QGP in the Universe and in the Laboratory

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

Graduate Students at The University of Arizona

What is special with Quark Gluon Plasma?

1. RECREATE THE EARLY UNIVERSE IN LABORATORY:
   The topic of this talk
2. PROBING OVER A LARGE DISTANCE THE CONFINING VACUUM STRUCTURE
3. STUDY OF THE ORIGIN OF MASS OF MATTER
4. OPPORTUNITY TO PROBE ORIGIN OF FLAVOR?
   Normal matter made of first flavor family $(u, d, e, [\nu_e])$.
   Strangeness-rich quark-gluon plasma the sole laboratory environment filled with 2nd family matter (s, c).

50 years ago 1964/65: Beginning of a new scientific epoch

- Quarks, Higgs → Standard Model of Particle Physics
- CMB discovered
- Hagedorn Temperature, Statistical Bootstrap
  → QGP: A new elementary state of matter

Topics today:

1. Hagedorn, Big Bang, hadronic matter – QGP theory
2. QGP in Universe and Laboratory
3. Discovery of QGP
4. Quark-gluon plasma in the Universe
5. Particles in the evolving Universe
6. New Ideas? Darkness

Hagedorn Temperature October 1964 in press:
Hagedorn Spectrum January 1965 $\Rightarrow$ March 1966

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

STATISTICAL THERMODYNAMICS OF STRONG INTERACTIONS AT HIGH ENERGIES

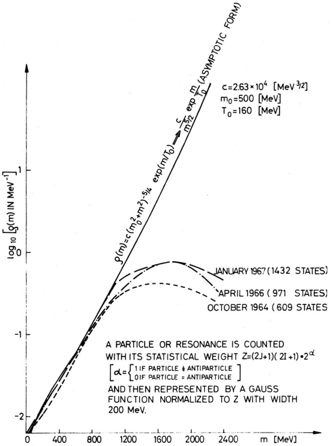
R. Hagedorn
CERN - Geneva

A B S T R A C T

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:

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

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.



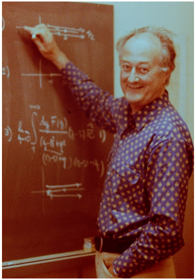
SBM only model providing 'the' initial singular condition 1967 many regard SBM as the Hot Big-Bang theory

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)

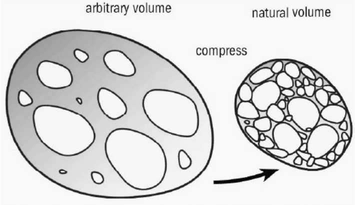
Wenn auch niemand dabei war, als das Universum entstand, so erlauben uns doch unsere heutigen Kenntnisse der Atom-, Kern- und Elementarteilchenphysik, verbunden mit der Annahme, dass die Naturgesetze unwandelbar sind, Modelle zu konstruieren, die mehr und mehr auf mögliche Beschreibungen der Anfänge 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.*

By 1970: Statistical Bootstrap Model=Model of Hot Big Bang

What is the Statistical Bootstrap Model (SBM)?



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

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

nature

article

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

Comments on the Big-bang

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*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

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

By 1980: SBM ⇒ Quark-Gluon Plasma
HI collisions+strangeness

Volume 97B, number 2 PHYSICS LETTERS 1 December 1980

THE IMPORTANCE OF THE REACTION VOLUME IN HADRONIC COLLISIONS

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and

Michael DANOS
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Received 10 October 1980

The pair production in the thermodynamic model is shown to depend sensitively on the (hadronic) reaction volume. Strangeness production in nucleus–nucleus collisions is treated as an example.

We consider particle production in the frame of the thermodynamic description [1] and explore the physical consequences arising from the conservation of quantum numbers which are conserved exactly during the strong interaction. An example treated here is the direct and associated production of strange particles.

The motivation for this study is the recent interest in high energy nucleus–nucleus (N–N) collisions. The main difference from the p–p scattering arises from the possibility of large reaction volumina. We will show that particle multiplicities can depend sensitively on the size of the reaction volume. Specifically, the production of heavy flavors (strangeness, etc.) is significantly enhanced.

[1] Guestworker, National Bureau of Standards.
[2] Supported in part by Deutsche Forschungsgemeinschaft.

PLB **97** pp.279-282 (1980)

FROM HADRON GAS TO QUARK MATTER II *)

J. Rafelski
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der Universität Frankfurt

and

R. Hagedorn
CERN--Geneva

Ref.TH.2969-CERN
13 October 1980

We describe a quark-gluon plasma coincident with the bootstrap critical curve found in the first lecture. We therefore argue that these possibly coinciding critical curves separate two phases in which strongly interacting matter can exist: a hadronic phase and a quark-gluon plasma phase. There is a finite region of coexistence between these two phases, which is determined by the usual Maxwell construction. Having thus joined the two models along their possibly common critical curves, we try to confront our model with experiments on relativistic heavy ion collisions. A signature of the quark-gluon phase surviving hadronization is suggested.

*) Invited lecture presented by J.R. at the "International Symposium on Statistical Mechanics of Quarks and Hadrons" University of Bielefeld, Germany, August 1980.

Birth of QGP/RHI formation: CERN theory division 1977-80

- 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
- Formation of quark matter in RHI collisions: 1978
  conference talks by Rafelski-Hagedorn
  unpublished document (MIT web page) Chapline-Kerman
- Hot interacting QCD QGP: 1979 (without errors!)
  J. Kapusta, *Nucl. Phys. B* **148**, 461 (1979)*QCD at high temperature*
- Formation of QGP in RHI collisions 1979-80
  CERN Theory Division talks etc Hagedorn, Kapusta, Rafelski, Shuryak
- Experimental signature:
  Strangeness and Strange antibaryons 1980
  Rafelski (with help of Danos, Hagedorn, Koch (grad student), Muller
- Statistical materialization model (SHM) of QGP: 1982
  Rafelski (with help of Hagedorn, Koch(grad student), Muller

and Antiproton Annihilation
Hotspot in a Nucleaus ⇒ QGP Formation

Volume 207, number 4 PHYSICS LETTERS B 30 June 1988

QUARK–GLUON PLASMA IN 4 GeV/c ANTIPROTON ANNIHILATIONS ON NUCLEI

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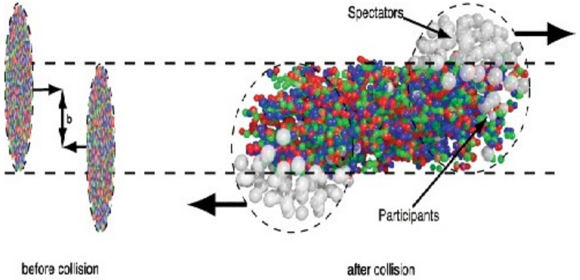
Received 8 February 1988, revised manuscript received 19 April 1988

Recent data on strange particle production in 4 GeV/c antiproton annihilations on Ta can be successfully interpreted if quark–gluon plasma formation is assumed along with a simple reaction model in which antiprotons deposit energy in the forward cone of nuclear matter within the target nucleus The observed spectra and total abundances of lambdas and kaons are consistent with the hypothesis that (super cooled) quark matter phase has been formed at a rather modest temperature $T \lesssim 60$ MeV The spectra can then be successfully interpreted both with reference to their form and relative abundance

In the annihilation reaction of antiprotons on nuclei it is possible to deposit in the target nucleus most of the annihilation energy In such a possibly rare reaction very excited forms of nuclear matter may be created [1,2] [#1] We will here present an interpretation of the strange particle production experiment [3] in which 4 GeV/c antiproton-annihilation on heavy nuclei (Ta) was studied It will be shown that an understanding of the experimental results can be arrived at with a great economy of effort employing as reaction mechanism the excitation of the quark matter (quark–gluon plasma QGP) state of nuclear matter [4] It should be noted that previous attempts to describe these data in terms of individual hadronic reactions have not been successful [5]

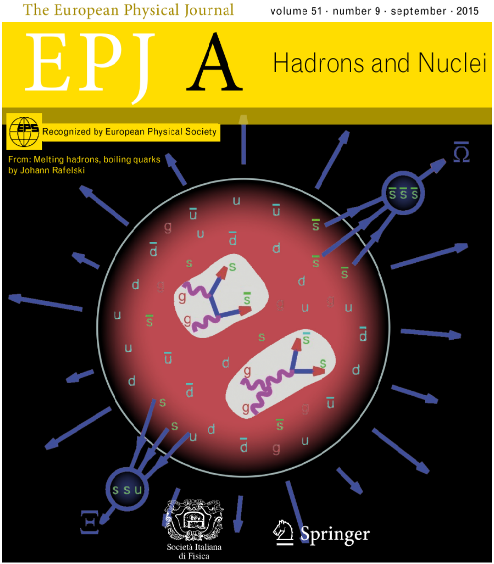
PARTICLE YIELDS: INTEGRATED SPECTRA

Particle yields allow exploration of the source bulk properties in the co-moving frame – collective matter flow dynamics integrated out. This avoids the dynamical mess:



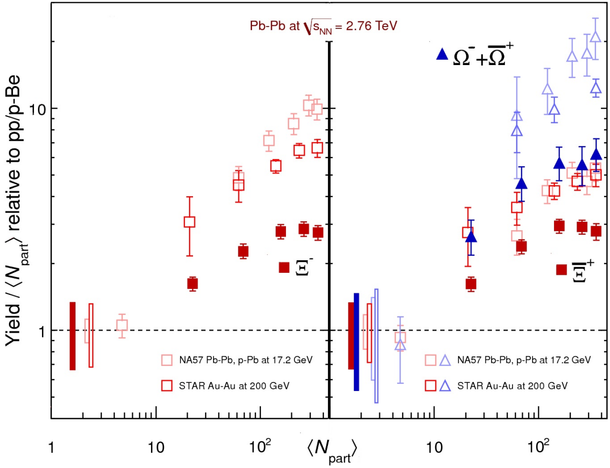
Our interest in the bulk thermal properties of the source evaluated independent from complex transverse dynamics is the reason to analyze integrated spectra.

Cooking strange quarks → strange antibaryons



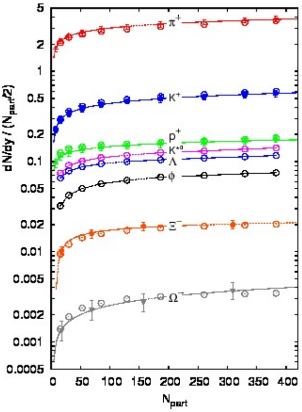
APS sticker from period

Prediction: 1980-86 confirmed by experimental results

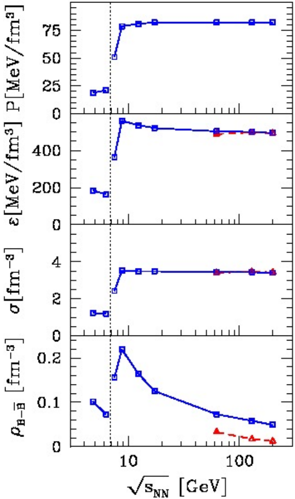


Statistical Hadronization Model Interpretation (SHM)

equal hadron production strength
yield depending on available phase space
Example data from LHC⇓



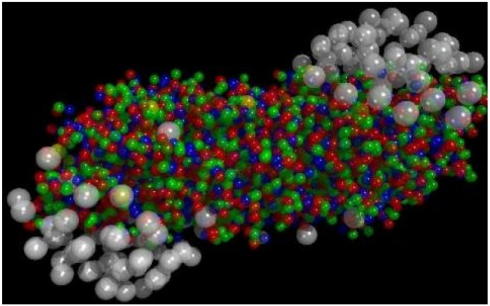
Bulk properties⇓



CERN press office

New State of Matter created at CERN

10 Feb 2000



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

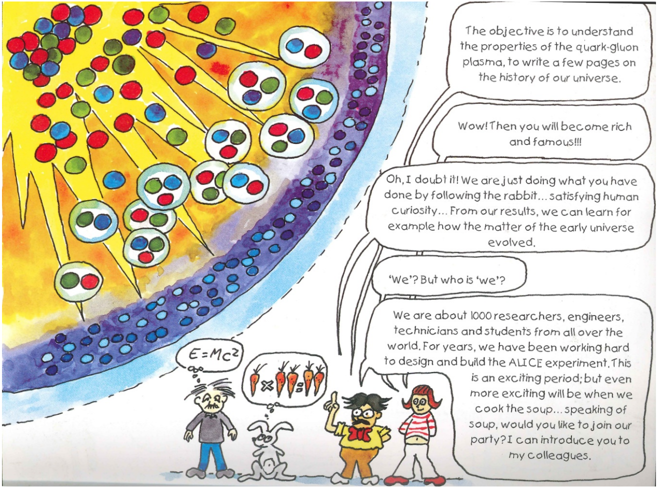
Preeminent signature: Strange antibaryon enhancement

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

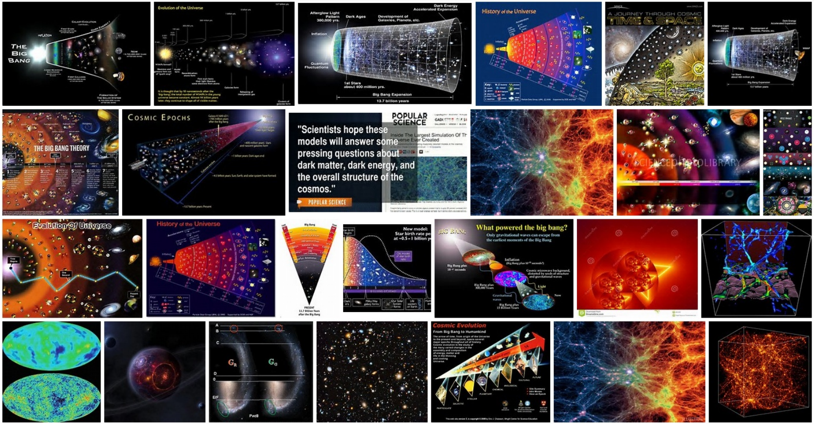
9AM, 18 April 2005; US – RHIC announces QGP Press conference APS Spring Meeting

Preeminent property: non-viscous flow

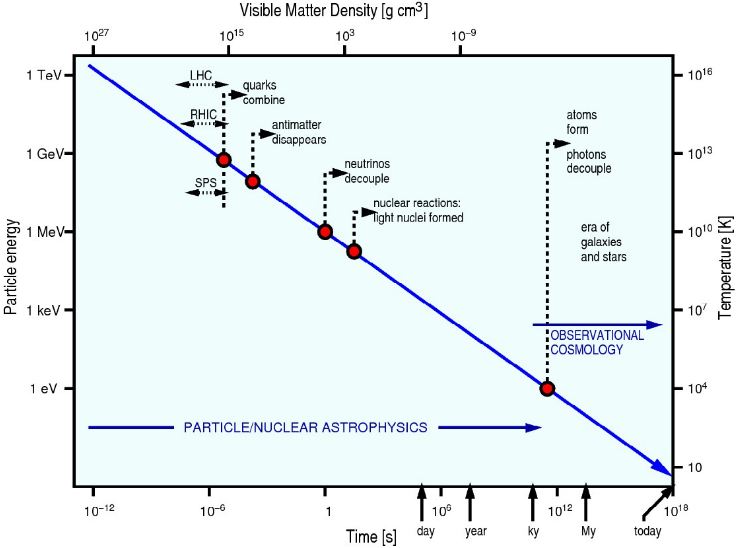
LHC-Alice: Exploration of QGP



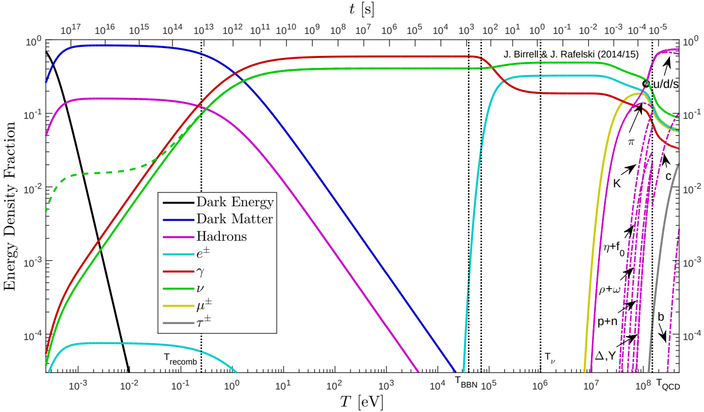
QGP in Universe and Laboratory



Experiments Probe the Universe



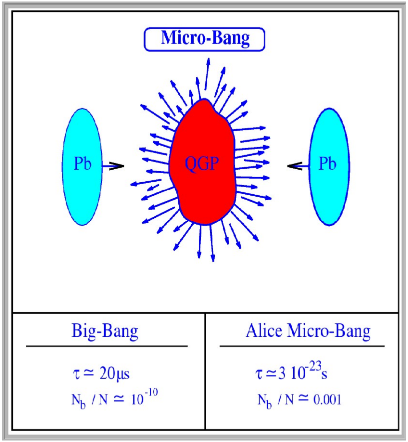
The Universe Composition Changes



dark energy matter radiation ν, γ leptons hadrons

$\Longrightarrow$ Different dominance eras

Connection to Relativistic Heavy Ion Collisions



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

$\Longrightarrow$ Theory connects RHI collision experiments to Universe

Universe: QGP and Hadrons in full Equilibrium

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

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

The lifespan $\tau_{\pi^0} = 8.4 \times 10^{-17}$ sec defines the strength of interaction which beats the time constant of Hubble parameter of the epoch. Inga Kuznetsova and JR, Phys. Rev. C82, 035203 (2010) and D78, 014027 (2008) (arXiv:1002.0375 and 0803.1588).

Equilibrium abundance of 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 (like photons later) at $T = \mathcal{O}$MeV

Particle Content and Chemical Potentials

Chemical potentials control particle/antiparticle abundances:

$$f_{p/a} = \frac{1}{e^{\beta(\varepsilon \mp \mu)} \pm 1}, \qquad \varepsilon = \sqrt{p^2 + m^2}$$

- **Quark side:** $d \leftrightarrow s \leftrightarrow b_{\rm ottom}$ oscillation means $\mu_d = \mu_s = \mu_{\rm bottom}$ and similarly $\mu_{\nu_e} = \mu_{\nu_\mu} = \mu_{\nu_\tau}$. WI reaction e.g. $d \to u + e^- + \bar{\nu}_e$ imply $\mu_d - \mu_u = \Delta\mu_l$ with

$$\Delta\mu_l = \mu_e - \mu_{\nu_e} = \mu_\mu - \mu_{\nu_\mu} = \mu_\tau - \mu_{\nu_\tau}$$

- **Hadron side:** Quark chemical potentials control valence quarks and can be used in the hadron phase, e.g. Σ^0 (*uds*) has chemical potential $\mu_{\Sigma^0} = \mu_u + \mu_d + \mu_s$. The baryochemical potential μ_B is:

$$\mu_B = \frac{1}{2}(\mu_p + \mu_n) = \frac{3}{2}(\mu_d + \mu_u) = 3\mu_d - \frac{3}{2}\Delta\mu_l$$

Three Constraints

The chemistry of particle reaction and equilibration in the Universe has three chemical potentials ‘free’ i.e. not only baryochemical potential μ_B. We need three physics constraints Michael J. Fromerth , JR e-Print: astro-ph/0211346:

i. Charge neutrality eliminates Coulomb energy

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

Q_i and n_i charge and number density of species i.

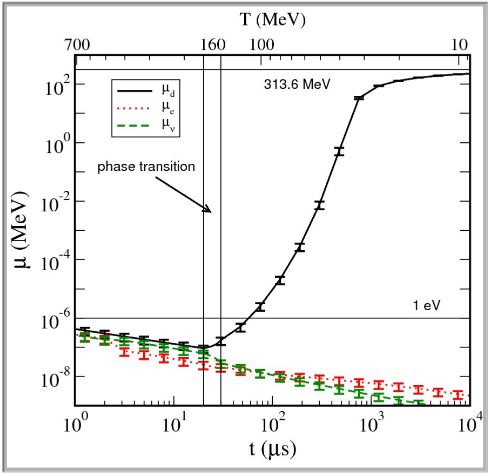
ii. Net lepton number equals net baryon number However, possible neutrino-antineutrino asymmetry can hide an imbalance

iii. Prescribed value of entropy-per-baryon

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

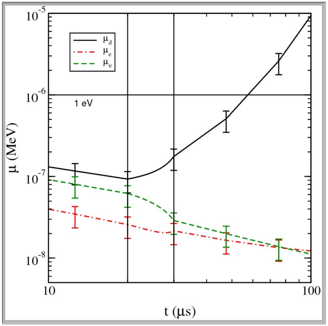
Today best est. $S/B = 3.5 \times 10^{10}$, results shown for 4.5×10^{10}

Chemical Potential in the Universe



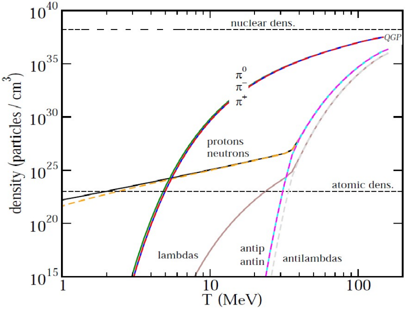
Minimum:

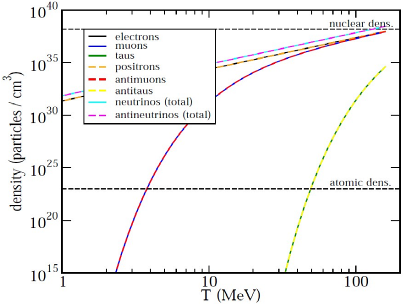
$\mu_B = 0.33^{+0.11}_{-0.08}$eV



$\Longrightarrow$ μ_B defines remainder of matter after annihilation

Particle Composition after QGP Hadronization





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

Particles in the Universe=Degrees of Freedom

The effective number of entropy degrees of freedom, g_*^S, defined by

$$S = \frac{2\pi^2}{45} g_*^S T_\gamma^3 a^3.$$

For ideal Fermi and Bose gases

$$g_*^S = \sum_{i=\text{bosons}} g_i \left(\frac{T_i}{T_\gamma}\right)^3 f_i^- + \frac{7}{8} \sum_{i=\text{fermions}} g_i \left(\frac{T_i}{T_\gamma}\right)^3 f_i^+.$$

g_i are the degeneracies, $f_i^\pm$ are varying functions valued between 0 and 1 that turn off the various species as the temperature drops below their mass.

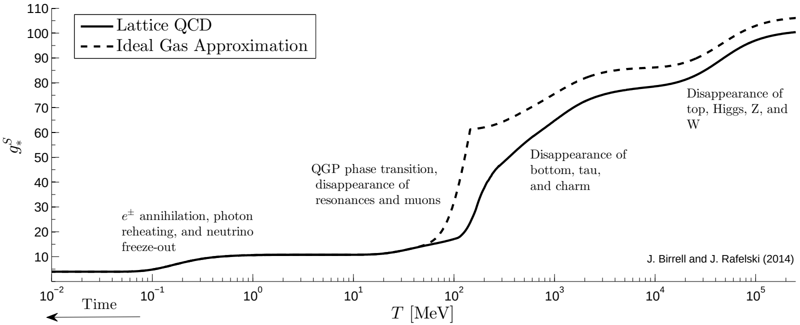
Speed of Universe expansion controlled by degrees of freedom thus g is an observable

Distinct Composition Eras

Composition of the Universe changes as function of T:

- From Higgs freezing to freezing of QGP
- QGP hadronization
- Antimatter annihilation
- Last leptons disappear just when
- Onset of neutrino free-streaming and begin of
- Big-Bang nucleosynthesis within a remnant lepton plasma
- Emergence of free streaming dark matter
- Photon Free-streaming – Composition Cross-Point
- Dark Energy Emerges – vacuum energy

Count of Degrees of Freedom



Distinct Composition Eras visible. In PDG ideal gas approximation (dashed) is not valid in QGP domain, equation of state from lattice-QCD, and at high T thermal-QCD must be used [1,2].

[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

Reheating History

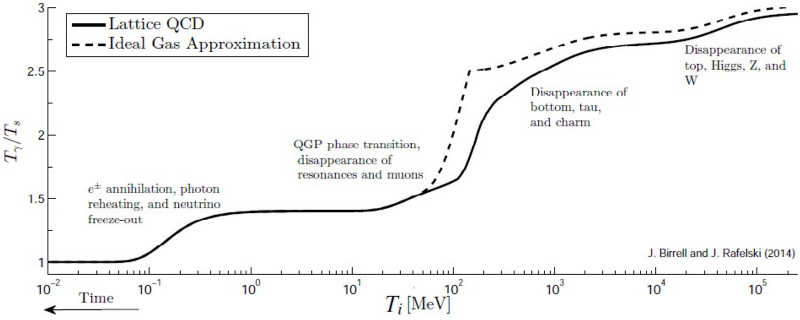


Figure: The reheating ratio reflects the disappearance of degrees of freedom from the Universe as function of T_i. These results are for adiabatic evolution of the Universe. Primordial dark matter colder by factor 3. Particles decouple at QGP hadronization colder by factor 2.

Connecting time to temperature

Friedmann–Lemaitre–Robertson–Walker (FRW) cosmology

- Einstein Universe:

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

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

We absorb the vacuum energy (Einstein Λ-term) into the energy ρ and pressure P

$$\rho \to \rho + \rho_\Lambda, \qquad P \to P + P_\Lambda$$

which contain other components in the Universe including CDM: cold dark matter; this is ΛCDM model.

$$\rho_\Lambda \equiv \Lambda/(8\pi G_N) = 25.6\ \text{meV}^4, \qquad P_\Lambda = -\rho_\Lambda$$

The pressure P_Λ has a) opposite sign from all matter contributions and b) $\rho_\Lambda/P_\Lambda = -1$. The independent measurement of ρ and P or, equivalently, expansion speed (next slide) allows to disentangle matter from dark energy

Definitions: Hubble parameter H and deceleration parameter q:

$$H(t) \equiv \frac{\dot{a}}{a}; \quad q \equiv -\frac{a\ddot{a}}{\dot{a}^2} = -\frac{1}{H^2}\frac{\ddot{a}}{a}, \Rightarrow \dot{H} = -H^2(1+q).$$

Two dynamically independent Einstein equations arise

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

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.

The contents of the Universe today and yesterday:

1. Photons and all matter coupled to photons:
   thermal matter = ideal Bose-Fermi gases
2. Free-streaming matter (particles that have ‘frozen’ out):
   - dark matter:from before QGP hadronization
   - darkness: at QGP hadronization
   - neutrinos: since $T =$ a few MeV
   - photons: since $T = 0.25$eV
3. Dark energy = vacuum energy

darkness: quasi-massless particles, like neutrinos but due to earlier decoupling small impact on Universe dynamics; includes recent speculations on dark photons for dark matter

Free-streaming matter contributions: solution of kinetic equations with decoupling boundary conditions at T_k (kinetic freeze-out)

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

$$n = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\Upsilon^{-1} e^{\sqrt{p^2/T^2+m^2/T_k^2}}+1}.$$

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).

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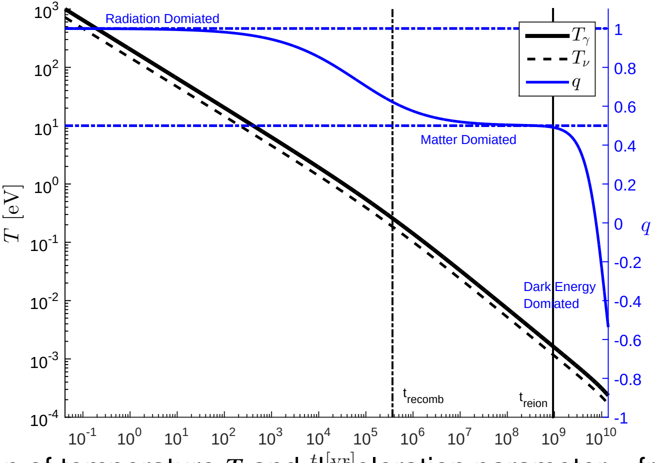
Evolution Eras and Deceleration Parameter q

Using Einsteins equations exact expression in terms of energy, pressure content

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

- 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 TODAY(!)

Today and recent evolution



Evolution of temperature T and deceleration parameter q from soon after BBN to the present day

Long ago: Hadron and QGP Era

- QGP era down to phase transition at $T \approx 150$MeV. Energy density dominated by photons, neutrinos, $e^{\pm}$, $\mu^{\pm}$ along with u,d,s.
- $2+1$-flavor lattice QCD equation of state used
- u,d,s lattice energy density is matched by ideal gas of hadrons to sub percent-level at $T = 115$MeV.
- Hadrons included: pions, kaons, eta, rho, omega, nucleons, delta, Y
- Pressure between QGP/Hadrons is discontinuous at up to 10% level. Causes hard to notice discontinuity in q (slopes match). Need more detailed hadron and quark-quark interactions input

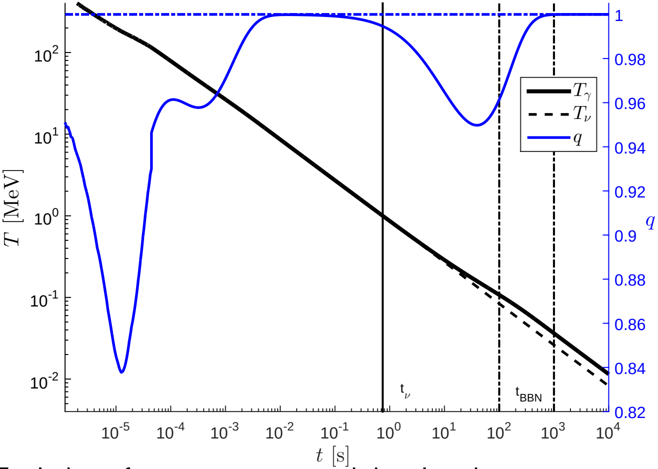


Figure: Evolution of temperature T and deceleration parameter q from QGP era until near BBN.

Are there additional dark degrees of freedom

Darkness Candidates

a) ‘True’ Goldstone bosons related to symmetry breaking in reorganization of QCD vacuum structure. My favorite candidate, theoretical details need work.

b) Super-WI neutrino partners. Connection to deconfinement not straightforward.

Massive $m > \mathcal{O}$(eV) sterile ν not within ‘Darkness’ context. Mass must emerge after CMB decouples, $m < 0.25$ eV. Allowing higher ‘sterile mass’ requires full reevaluation of many steps in the analysis including key elements we do not control (PLANCK CMB fluctuations).

How understanding the Universe enters laboratory experiments: Example

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Quark–gluon plasma as the possible source of cosmological dark radiation

Jeremiah Birrell, Johann Rafelski

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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

Activation of QCD Scale Interactions

QGP activation: Missing Energy in RHI Collisions

- Breakup: Counting degrees of freedom and presuming Darkness equilibration before hadronization, approximately $12 \pm 8\%$ of all entropy content of the QGP is in Darkness.
- Continuous emission: Darkness stops interacting at the QGP surface – escapes freely during the entire lifespan of the QGP. This Dark-radiation loss proportionally largest for long-lived QGP $\rightarrow$ Does energy in/out balance in large AA collision systems beyond threshold of QGP formation?
- Experiment: A systematic exploration of the energy balance as function of $\sqrt{s}$ and A at energies near to QGP formation threshold: = NA61 experiment..

Summary

- 50 years ago particle production in pp reactions prompted introduction of Hagedorn Temperature $T_{\rm H}$; soon after recognized as the critical temperature at which matter surrounding us dissolves into primordial new phase of matter made of quarks and gluons – QGP.
- Laboratory discovery of QGP leading to models of properties of the Universe below the age of 18μs.
- Universe expansion before CMB freeze-out a rich domain bridging QGP era to BBN and BBN to CMB
- Speed of Universe expansion expressed by unseen ‘neutrino’ effective degrees of freedom offer a a connection between observational cosmology and hadronization stage of the Quark Universe: Released Darkness could be a new component pushing the Universe apart. Experimental precision to improve and constrain the theoretical discussion in next generation CMB experiments.

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