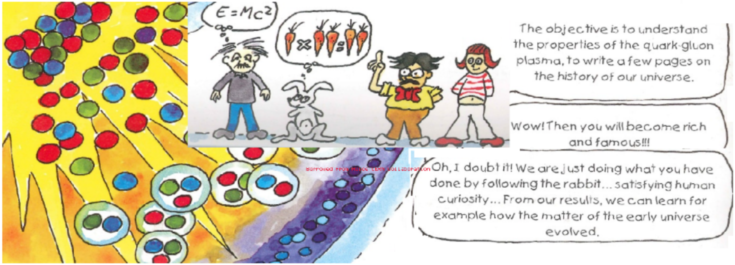
Evolution of Matter in the Universe:
from quark-gluon plasma era to the present

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



Today we connect the present day visible Universe with prior eras, beginning with the primordial period above Hagedorn temperature before the emergence of matter as we know it. This was the quark-gluon plasma (QGP), a new phase of matter discovered in recent experimental laboratory work. QGP was omni-present up to when the Universe was 13 microseconds old. As the universe expands and cools QGP hadronizes, forming abundant matter and antimatter. Only a nano-fraction surplus of matter survives the ensuing annihilation process. A dense electron positron photon neutrino plasma remains. Electrons and positrons annihilate while neutrinos decouple. All this takes less than a second, and within this time also the few remaining neutrons are fixed in their final abundance; the first second creates the context for the big-bang nucleo-synthesis and ultimately leads to the visible Universe around us; we show how different components in the Universe evolves from QGP to the present era.

Outline

1. Convergence of 1964-68 ideas
   1.1 Quarks + Higgs $\rightarrow$ Standard Model of particle physics
   1.2 CMB discovered $\rightarrow$ Big Bang
   1.3 Hagedorn Temperature T_{H}, Statistical Bootstrap initial singularity $\rightarrow$ A new elementary form of matter made of quark-gluon plasma: QGP
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

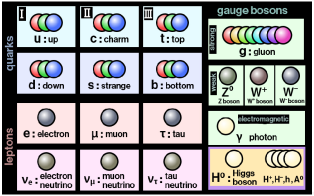
California Institute of Technology, Pasadena, California, USA

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

1965: Penzias and Wilson discover CMB

1966-1968: Hot Big-Bang becoming conventional wisdom

physicstoday

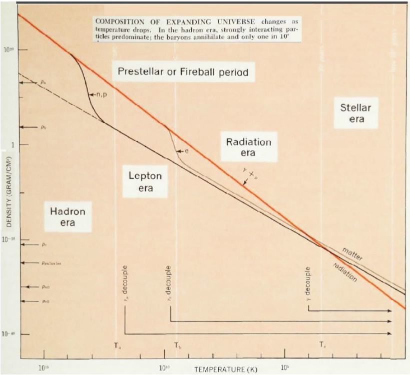
The early universe

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



We did NOT know what was there at the 'Beginning' how matter was created.

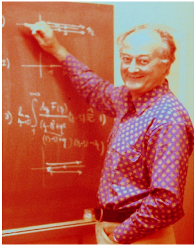
1965-7 – Hagedorn's singular Statistical Bootstrap Model accepted as 'the' initial singular hot Big-Bang theory

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.*

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

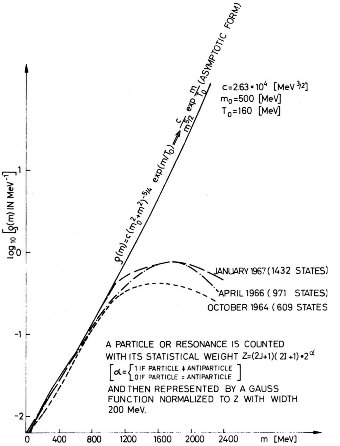
R. Hagedorn
CERN - Geneva

ABSTRACT

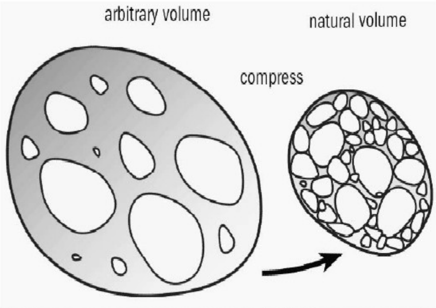
In this statistical-thermodynamical approach to strong interactions at high energies it is assumed that higher and higher resonances of strongly interacting particles occur and take part in the thermodynamics as if they were particles. For $m \to \infty$ these objects are themselves very similar to those 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:

$$\rho(m) \xrightarrow[m \to \infty]{} \mathrm{const.}\, m^{-5/2} \exp\left(\frac{m}{T_0}\right).$$

T_0 is a remarkable quantity: the partition function corresponding to the above $\rho(m)$ diverges for $T \to T_0^-$. T_0 is therefore the highest possible temperature for strong interactions. It should - via a 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_0 is about 158 MeV ($\approx 10^{12}$ °K). With this value of T_0 the asymptotic mass spectrum of our theory has a good chance to be the correct extrapolation of the experimentally known spectrum.



What is the Statistical Bootstrap Model (SBM)?



A volume comprising a gas of fireballs compressed tonatural volume is itself again a fireball.

$$\tau(m^2)\mathrm{d}m^2 \equiv \rho(m)\mathrm{d}m \quad \rho(m) \propto m^{-a}\exp(m/T_{\mathrm{H}}).$$

nature

article

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

Comments on the Big-bang

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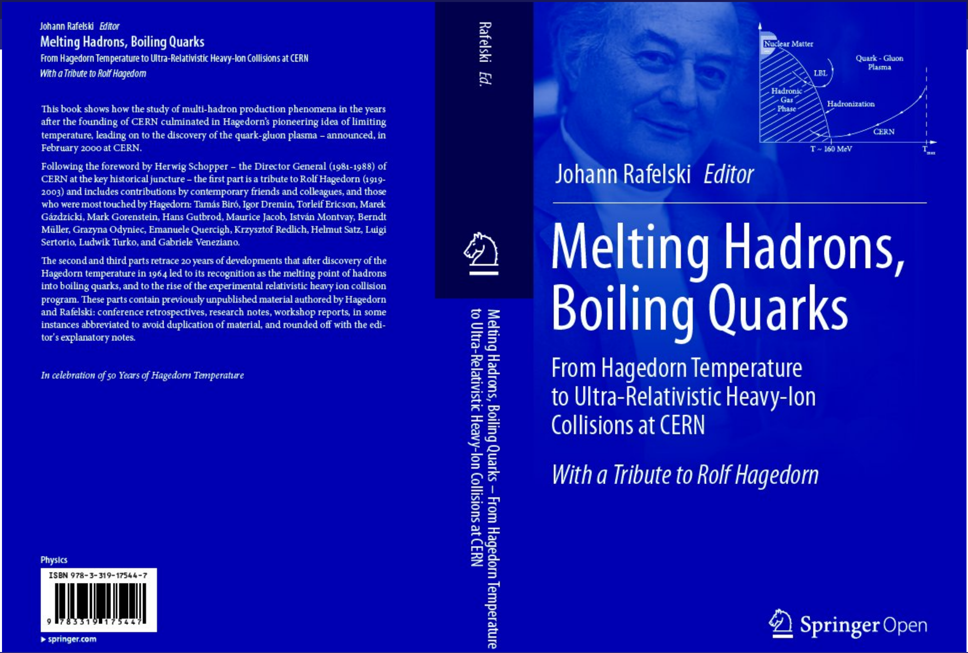
Is the big-bang hot, warm or cold? And are galactic masses determined by the interplay of gravitational and strong interactions in the very early universe?

References

1. Harrison, E. R., *Nature*, **215**, 151 (1967).
2. Harrison, E. R., *Phys. Rev.* (in the press).
3. Harrison, E. R., *Mon. Not. Roy. Astro. Soc.*, **148**, 119 (1970).
4. Dicke, R. H., Peebles, P. J. E., Roll, P. G., and Wilkinson, D. T., *Astrophys. J.*, **142**, 414 (1965).
5. Wagoner, R. V., Fowler, W. A., and Hoyle, F., *Astrophys. J.*, **148**, 3 (1967).
6. Harrison, E. R., *Phys. Rev.*, **167**, 1170 (1968).
7. Misner, C. W., *Phys. Rev. Lett.*, **22**, 1071 (1969).Khalatnikov, I. M., and Lifshitz, E. M., *Phys. Rev. Lett.*, **24**, 76 (1970).
8. Harrison, E. R., *Astrophys. J.*, **142**, 1643 (1965).
9. Zel'dovich, Ya. B., *Sov. Phys., JETP*, **14**, 1143 (1962).
10. Harrison, E. R., *Mon. Not. Roy. Astro. Soc.*, **140**, 281 (1968).
11. Layzer, D., *Astrophys. Lett.*, **1**, 93 (1968).
12. Kaufman, M., *Astrophys. J.*, **160**, 459 (1970).
13. Rees, M. J., *Observatory*, **89**, 972 (1969).
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).


Johann Rafelski Editor
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
springer.com
Rafelski Ed.
Melting Hadrons, Boiling Quarks – From Hagedorn Temperature to Ultra-Relativistic Heavy-Ion Collisions at CERN
Nuclear Matter
Quark - Gluon Plasma
LBL
Hadronic Gas Phase
Hadronization
CERN
T ~ 160 MeV
Johann Rafelski Editor
Melting Hadrons, Boiling Quarks
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With a Tribute to Rolf Hagedorn
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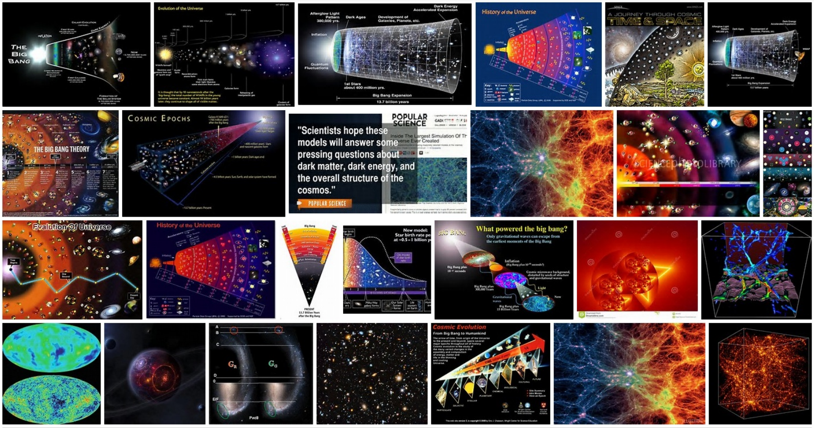
Forward 50 Years



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.

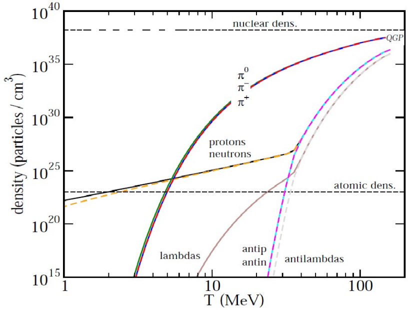
ii. Net lepton number equals(?) net baryon number
B/L-asymmetry can hide in neutrino-antineutrino imbalance

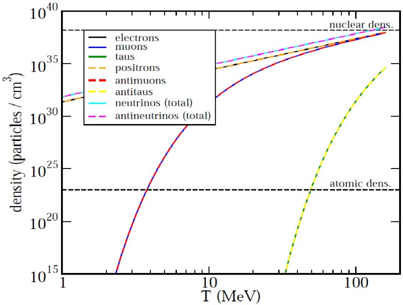
iii. Prescribed value of entropy-per-baryon $\equiv n_B/n_\gamma$

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

$S/B \simeq 3$–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:

$$\pi^0 + \pi^0 \leftrightarrow \pi^+ + \pi^-. \quad \rho \leftrightarrow \pi + \pi, \quad \rho + \omega \leftrightarrow N + \bar{N}, \quad etc$$

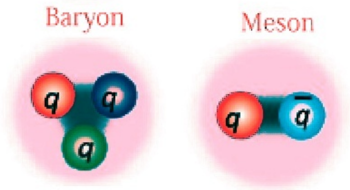
The π^0 remains always in chemical equilibrium All charged leptons always in chemical equilibrium – with photons

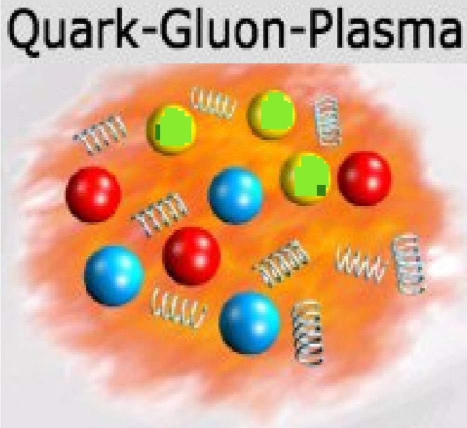
Neutrinos freeze-out at $T = \mathcal{O}$2-4MeV, more discussion follows

Photons freeze-out at $T = 0.25$ eV

But is the early Universe really made of hadrons?

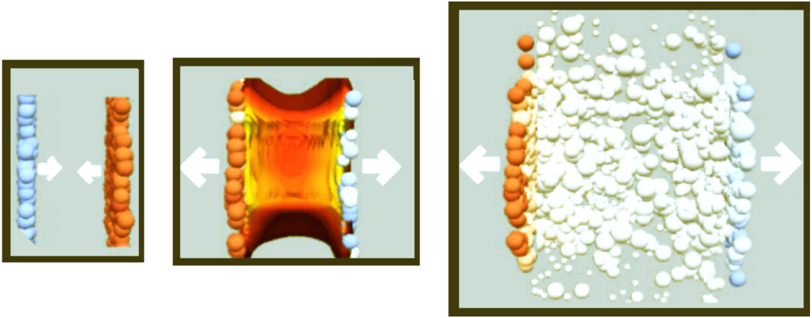
Quarks make pions (mesons); squeeze many together



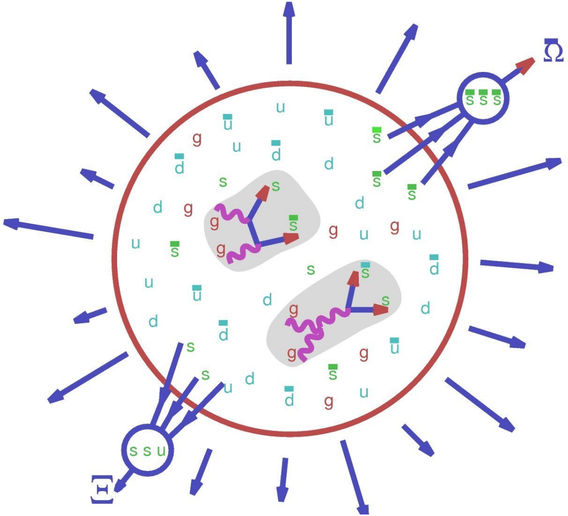


In the early Universe the building blocks of baryons and mesons were liberated!

relativistic Heavy Ions Make QGP



QGP explodes making hadrons



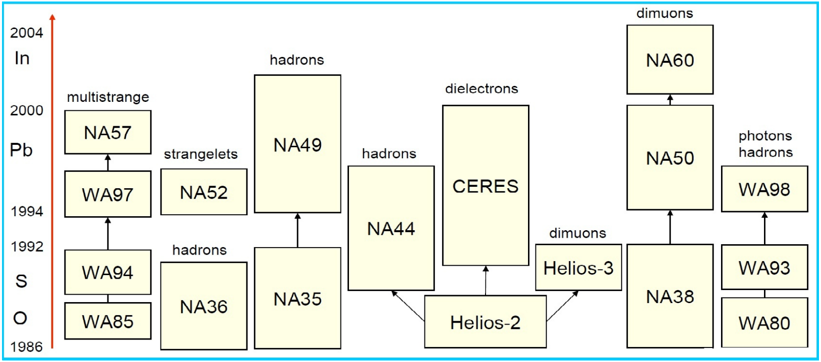
Hadrons → Quarks → laboratory tests: 1965-82

- Cold quark matter in diverse formats from day 1: 1965
  D.D. Ivanenko and D.F. Kurdgelaidze, *Astrophysics* **1**, 147 (1965)
  Hypothesis concerning quark stars
- Interacting QCD quark-plasma: 1974
  P. Carruthers, *Collect. Phenomena* **1**, 147 (1974)
  Quarkium: a bizarre Fermi liquid
- Quark confining vacuum structure dissolved at high T
  A.M.Polyakov, *Phys. Lett. B* **72**, (1978)
  Thermal properties of gauge fields and quark liberation
- Formation of hot quark-gluon matter in RHI collisions:
  conference talks by Rafelski-Hagedorn (CERN) 1978-9
  Chapline-Kerman MIT-CTP 695 unpublished 1978
- First practical experimental signature:
  Strangeness and Strange antibaryons 1980 ff.
  Rafelski (with Danos, Hagedorn, Koch (grad student), B. Müller
- Statistical materialization model (SHM) of QGP: 1982
  Rafelski (with Hagedorn, Koch(grad student), B. Müller

What is special with Quark Gluon Plasma made in lab?

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 $(s, c, [\mu, \nu_\mu]))$.

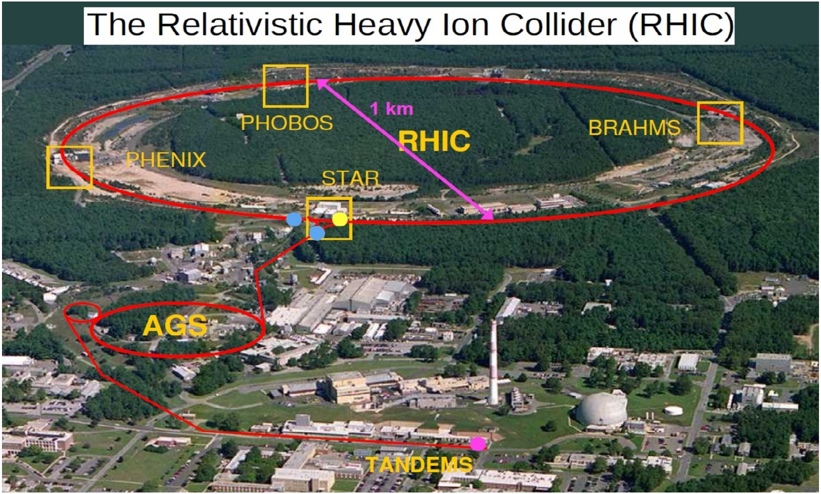
RHI experimental program is born 1980-86



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

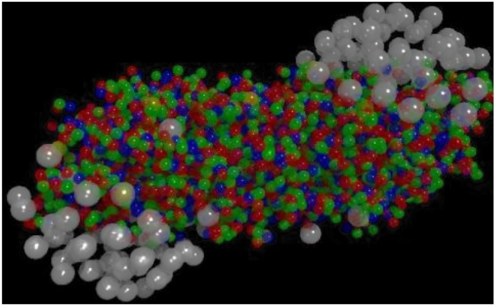
particle and nuclear physics united for RHI in Europe

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



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

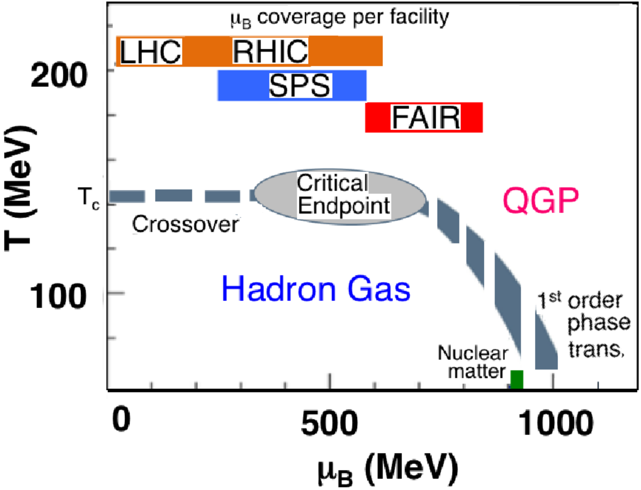
See:*From Strangeness Enhancement to Quark-Gluon Plasma Discovery*

arXiv 1708.0811 P Koch, B Müller, J Rafelski

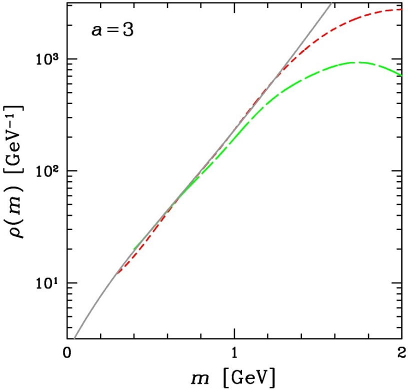
9AM, 18 April 2005; US – RHIC announces QGP Press conference APS Spring Meeting

Preeminent feature: matter flow at quantum limit

Current interest I: Exploration of the QGP phase diagram



Current interest II: Exploration of exponential mass spectrum

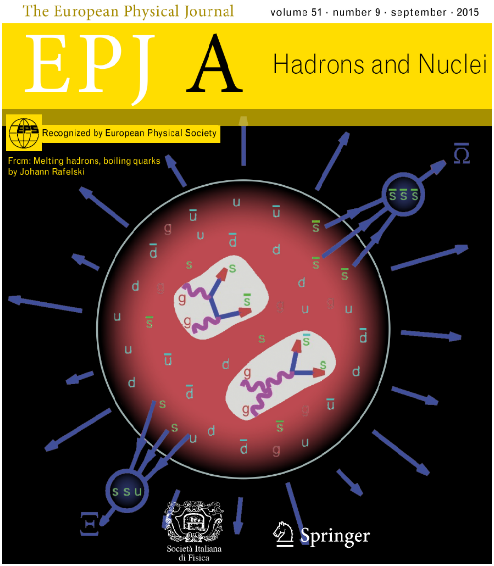


Slope for prescribed pre-exponential shape is the Hagedorn Temperature: another way to determine critical properties of deconfinement phase change

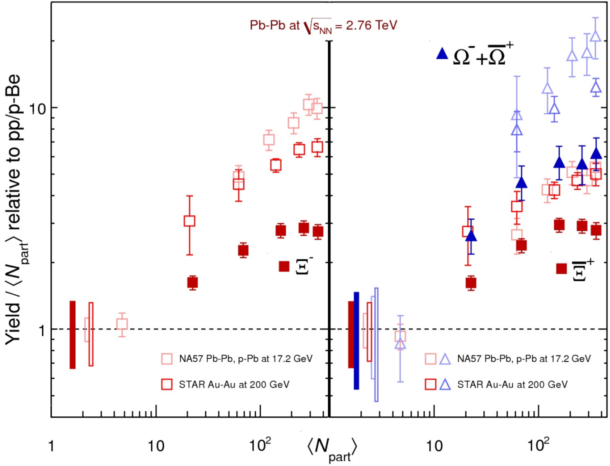
My interest:

Cooking strange quarks $\longrightarrow$ strange antibaryons

APS car sticker from period

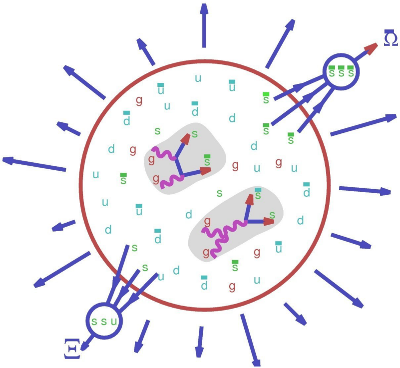


Prediction: 1980-86 confirmed



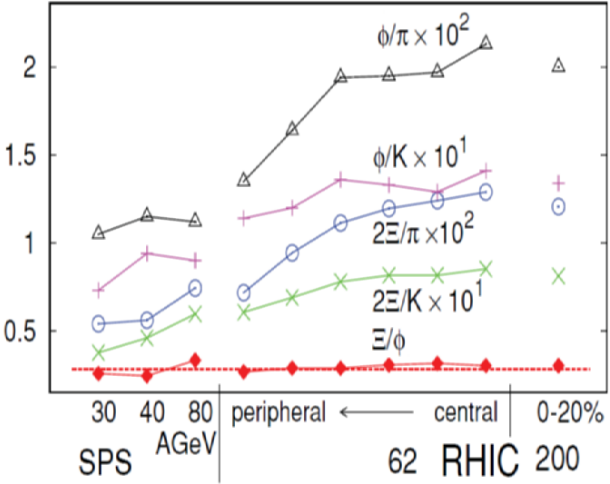
Largest medium effect attributed to QGP formation; systematics as predicted

Recombination two step production



Cooking strangeness + recombination emission means
$\Xi(qss)/\phi(s\bar{s}) \rightarrow Const.$

Verification of quark recombination mechanism



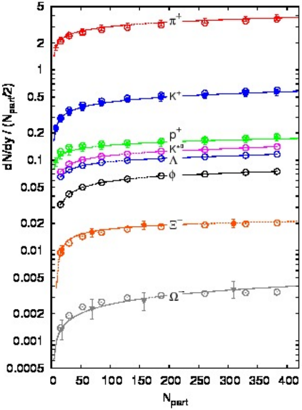
Note only $\Xi(qss)/\phi(s\bar{s}) \rightarrow Const.$

Verification of matter creation model

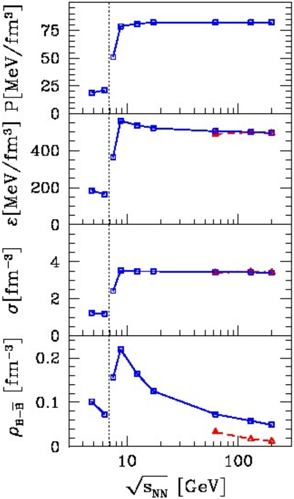
equal hadron production strength

yield depending on available phase space

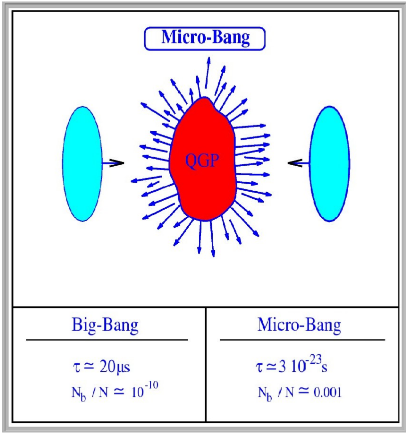
Example data from LHC⇓



Bulk properties⇓



Is lab/RHI collision a good simulation of Big-Bang?



- 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

Next‘: connect present day to the QGP epoch

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

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 $m_\nu << T_k$.

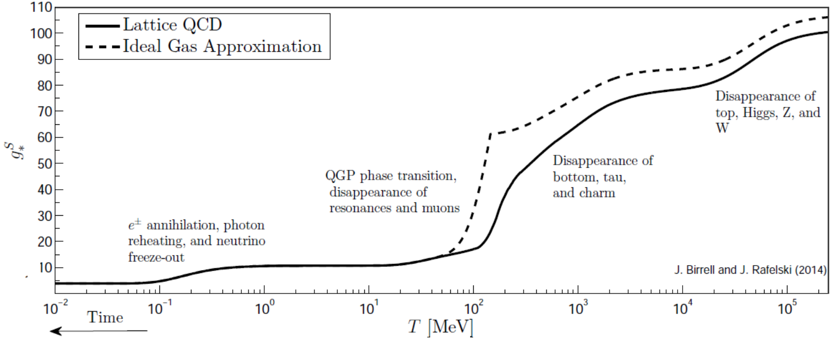
C. Cercignani, and G. Kremer. The Relativistic Boltzmann Equation: Basel, (2000).
H. Andreasson, "The Einstein-Vlasov System"Living Rev. Rel. **14***, 4 (2011) Y. Choquet-Bruhat. General Relativity and the Einstein Equations, Oxford (2009).*

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

Connecting Universe age to temperature

Friedmann–Lemaitre–Robertson–Walker (FRW) cosmology

- Einstein Universe:

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

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

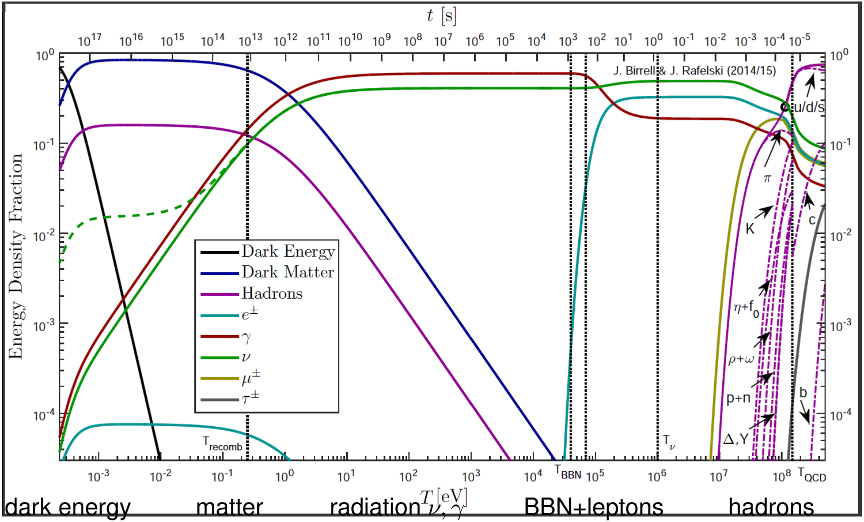
$$\frac{8\pi G_N}{3}\rho = \frac{\dot{a}^2 + k}{a^2} = H^2\left(1 + \frac{k}{\dot{a}^2}\right), \quad \frac{4\pi G_N}{3}(\rho + 3P) = -\frac{\ddot{a}}{a} = qH^2.$$

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.

The Universe Composition in Single View



Different dominance eras: Temperature grows to right

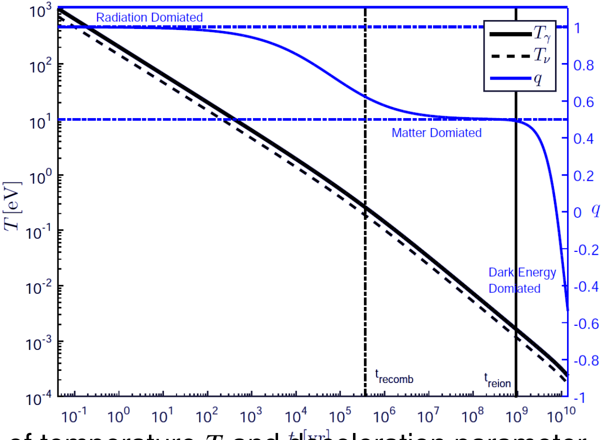
Evolution Eras and Deceleration Parameter q

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

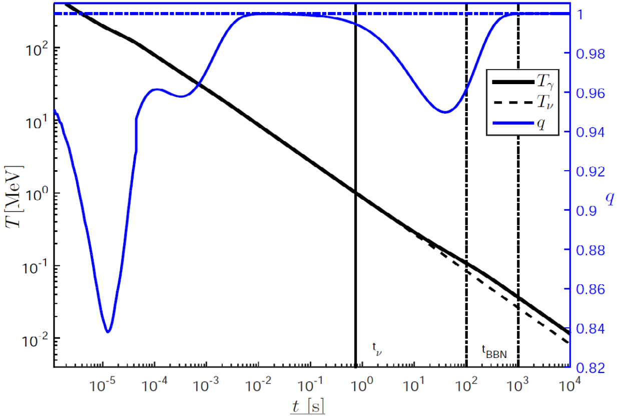


Evolution of temperature T and deceleration parameter q from near/after BBN to the present day: time grows to right

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.

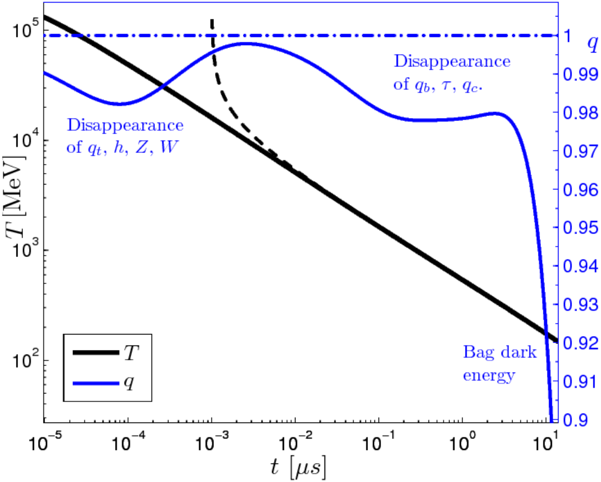
From QGP across BBN



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

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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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

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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

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

- 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 and strangeness; In cosmology: we study the evolution of the Quark-Universe across many domains to the present day.
- We have detailed understanding how quark Universe evolves and the matter 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.