature $T_{\rm H}$, Statistical Bootstrap=initial singularity
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

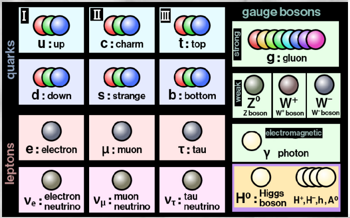
G. Zweig ×)
CERN – Geneva

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

Peter W. Higgs
Phys. Rev. Lett. 13, 508 (1964)
Published October 19, 1964

Broken Symmetry and the Mass of Gauge Vector Mesons

F. Englert and R. Brout
Phys. Rev. Lett. 13, 321 (1964)
Published August 31, 1964

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

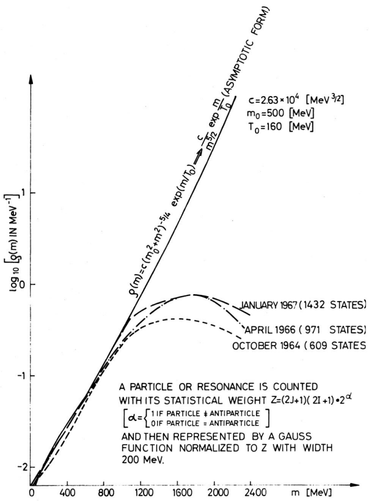
R. Hagedorn
CERN - Geneva

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 $m \to \infty$ these objects are themselves very similar to those which shall be described by this thermodynamics. Expressed in a slogan: "We describe by thermodynamics fire-balls which consist of fire-balls, which consist of fire-balls, which ...". This principle, which could be called "asymptotic bootstrap", leads to a self-consistency requirement for the asymptotic form of the mass spectrum. The equation following from this requirement has only a solution if the mass spectrum grows exponentially:

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

T_o is a remarkable quantity: the partition function corresponding to the above $\rho(m)$ diverges for $T \to T_o$. 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.



1965: Microwave Background Penzias and Wilson

 1965ApJ...142..419P

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

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

Note added in proof.—The highest frequency at which the background temperature of the sky had been measured previously was 404 Mc/s (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

Penzias and Wilson were awarded the Nobel Prize in 1978

1966-1968: SBM Hot Big-Bang 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

E. 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?

References

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

14. Hagedorn, R., *Suppl. Nuovo Cim.*, **3**, 147 (1965); *ibid.*, **6**, 311 (1968); *Nuovo Cim.*, **52**A, 1336 (1967); *ibid.*, **56**A, 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."

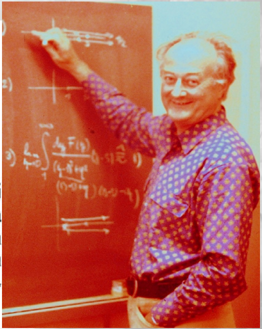
accepted as 'the' initial singular hot Big-Bang theory

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

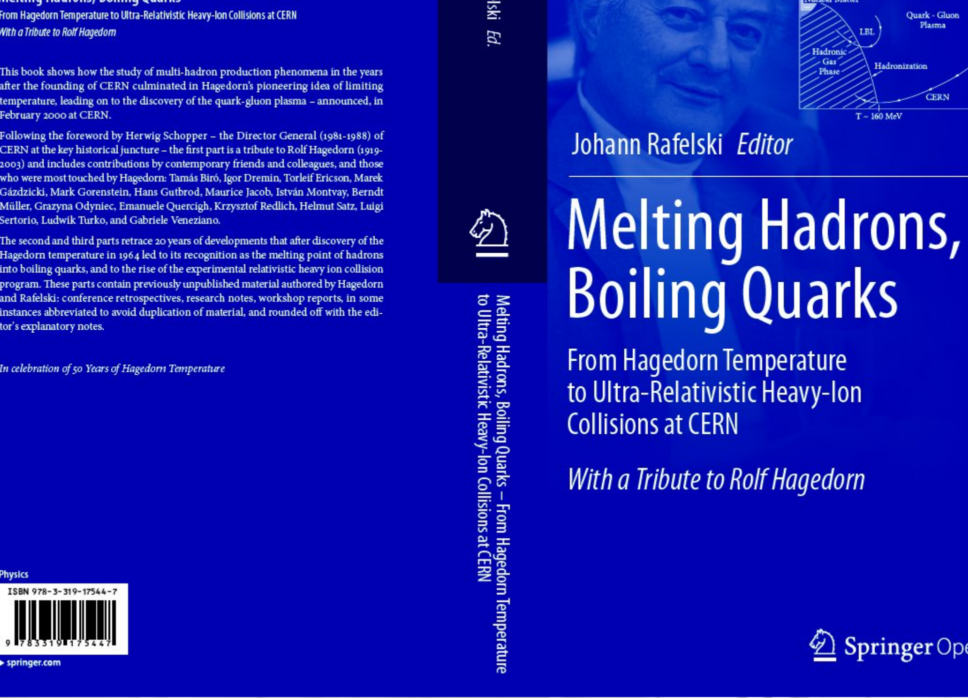
Siedende Urmaterie

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.*



Melting Hadrons, Boiling Quarks

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

With a Tribute to Rolf Hagedorn

This book shows how the study of multi-hadron production phenomena in the years after the founding of CERN culminated in Hagedorn's pioneering idea of limiting temperature, leading on to the discovery of the quark-gluon plasma – announced, in February 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

9 783319 175447

▸ springer.com

lski *Ed.*

Melting Hadrons, Boiling Quarks – From Hagedorn Temperature to Ultra-Relativistic Heavy-Ion Collisions at CERN

Johann Rafelski *Editor*

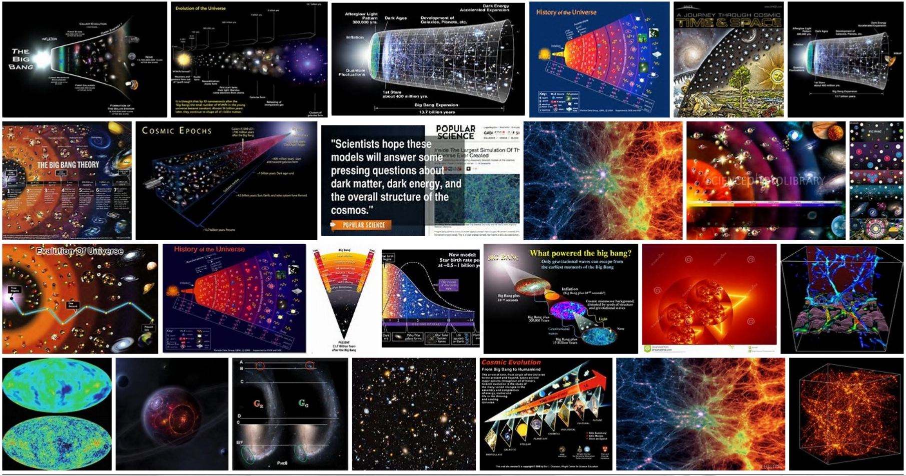
Melting Hadrons, Boiling Quarks

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

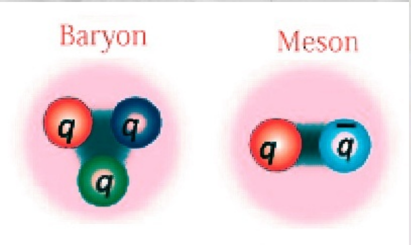
With a Tribute to Rolf Hagedorn

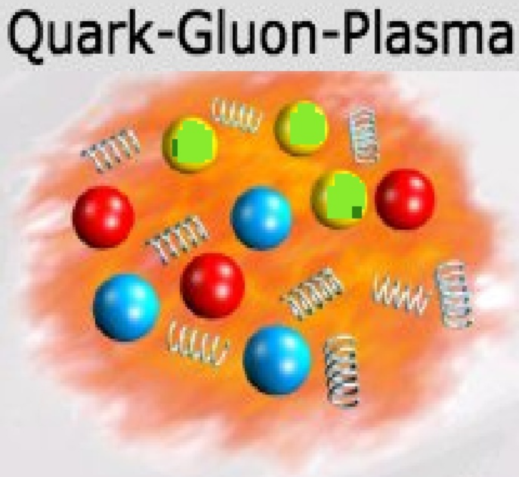
Springer Ope

Time travel forward 15 Years to 1980



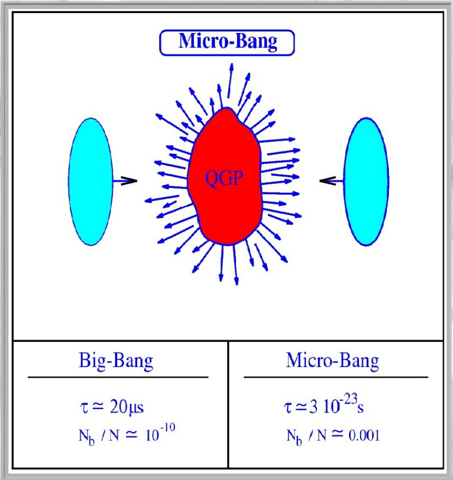
Quarks make pions (mesons); squeeze many together





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

Can we recreate Big-Bang in lab?



Relativistic Heavy Ion Collisions

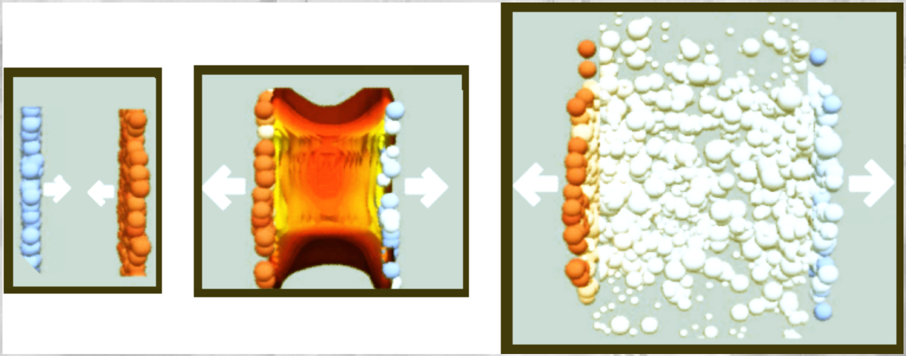
- Universe time scale 18 orders of magnitude longer, hence equilibrium of leptons & photons
- Baryon asymmetry six orders of magnitude larger in Laboratory, hence chemistry different
- Universe: dilution by scale expansion, Laboratory explosive expansion of a fireball

$\Longrightarrow$ Theory connects RHI collision experiments to Universe

What is special with Quark Gluon Plasma made in RHI collisons?

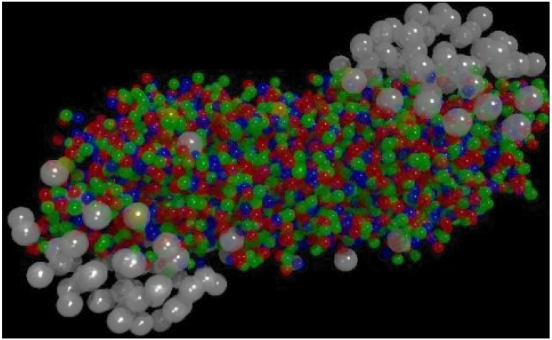
1. RECREATE THE EARLY UNIVERSE IN LABORATORY
   Recreate and understand the high energy density conditions prevailing in the Universe when matter formed from elementary degrees of freedom (quarks, gluons) at about 20 μs after the Big-Bang.
2. PROBING OVER A 'LARGE' DISTANCE THE (DE)CONFINING QUANTUM VACUUM STRUCTURE
   The quantum vacuum determines prevailing form of matter and laws of nature.
3. STUDY OF THE ORIGIN OF MASS OF MATTER
   The confining vacuum is the origin of the dominant part of the mass of matter.
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 with 2nd family matter $(s, c, [\mu, \nu_\mu]))$.

relativistic Heavy Ions Make QGP – Really?



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

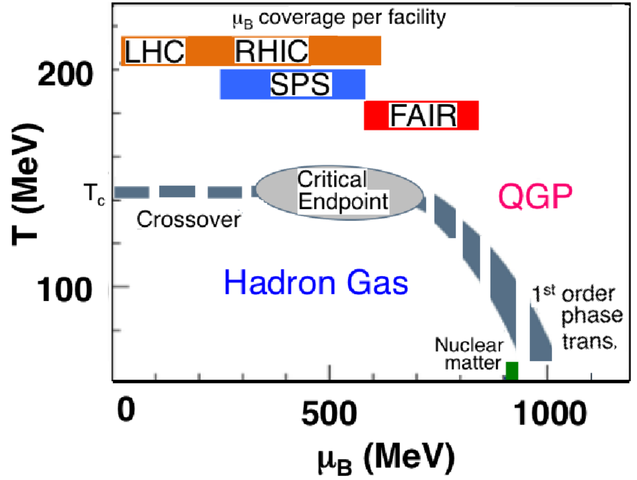
About signatures of QGP discovery see discussion presented by **P Koch, B Müller, J Rafelski** in the review “From Strangeness Enhancement to Quark-Gluon Plasma Discovery” *Int. J. of Modern Physics A* **32** (2017) 1730024;

DOI: 10.1142/S0217751X17300241; and arXiv 1708.0811

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

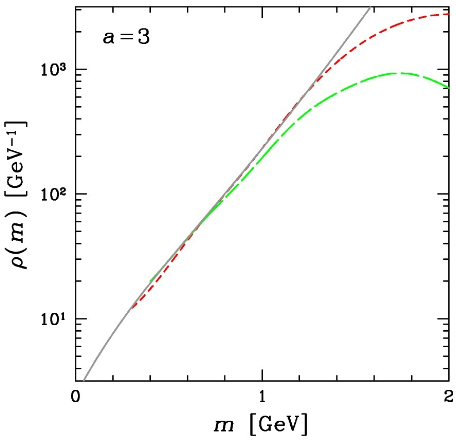
Preeminent feature: matter flow at quantum limit

Current interest I: Explore QGP phase diagram



See e.g. Hagedorn Model of Critical Behavior: Comparison of Lattice and SBM Calculations **Ludwik Turko** Hagedorn Blue book pp 81-86 and arXiv:1502.03647

Current interest II: Explore Hagedorn exponential hadron mass spectrum

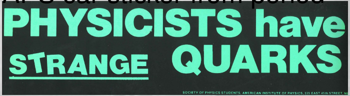


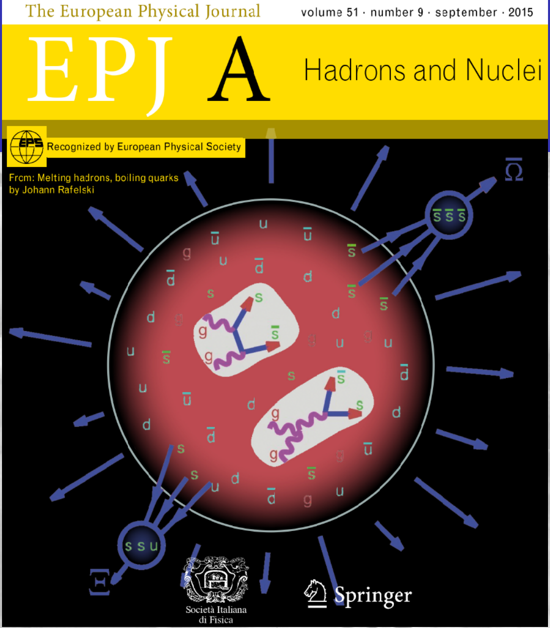
Slope for prescribed pre-exponential shape is the Hagedorn Temperature: this is a way to determine critical properties of deconfinement phase change. See e.g. The Legacy of Rolf Hagedorn: Statistical Bootstrap and Ultimate Temperature **Krzysztof Redlich**, and Helmut Satz Hagedorn Blue book pp 49-68 and arXiv:1501.07523

My interest 1:

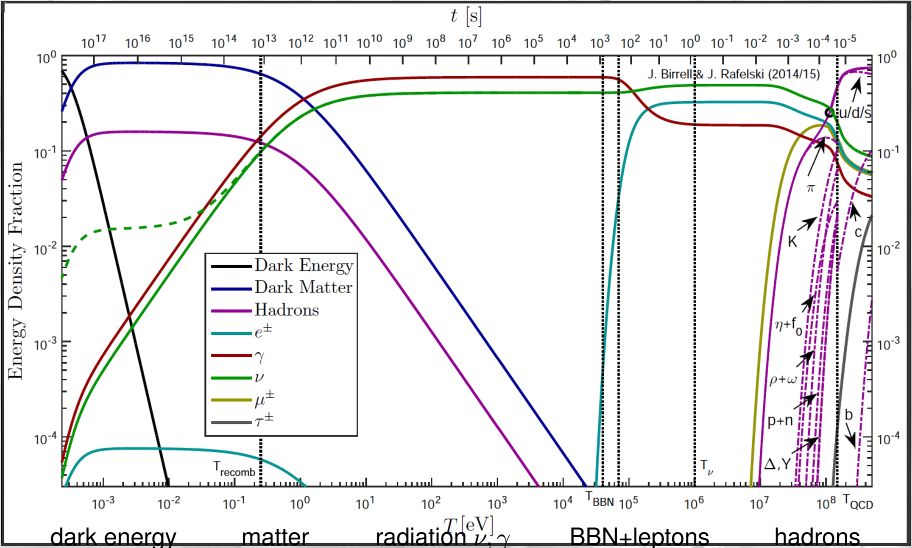
Cooking strange quarks → strange antibaryons

APS car sticker from period





The Universe Composition in Single View



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.

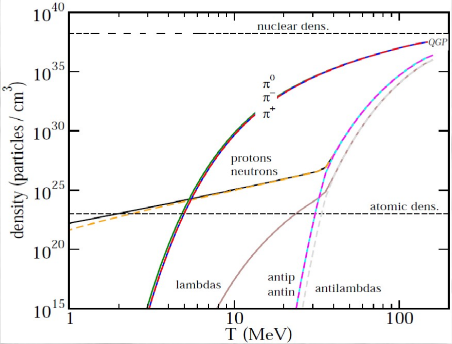
ii. Net lepton number equals(?) net baryon number
B/L-asymmetry can hide in neutrino-antineutrino imbalance

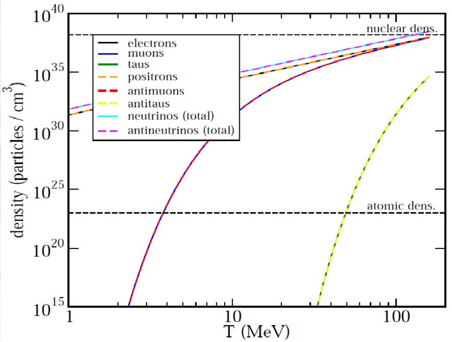
iii. Prescribed value of entropy-per-baryon $\equiv n_B/n_\gamma$

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

$S/B \simeq 3$–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 $m_\nu << T_k$.

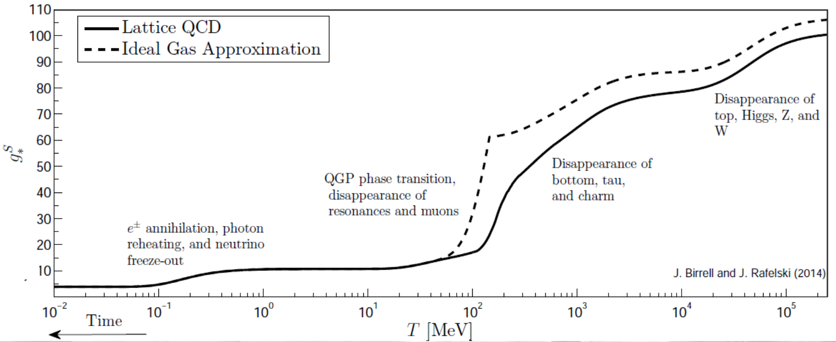
C. Cercignani, and G. Kremer. The Relativistic Boltzmann Equation: Basel, (2000).
H. Andreasson, "The Einstein-Vlasov System"Living Rev. Rel. **14***, 4 (2011) Y. Choquet-Bruhat. General Relativity and the Einstein Equations, Oxford (2009).*

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 $8\pi G_N/3 \rightarrow$ 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. Knowing the Universe composition in present era we can integrate back IF we know what is the contents.

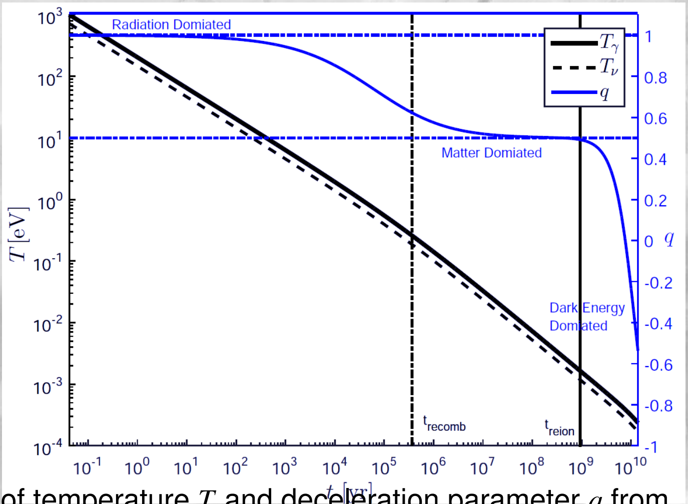
Evolution Eras and Deceleration Parameter q

Using Einsteins equations solving for $G_N = G_N$

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

- 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

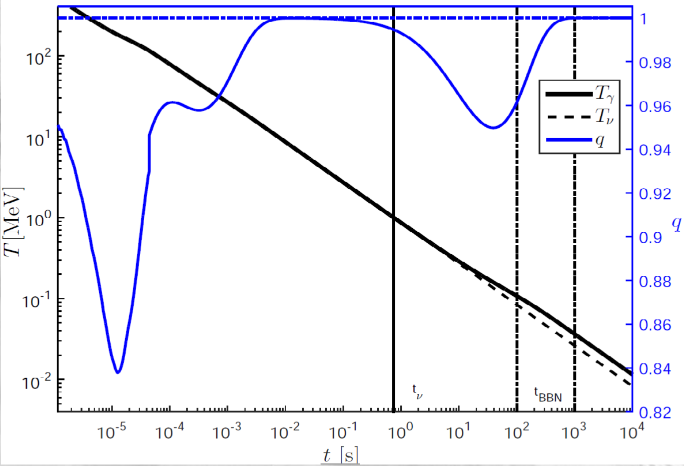


Evolution of temperature T and deceleration parameter q from near/after BBN to the present day: time grows to right

Long ago: Hadron and QGP Era

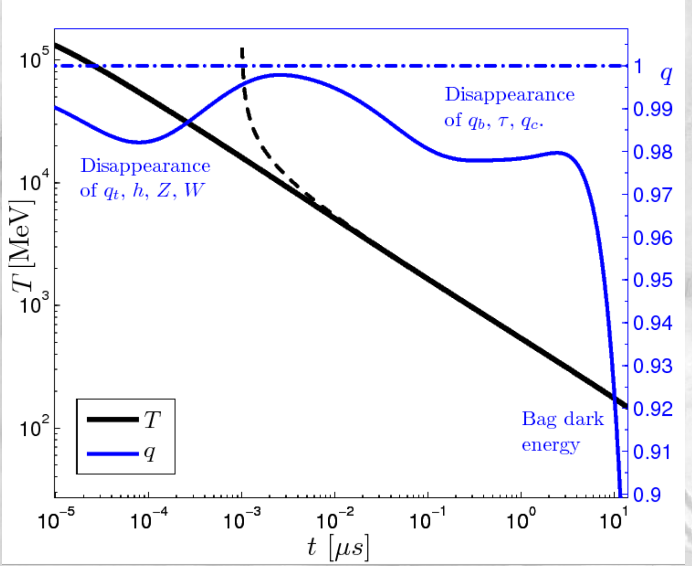
- QGP era down to phase transition at $T \approx 150$MeV. Energy density dominated by photons, neutrinos, $e^{\pm}$, $\mu^{\pm}$ along with u, d, s quarks.
- $2+1$-flavor lattice QCD equation of state used
- u, d, s, G lattice energy density is matched by ideal gas of hadrons to sub percent-level at $T = 115$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

ELSEVIER

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_{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_{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 a connection between N_{eff} and the QGP transformation for laboratory studies of QGP.

What is this all good for? A few examples

Time independence of natural constants

Available online at www.sciencedirect.com
ScienceDirect
Nuclear Physics B 890 (2015) 481–517
NUCLEAR PHYSICS B
www.elsevier.com/locate/nuclphysb

Relic neutrino freeze-out: Dependence on natural constants

Jeremiah Birrell [a,b,*], Cheng Tao Yang [b,c], Johann Rafelski [b]

[a] *Program in Applied Mathematics, The University of Arizona, Tucson, AZ 85721, USA*
[b] *Department of Physics, The University of Arizona, Tucson, AZ 85721, USA*
[c] *Department of Physics and Graduate Institute of Astrophysics, National Taiwan University, Taipei, 10617, Taiwan*

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

Jeremiah Birrell[a], **Johann Rafelski**

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

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...

Find

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Dynamical emergence of the Universe into the false vacuum

Johann Rafelski and Jeremiah Birrell

Department of Physics, University of Arizona,
1118 E. 4th Street, Tucson, Arizona, 85721, U.S.A.

E-mail: rafelski@physics.arizona.edu, jbirrell@email.arizona.edu

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

Jeremiah Birrell,[1] Cheng-Tao Yang,[2,3] Pisin Chen,[2,3,4] and Johann Rafelski[5]

[1]*Program in Applied Mathematics, The University of Arizona, Tucson, Arizona 85721, USA*

[2]*Department of Physics and Graduate Institute of Astrophysics, National Taiwan University, Taipei, Taiwan 10617*

[3]*Leung Center for Cosmology and Particle Astrophysics (LeCosPA), National Taiwan University, Taipei, Taiwan 10617*

[4]*Kavli Institute for Particle Astrophysics and Cosmology, SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*

[5]*Department of Physics, The University of Arizona, Tucson, Arizona 85721, USA*

(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

- 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.