Traveling through the Universe:
Back in Time to the Quark-Gluon Plasma Era

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Physics Colloquium, Notre Dame, April 30, 2014

The next 50min is about

- The history of the Universe
- How nuclear physics explains what the Universe is made of
- . . . the questions of today
  Quark-gluon plasma in the early Universe
  Neutrinos pushing the Universe apart
  Big Bang Nucleosynthesis

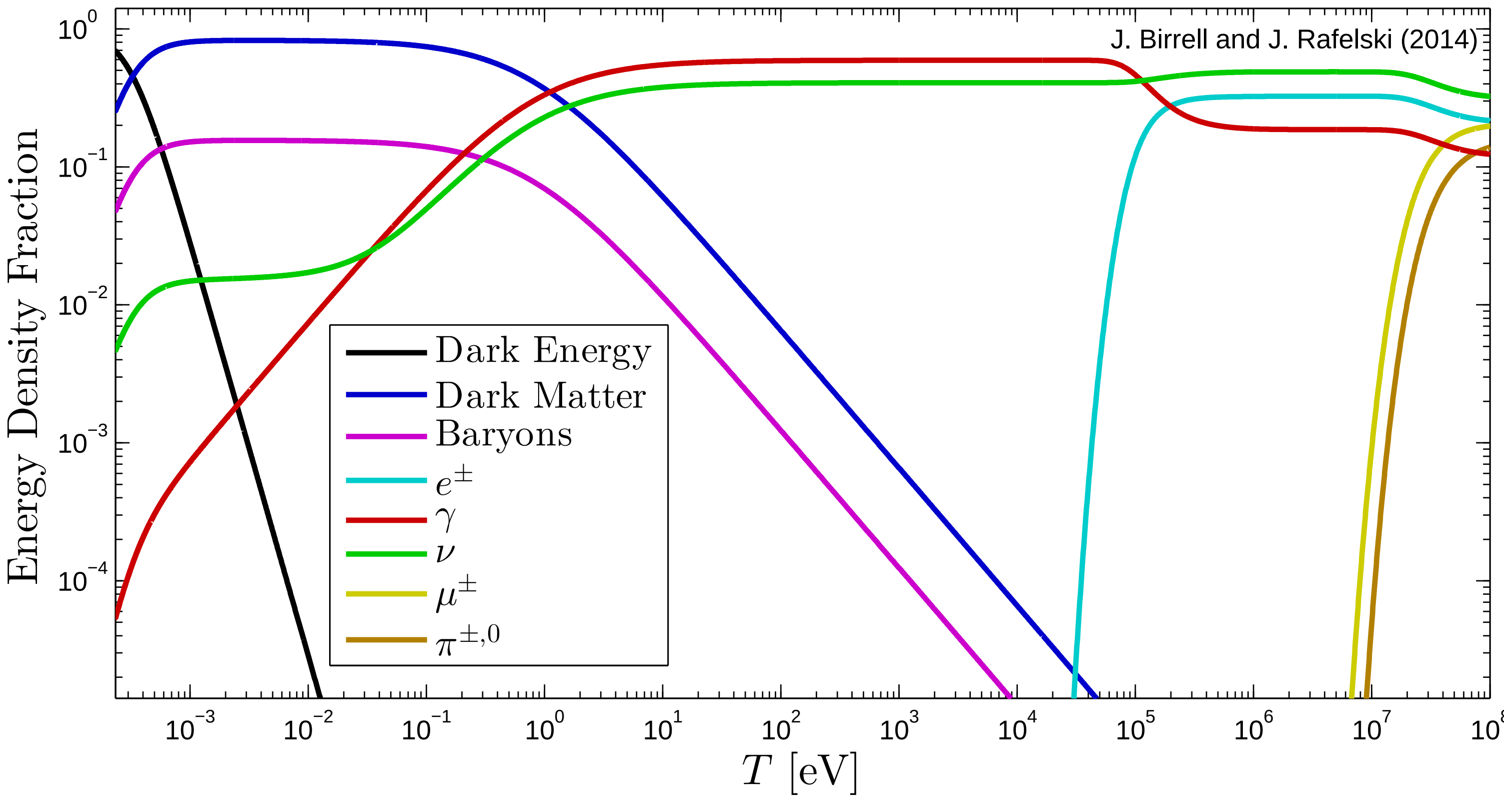
Past decade primary contributors: (former) students were (αbetic):

Jeremey Birrell, Michael Fromerth, Inga Kuznetsowa
Lance Labun Michal Petran, Giorgio Torrieri

supported by the U.S. Department of Energy, grant DE-FG03-95ER41318.

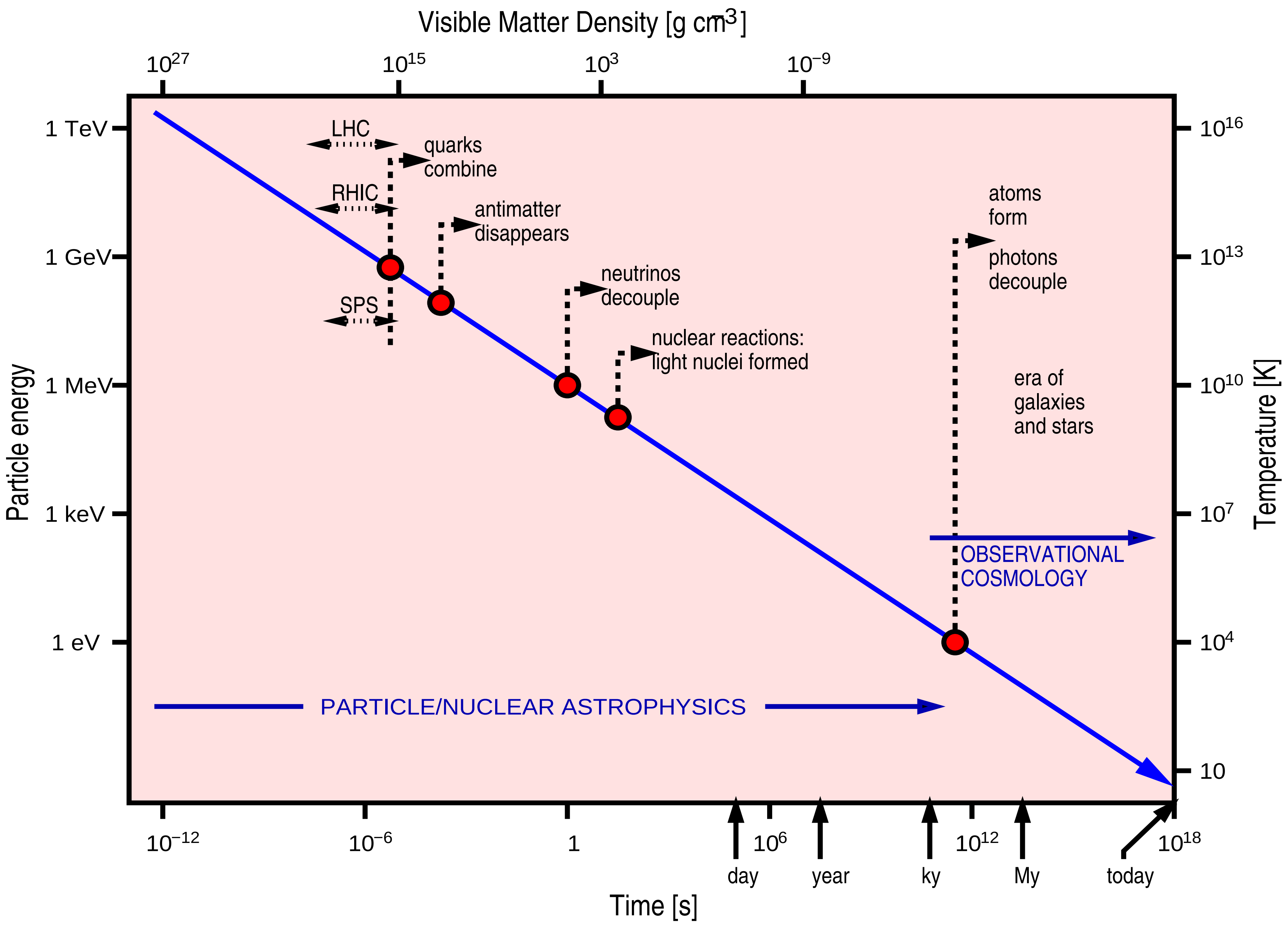
We survey the early history of the discovery of quark gluon plasma and the early history of the Universe, beginning with the present day and reaching deep into QGP and almost beyond. We introduce cosmological Universe dynamics and connect the different Universe epochs with one another. We describe some of the many remaining open questions that emerge.

A first look at the history of the Universe



PLANCK analysis used to fix current era: 69% dark energy, 26% dark matter, 5% baryons, $< 1\%$ photons and neutrinos, 1 massless and 2×0.1 eV neutrinos. QGP hadronization, antimatter annihilation not shown –beyond right edge

Overview of $T(t)$ of the Universe



Outline

- **Recreating early Universe in laboratory: the intellectual and historical pillars**

- **Introduction to cosmology and how this relates to conditions in the Universe**
- **Pivotal epochs of cosmic evolution:**
  1. **Today**
  2. **Ion-electron Recombination**
  3. **Big-Bang nucleosynthesis, and e^+e^--annihilation,**
  4. **ν-decoupling**
  5. **Antimatter annihilation,**
  6. **QGP hadronization, noting differences to QGP in laboratory: time scale, baryon content, size scale, mixed quark-hadron phase, Quark-lepton chemistry**

Intellectual Pillars

AETHER AND STRUCTURED QUANTUM VACUUM (Einsteins 1920+ Aether)
The vacuum state determines prevailing fundamental laws of nature. Demonstrate by changing the vacuum from hadronic matter to the deconfined quark matter ground state.

RECREATE THE EARLY UNIVERSE IN LABORATORY:
Recreate and understand in relativistic heavy ion collisions the high energy density conditions prevailing in the Universe when matter formed from elementary degrees of freedom (quarks, gluons) at about 20-30 μs after big bang.

QGP-Universe hadronization led to a nearly matter-antimatter symmetric state, the later ensuing matter-antimatter annihilation leaves behind as our world the tiny 10^{-10} matter asymmetry. There is no understanding of when and how this asymmetry arises.

STUDY ORIGIN OF MASS OF MATTER –(DE)CONFINEMENT
The confining quark vacuum state is the origin of 99.5% of mass, the Higgs mechanism applies to the remaining 0.5%. We want to confirm the quantum zero-point energy of confined quarks as the mass of matter. When we 'melt' the vacuum structure setting quarks free the energy locked in mass of nucleons is transformed into thermal QGP energy.

SEARCH FOR THE ORIGIN AND MEANING OF FLAVOR
Normal matter made of first flavor family (u, d, e, ν_e). Strangeness and charm rich quark-gluon plasma the sole laboratory environment filled with 2nd family quark matter (s, c) – arguable the only experimental environment where we could study matter made of 2nd flavor.

Relativistically Invariant Aether 1920: Albert Einstein at first rejected æther as unobservable when formulating special relativity, but later changed his position. *"It would have been more correct if I had limited myself, in my earlier publications, to emphasizing only the non-existence of an æther velocity, instead of arguing the total non-existence of the æther, for I can see that with the word æther we say nothing else than that space has to be viewed as a carrier of physical qualities."* **letter to H.A. Lorentz of November 15, 1919**

In a lecture published in Berlin by Julius Springer, in May 1920, presentation at Reichs-Universität zu Leiden, addressing H. Lorentz delayed till 27 October 1920 by visa problems, also in Einstein collected works:
In conclusions: *. . . space is endowed with physical qualities; in this sense, therefore, there exists an æther. According to the general theory of relativity space without æther is unthinkable; for in such space there not only would be no propagation of light, but also no possibility of existence for standards of space and time (measuring-rods and clocks), nor therefore any space-time intervals in the physical sense. But this æther may not be thought of as endowed with the quality characteristic of ponderable media, as consisting of parts which may be tracked through time. The idea of motion may not be applied to it.*

The QGP in laboratory is a ponderable fragment of the early Universe: quantum physics makes this possible. Work in Frankfurt (Walter Greiner, Berndt Muller, J.R.) on local 'Charged Vacuum' quantum structure laid the ground in 1971-73 for QCD-Vacuum structure characterization of quark confinement and its implementation in e.g. the MIT bag model 1974-76.

Relativistic Heavy Ions - the Beginning

Developments at CERN

G. Cocconi
ion Européenne pour la Recherche Nucléaire, Geneva, Switzerland

, a group belonging to the Proton Synchrotron Division is preparing ı two-year study on polarized beam and light-ion acceleration in the raft will be ready at the beginning of 1975). Injection into the PS of s becoming compatible with that of ordinary protons because, within npletion of the new linac will leave free the 50-MeV linac that is now into the PS. Another incentive for this project is that at CERN there of transferring the particles accelerated in the PS to the intersecting SR) and eventually to the 400-GeV superconducting PS. This en- ıbly the scope of the experimental program. In Table 1 are given the present considered realistic for the PS and the ISR for fully stripped ıs have yet been made for the acceleration of heavy ions. If approved t could lead to usable beams before 1980.

Table 1

Luminosity of Fully Stripped Nuclei in PS and ISR

	PS ($\leqslant 28q/e$ GeV)	ISR [equiv. lab $E \leqslant 2000(q/e)^2/A$ GeV]	
ι, cm²	Particles/pulse	Luminosity, $cm^{-2}\ sec^{-1}$	Interaction rate, sec^{-1}
-25.5	$10^{12.5}$	10^{31}	$10^{5.5}$
-25.5	10^{10}	10^{27}	$10^{1.5}$
-24.5	$10^{9.5}$	10^{26}	$10^{1.5}$
-24	10^{9}	10^{25}	10^{1}

nance.

BNL 50445
(Physics, Nuclear - TID-4500)

Report of the Workshop on
BEV/NUCLEON COLLISIONS OF HEAVY IONS - HOW AND WHY

November 29-December 1, 1974
Bear Mountain, New York

Supported by
NATIONAL SCIENCE FOUNDATION
and
NEVIS LABORATORIES, COLUMBIA UNIVERSITY

Organizing Committee
A. KERMAN, L. LEDERMAN, T.D. LEE, M. RUDERMAN, J. WENESER

Scientific Reporters
LAWRENCE E. PRICE, JAMES P. VARY

'Bear Mountain' meeting to advance RHI program at LBNL also stimulated interest at CERN where there was already a tradition of thermal particle physics (Rolf Hagedorn). First theorists interested in quark deconfinement, and ultimately, much of the experimental Relativistic Heavy Ion Program converged there while the US community kept on 10y long discussion of what and how to do. Phase transition at Quark Matter September 1983 at BNL!

RHI experiments needed a signature of QGP and deconfinement

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

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

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

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

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

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

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

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

$\Longleftarrow$ JR & Rolf Hagedorn, preprint CERN-TH-2969, Oct.1980 ***From Quark Matter to Hadron gas*** **in "Statistical Mechanics of Quarks and Hadrons", H.Satz, ed.,Elsev. 1981.**

$\bar{s}/\bar{q} \to K^+/\pi^+, \to \overline{\Lambda}/\bar{p}$ are proposed as signatures of chemically equilibrated deconfined QGP phase, near matter-antimatter symmetry discussed.

As of 1981 kinetic strangeness production by gluon fusion in QGP, PRL with Berndt Muller submitted in December 1981. Details on multistrange antibaryons appeared in Phys. Reports Fall 1982. Hadronization developed 1982-5, pubs with Peter Koch, PhD thesis $\Rightarrow$ 1985/6, Phys. Reports.

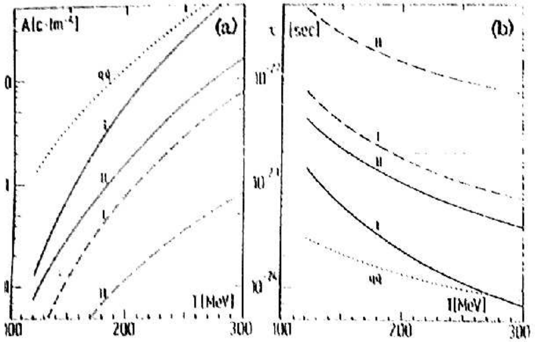


FIG. 2. (a) Rates A. (b) Time constants τ as func-
ons of temperature T. Full lines, $q\bar{q}\to s\bar{s}$ and $gg\to ss$;
shed lines, $q\bar{q}\to s\bar{s}$; dotted lines, $gg\to q\bar{q}$ ($M = 15$
eV). Curves marked I are for $\alpha_s = 2.2$ and $M = 280$
eV; those marked II are for $\alpha_s = 0.6$ and $M = 150$
eV.

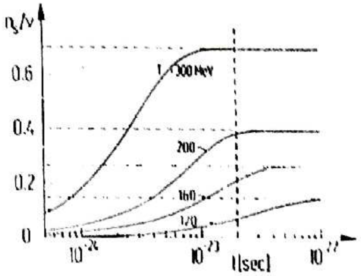


FIG. 3. Time evolution of the relative strange-quark to baryon-number abundance in the plasma for various temperatures

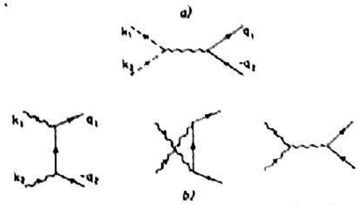


FIG. 1. Lowest-order QCD diagrams for $s\bar{s}$ production (a) $q\bar{q}\to s\bar{s}$, (b) $gg\to s\bar{s}$.

Strangeness Production in the Quark-Gluon Plasma

Johann Rafelski and Berndt Müller
Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, D-6000 Frankfurt am Main, Germany

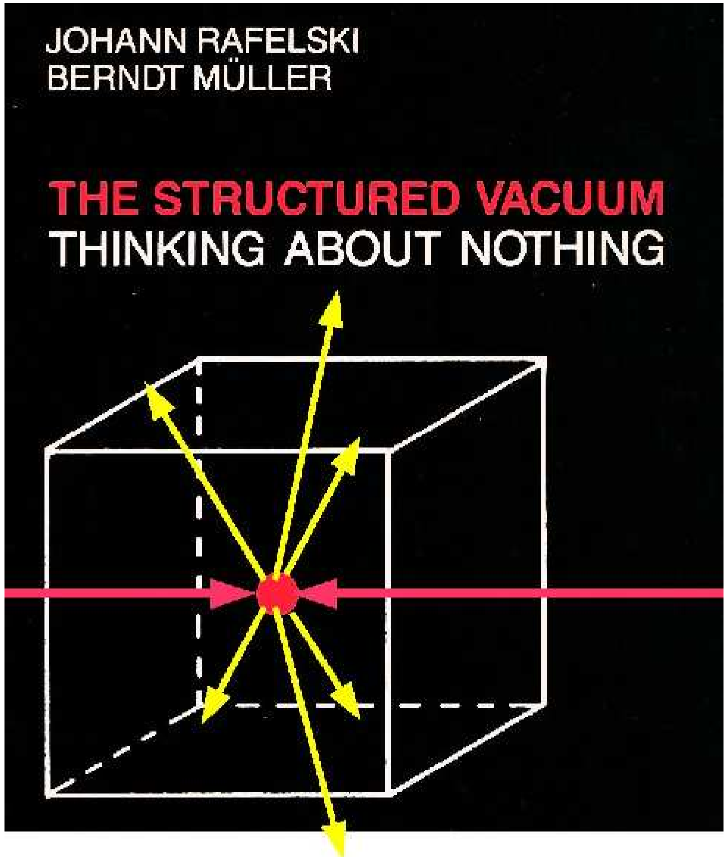
(Received 11 January 1982)

Rates are calculated for the processes $gg\to s\bar{s}$ and $u\bar{u}, d\bar{d}\to s\bar{s}$ in highly excited quark-gluon plasma. For temperature $T \geq 160$ MeV the strangeness abundance saturates during the lifetime ($\sim 10^{-23}$ sec) of the plasma created in high-energy nuclear collisions. The chemical equilibration time for gluons and light quarks is found to be less than 10^{-24} sec

In QGP strangeness production by gluon fusion

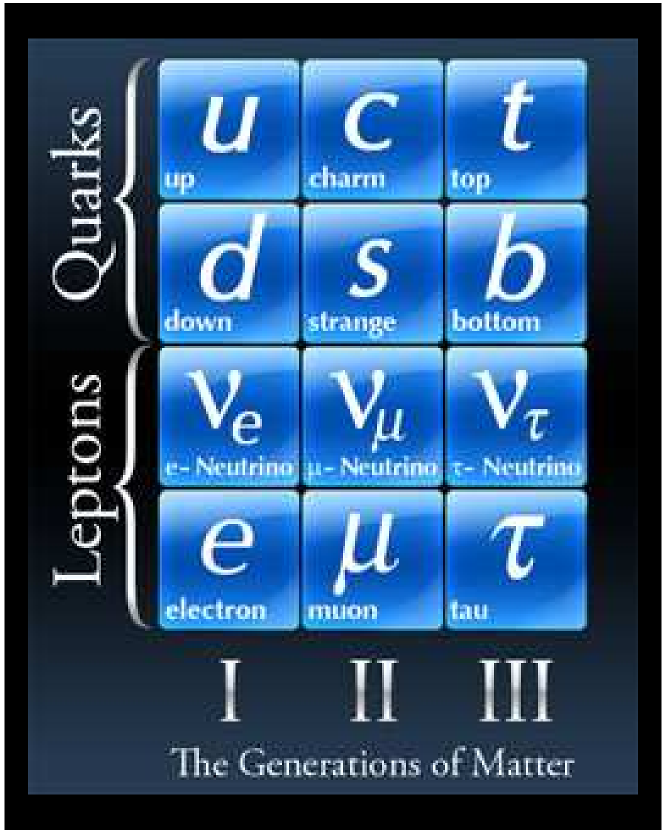
SERENDIPITY: I shared an office at CERN 1977-79 with Brian Combridge who studied the mechanisms of perturbative QCD charm production, showing glue based process dominated – Berndt Muller and I used Brian's cross sections to compute the thermal invariant rates and prove that equilibration of strangeness in QGP is in experimental reach. This creates the need to introduce approach to chemical equilibrium yield in QGP. Dependent on aspect ratio of quark densities in QGP and streaming hadrons this can result in just about any level of strange hadron abundance in the final hadron count.

The Structured Vacuum 1985 booklet: Mass of Matter



We presented the conceptual interdisciplinary relation between Strong Fields–Casimir–High T–Deconfinement–Higgs vacuum and connected mass of matter to confinement

In QGP we excite a large number of particles of Generation II – this should present an opportunity to explore foundation of flavor physics.



The Riddle of Three Generations of Matter

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Introduction to Cosmological Evolution I

Standard cosmological Friedmann-Lemaître-Robertson-Walker (FLRW) model is based on space-time metric

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

The space has (expanding) flat-sheet properties for the experimentally preferred value $k = 0$. The Einstein equations are

$$G^{\mu\nu} = R^{\mu\nu} - \left(\frac{R}{2} - \Lambda\right) g^{\mu\nu} = 8\pi G_N T^{\mu\nu}, \qquad R = g_{\mu\nu}R^{\mu\nu}, \qquad T^\mu_\nu = \mathrm{diag}(\varepsilon, -P, -P, -P).$$

It is common to absorb Λ into the energy and pressure, $\varepsilon_\Lambda = \Lambda/8\pi G_N$, $P_\Lambda = \Lambda/8\pi G_N$ and we implicitly consider this done from now on. There are two dynamically independent Friedmann equations

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

where Universe dynamics is characterized by two quantities, the Hubble parameter $H(t)$, a strongly time dependent quantity on cosmological time scales, and the acceleration parameter $q(t)$, a highly useful diagnostic of Universe behavior

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

Introduction to Cosmological Evolution II

Solving both Friedmann equations for $8\pi G/3$ and equating we find a constraint for the acceleration parameter:

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

Restricting to case $k = 0$:
Radiative Universe $3P = \varepsilon \;\rightarrow\; q \simeq 1$; In the early Universe almost always radiation dominance
Matter dominated Universe $P/\varepsilon << 1 \;\rightarrow\; q \simeq 1/2$;
Dark energy dominated Universe $P = -\varepsilon \;\rightarrow\; q = -1$.

The third independent equation arises directly from divergence freedom of the homogeneous energy momentum tensor of matter

$$T^{\mu\nu}||_\nu = 0 \Rightarrow -\frac{\dot{\varepsilon}}{\varepsilon + P} = 3\frac{\dot{a}}{a} = 3H,$$

same condition follows from local conservation of entropy, $dE + PdV = TdS = 0,\ dE = d(\varepsilon dV),\ dV = d(a^3)$ and divergence freedom of the left hand side of Einstein equations.

The composition of the Universe at any given epoch defines prevailing equation of state relation of P, ε. For $k = 0$ the energy density must be 'critical', $\varepsilon_{\rm cr} \equiv 3H^2/8\pi G_N$. Given the initial conditions today we integrate back in time. We assume 'Planck' fit to present day conditions defining the equations of state 69% dark energy, 26% dark matter, 4.8% Baryons.

Tacit 'natural' assumptions: Dark matter mass scale outside energy range of our study, dark matter decay and/or annihilation is mostly complete before QGP hadronization and does not impact the inventory of visible matter.

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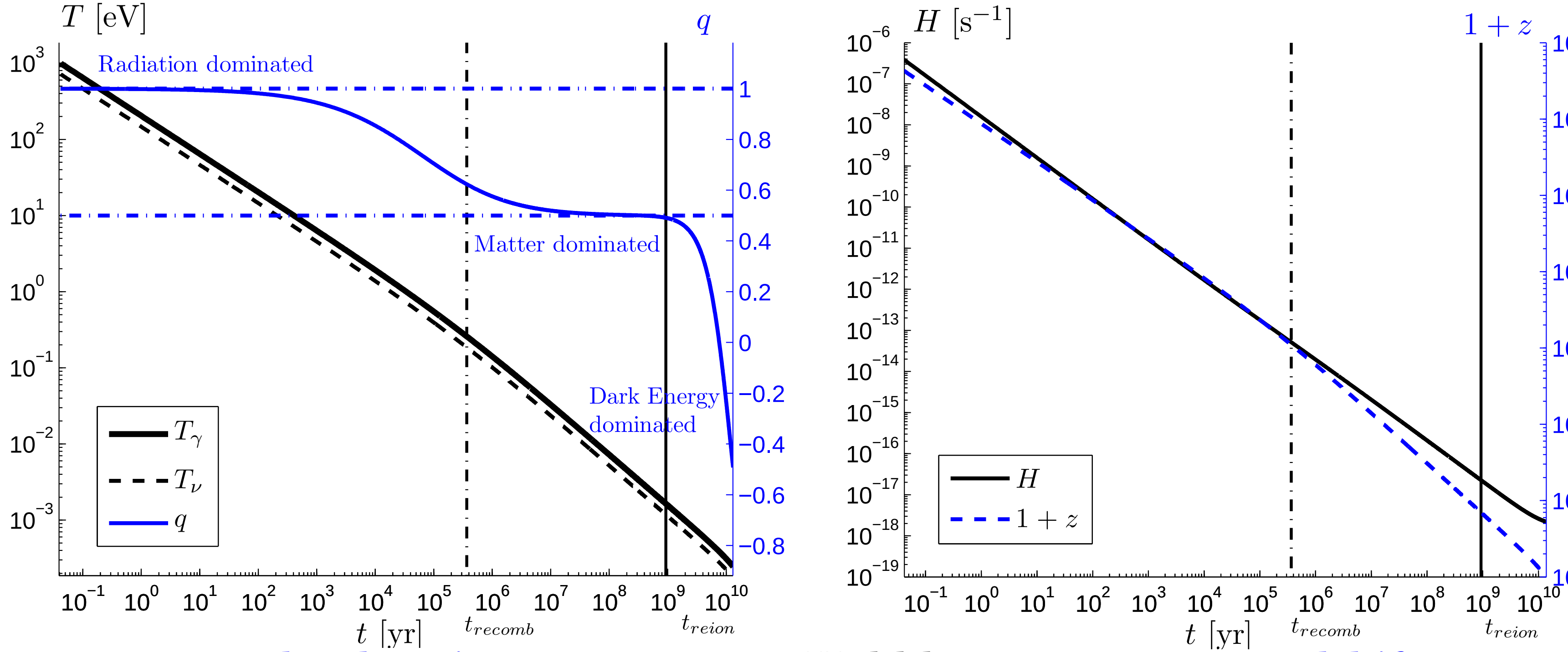
From the present day back beyond ion recombination: the almost 'visible universe'

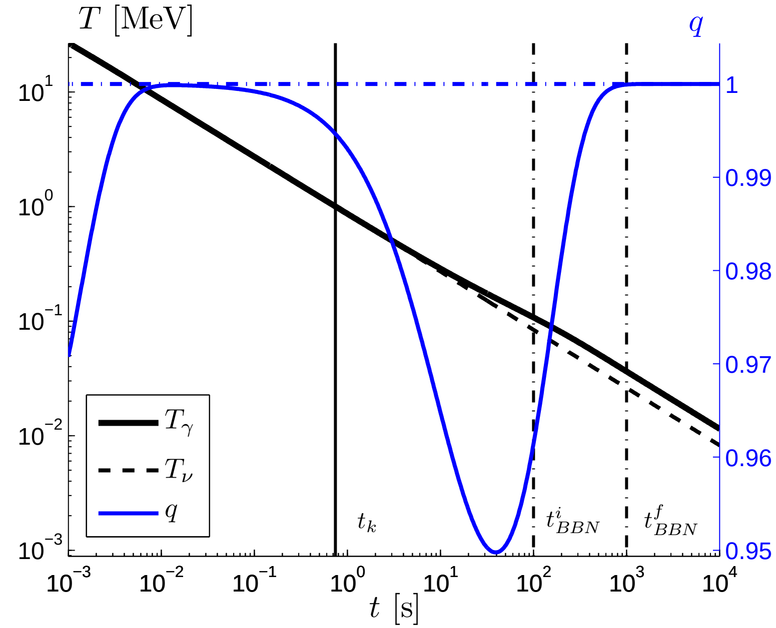


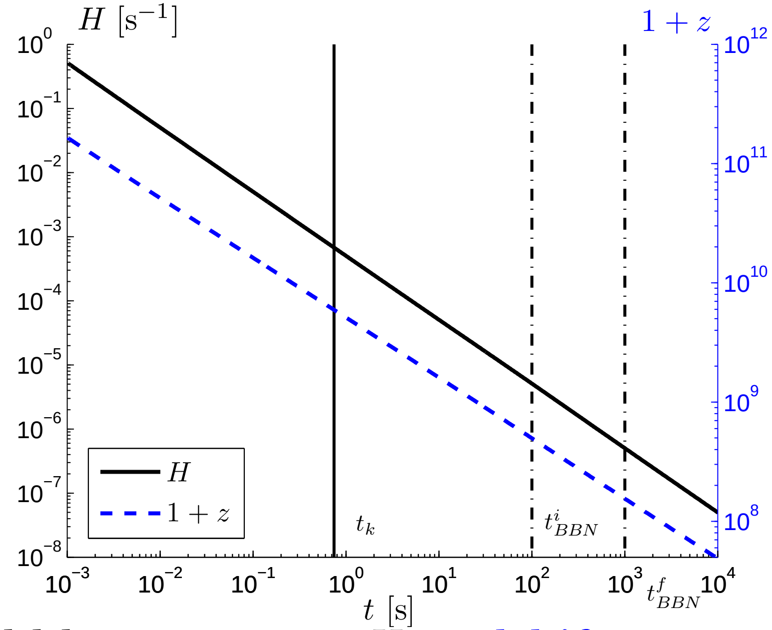
Temperature T, deceleration parameter q; Hubble parameter H, redshift $z + 1$.

TODAY is at right edge

NOTE: this is in essence reproduction of the 'Planck' study of the connection of cosmic microwave background fluctuations, SN-standard candles which we employed. Started with Planck value $H_{\rm now}$

Going back from before BBN to before antimatter era: the 'connection'





Temperature T, deceleration parameter q; Hubble parameter H, redshift $z+1$

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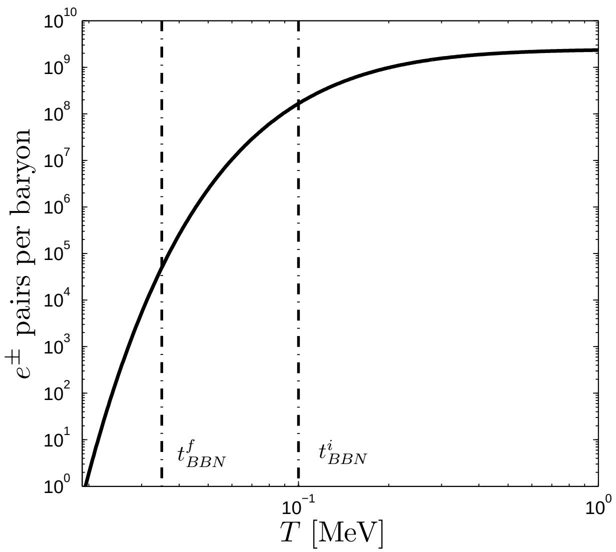

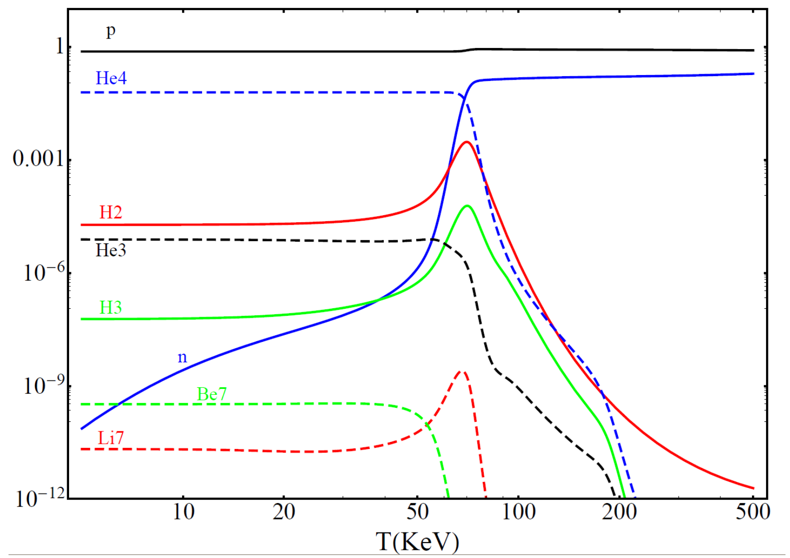

Number of e^+e^--pairs per baryon through BBN. e^+e^- pairs dominates largely the number of baryons through the BBN period, a fact which deserves more thought.

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Brief Remarks Neutrino Freeze-out

- **If energy and entropy from $e^{\pm}$ annihilation is going into photons, the relic neutrino background and CMB temperatures differ by a reheating factor $R_\nu \equiv T_\nu/T_\gamma = (4/11)^{1/3}$. Photons are the 'thermal bath' with reference T.**

- **The effective number of neutrinos is defined by comparing the total neutrino energy density to the energy density of a massless fermion with two degrees of freedom and standard reheating ratio R_ν**

$$N_\nu \to N_{\rm eff} \equiv \frac{\rho_\nu}{\frac{7}{120}\pi^2 \left(R_\nu T_\gamma\right)^4}. \qquad \rho_\nu = (1 + (7/8)R_\nu^4 N_{\rm eff})\rho_\gamma, \tag{1}$$

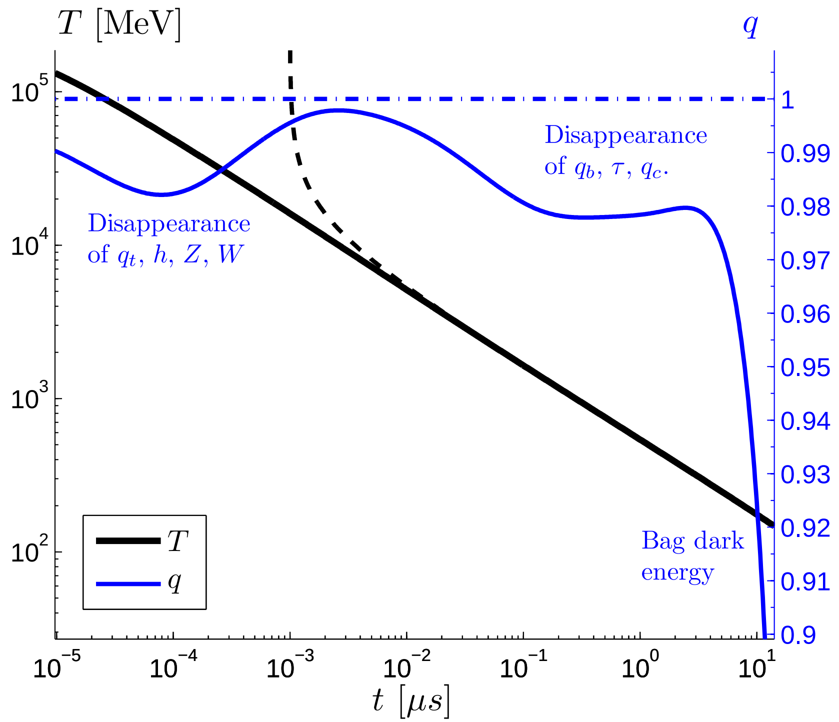
  Meaning that energy ρ_ν in neutrinos impacts speed of Universe expansion and can be measured:

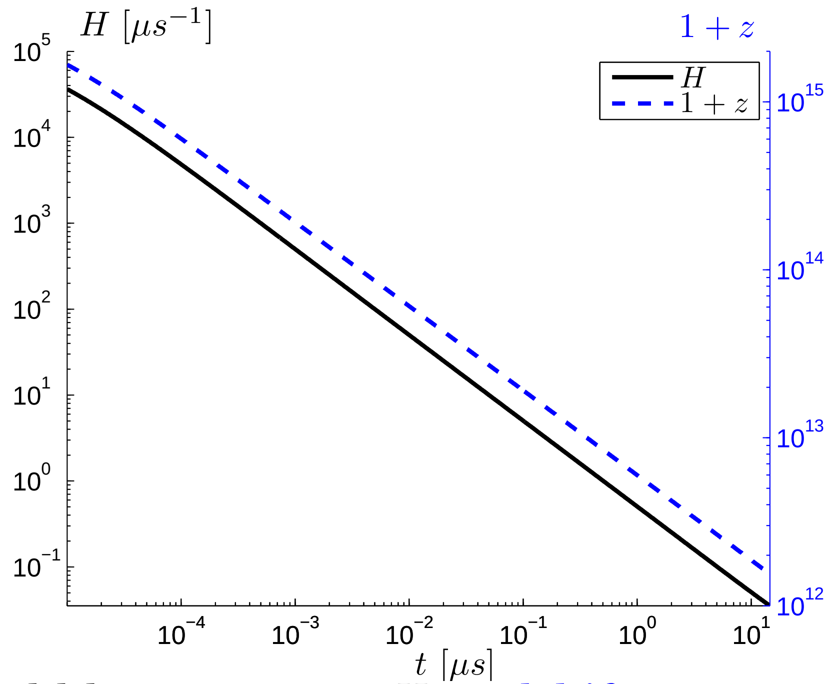
  1. **Planck satellite data gives $N_\nu = 3.36 \pm 0.34$ (CMB alone) and $N_\nu = 3.62 \pm 0.25$ (CMB+H_0) [1].**
  2. **The currently used theoretical value – Boltzmann scattering – is $N_\nu = 3.046$ [2].**
  3. **This tension between the Planck result and reheating study inspired work on new particles e.g.[3], eventually connecting $N_{\rm eff}$ with QGP phase [4]**
  4. **A more conservative explanation is that some extra energy went into neutrinos during $e^{\pm}$ annihilation i.e. neutrino reheating [5]**

- **The present day background of neutrinos: number and momentum distribution depend on $N_{\rm eff}$**

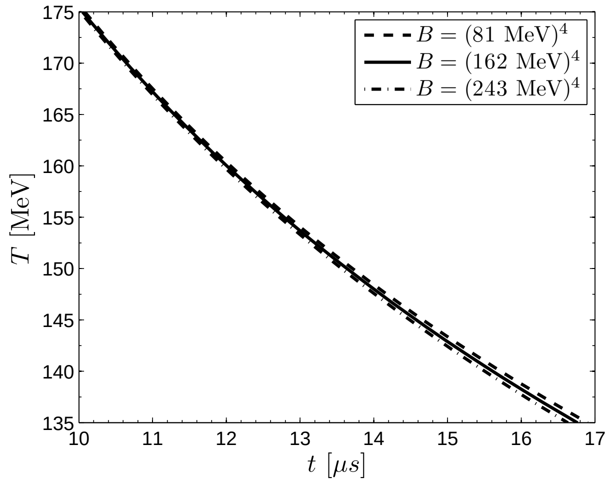
[1] Planck Collaboration, arXiv:1303.5076
[2] G. Mangano et. al., Nucl. Phys. B 729, 221 (2005)
[3] Steven Weinberg Phys. Rev. Lett. 110, 241301 (2013)
[4] J. Birrell, JR arXiv:1404.6005
[5] J. Birrell, JR et.al.Phys. Rev. D 89, 023008 (2014)

Forward: from EW symmetric world to QGP hadronization



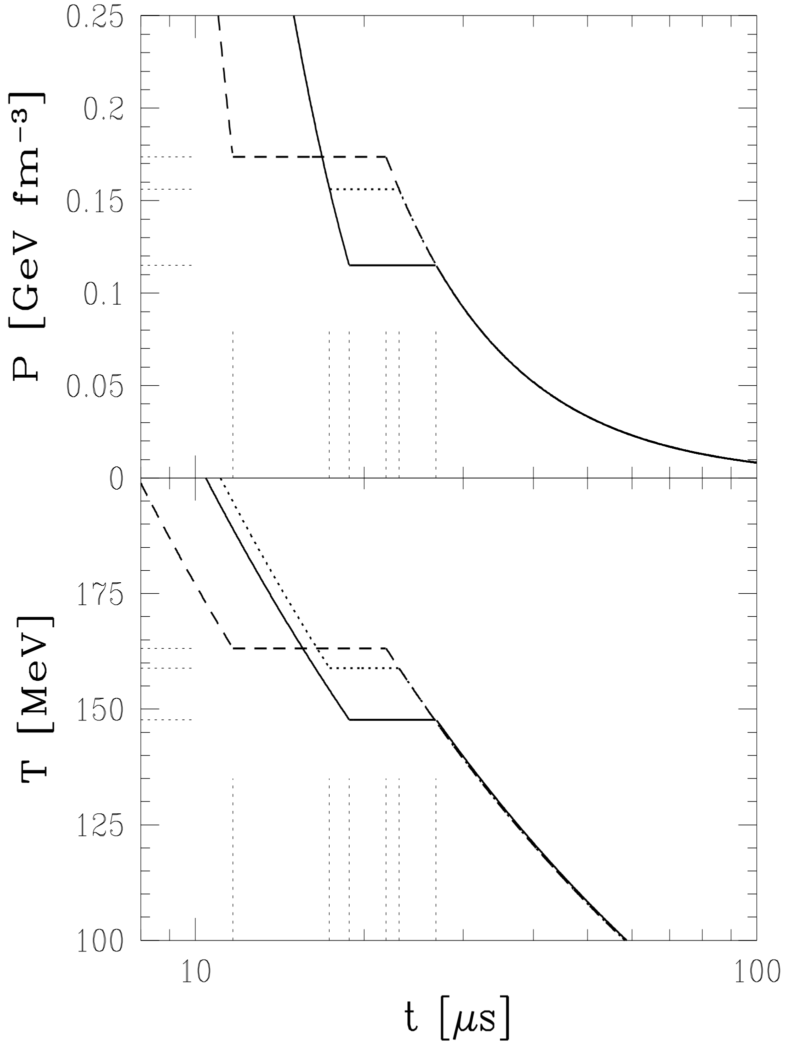


Temperature T, deceleration parameter q; Hubble parameter H, redshift $z+1$.



T near the QGP phase transition for several values of the bag energy density.

What Controls Quark-Hadron Time Scale in the Universe?



- case studies - QGP-Hadron Universe: Pressure (upper) and temperature (lower part) as function of time

with $\epsilon + P = (4/3)(\varepsilon - \mathcal{B})$ **and entropy conserving evolution in Friedmann equation:**

$$3\dot{\varepsilon}^2 = 128\pi G\,\varepsilon\,(\varepsilon - \mathcal{B})^2,$$

Set $\varepsilon = z^2\mathcal{B}$ **and** $t = x\tau_{\rm U}$ **with:**

$$\boxed{\tau_{\rm U} = \sqrt{\frac{3c^2}{32\pi G\mathcal{B}}} = 25\sqrt{\frac{\mathcal{B}_0}{\mathcal{B}}}\,\mu\mathrm{s}, \quad \mathcal{B}_0 = 0.4\,\frac{\mathbf{GeV}}{\mathbf{fm}^3}}$$

leads to $(z')^2 = (z^2-1)^2$ **. Physical solution:**

$$\epsilon = \mathcal{B}\coth^2\left(\frac{t_0+t}{\tau_{\rm U}}\right), \qquad x = t/\tau_{\rm U},$$

for $\mathcal{B} \to 0$**: massless particles=radiative universe:**

$$\epsilon = \frac{3}{32\pi G}\frac{1}{(t_0+t)^2}$$

The QGP Universe expands as,

$$H = \frac{\coth\left(\frac{t_0+t}{\tau_{\rm U}}\right)}{2\tau_{\rm U}}, \qquad a = a_0\sqrt{\sinh\left(\frac{t_0+t}{\tau_{\rm U}}\right)}$$

We see that characteristic time of evolution (and phase transformation) is measured in 10'sμs. Collision time in laboratory is 17 orders of magnitude shorter. Test of QGP equilibration vital to understand how to use lab results to characterize the early Universe.

Size of the Quark Universe

There is a simple relation between the net baryon number b and the volume of QGP source of this baryon number:

$$V_{\rm QGP} = b\frac{S/b}{S/V} = \frac{3.5\,10^{10}}{10/{\rm fm}^3} = b \times 3.5\,10^9\,{\rm fm}^3$$

Where in entropy density at hadronization we included leptonic component, and we employed present day value of $S/b = 3.5\,10^{10}$

GALAXY baryon content: Solar mass is $M_{\rm Sun} = 2 \times 10^{30}{\rm kg} = 1.2 \times 10^{57}$ protons. Galactic mass is $M_{\rm galaxy} = 5 \times 10^{11} M_{\rm Sun}$, Therefore, assuming 1/4 is visible matter the galaxy has about $N_B^{\rm Milky\ \ Way} = (6/4) \times 10^{68}$ proton masses. To make a galaxy we need a QGP in the Universe of the magnitude $V = 0.5 \times 10^{78}{\rm fm}^3$, that is $R = 0.5\,10^{11}$ meter

UNIVERSE baryon content: The baryon content of the Universe requires estimated of 'unseen' galaxies, leading to $N_{\rm galaxie} = 510^{11}$, thus the total baryon number bound in stars within the current horizon of the Universe is given as $B_{\rm all\ \ stars} \simeq 0.510^{80}$. Astrophysicists fight about how much baryon number is in interstellar dust - we solve the problem by rounding up the number $B_{\rm Universe} \simeq 10^{80}$

Size of QGP Universe: at time hadronization $V_{\rm QGP} \simeq (10^{15}{\rm meter})^3$, light needs to travel a month across this domain. However, the Universe is only about 30μs old; we see the need for a gigantic inflation prior to QGP era, factor: 10^{11} Keep in mind b big differences to RHI: time and size scale $\Rightarrow$ equilibrium!

Chemical composition and evolution of the early Universe

Our Objectives:

1) Describe in quantitative terms the chemical composition of the Universe before, at, and after EQUILIBRIUM hadronization near to:

$$T \simeq 150\,\mathbf{MeV} \qquad t \simeq 30\mu s,$$

including period of matter-antimatter annihilation, the residual matter and hadronic particles evolution.

2) Somewhat beyond current capability: describe the dynamics of quark-hadron phase transformation (preferably with nucleation dynamics) allowing for contrast ratios and baryon and strangeness number distillation; opportunities for future research.

3) Describe precisely the composition of the Universe during evolution towards the condition of neutrino kinetic decoupling

$$T \simeq 1\,\mathbf{MeV} \qquad t \simeq 3\,s$$

4) Connect to BBN in a study of neutrino freeze-out, $e\bar{e}$-plasma annihilation.

We will require input from experimental anchor points

Chemical potentials control particle abundances

$$f(\varepsilon = \sqrt{p^2 + m^2}) = \frac{1}{e^{\beta(\varepsilon-\mu)} \pm 1}$$

Relativistic Chemistry (with particle production)

- **Photons in chemical equilibrium, assume the Planck distribution, implying a zero photon chemical potential; i.e., $\mu_\gamma = 0$.**

- **Because reactions such as $f + \bar{f} \rightleftharpoons 2\gamma$ are allowed, where f and $\bar{f}$ are a fermion – antifermion pair, we immediately see that $\mu_f = -\mu_{\bar{f}}$ whenever chemical and thermal equilibrium have been attained.**

- **More generally for any reaction $\nu_i A_i = 0$, where ν_i are the reaction equation coefficients of the chemical species A_i, chemical equilibrium occurs when $\nu_i \mu_i = 0$, which follows from a minimization of the Gibbs free energy.**

- **Weak interaction reactions assure:**

$$\mu_e - \mu_{\nu_e} = \mu_\mu - \mu_{\nu_\mu} = \mu_\tau - \mu_{\nu_\tau} \equiv \Delta\mu_l, \qquad \mu_u = \mu_d - \Delta\mu_l, \qquad \mu_s = \mu_d\ ,$$

- **Neutrino oscillations $\nu_e \rightleftharpoons \nu_\mu \rightleftharpoons \nu_\tau$ imply equal chemical potential:**

$$\mu_{\nu_e} = \mu_{\nu_\mu} = \mu_{\nu_\tau} \equiv \mu_\nu,$$

and the mixing is occurring fast in 'dense' early Universe matter.

Remarks:

1. **These considerations leave undetermined three chemical potentials and we choose to solve for μ_d, μ_e, and μ_ν. We will need three experimental inputs.**

2. **Quark chemical potentials can be used also in the hadron phase, e.g. $\Sigma^0\,(uds)$ has chemical potential $\mu_{\Sigma^0} = \mu_u + \mu_d + \mu_s$**

3. **The baryochemical potential is:**

$$\mu_b = \frac{1}{2}(\mu_p + \mu_n) = \frac{3}{2}(\mu_d + \mu_u) = 3\mu_d - \frac{3}{2}\Delta\mu_l = 3\mu_d - \frac{3}{2}(\mu_e - \mu_\nu).$$

(Chemical) Conditions/constraints fixing three parameters

Three chemical potentials follow solving the 3 available constraints:

i. *Global charge neutrality* **($Q = 0$) is required to eliminate Coulomb energy. Local condition:**

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

where Q_i and n_i are the charge and number density of species i.

ii. *Net lepton number equals net baryon number* **($L = B$): often used condition in baryo-genesis:**

$$n_L - n_B \equiv \sum_i (L_i - B_i)\, n_i(\mu_i, T) = 0,$$

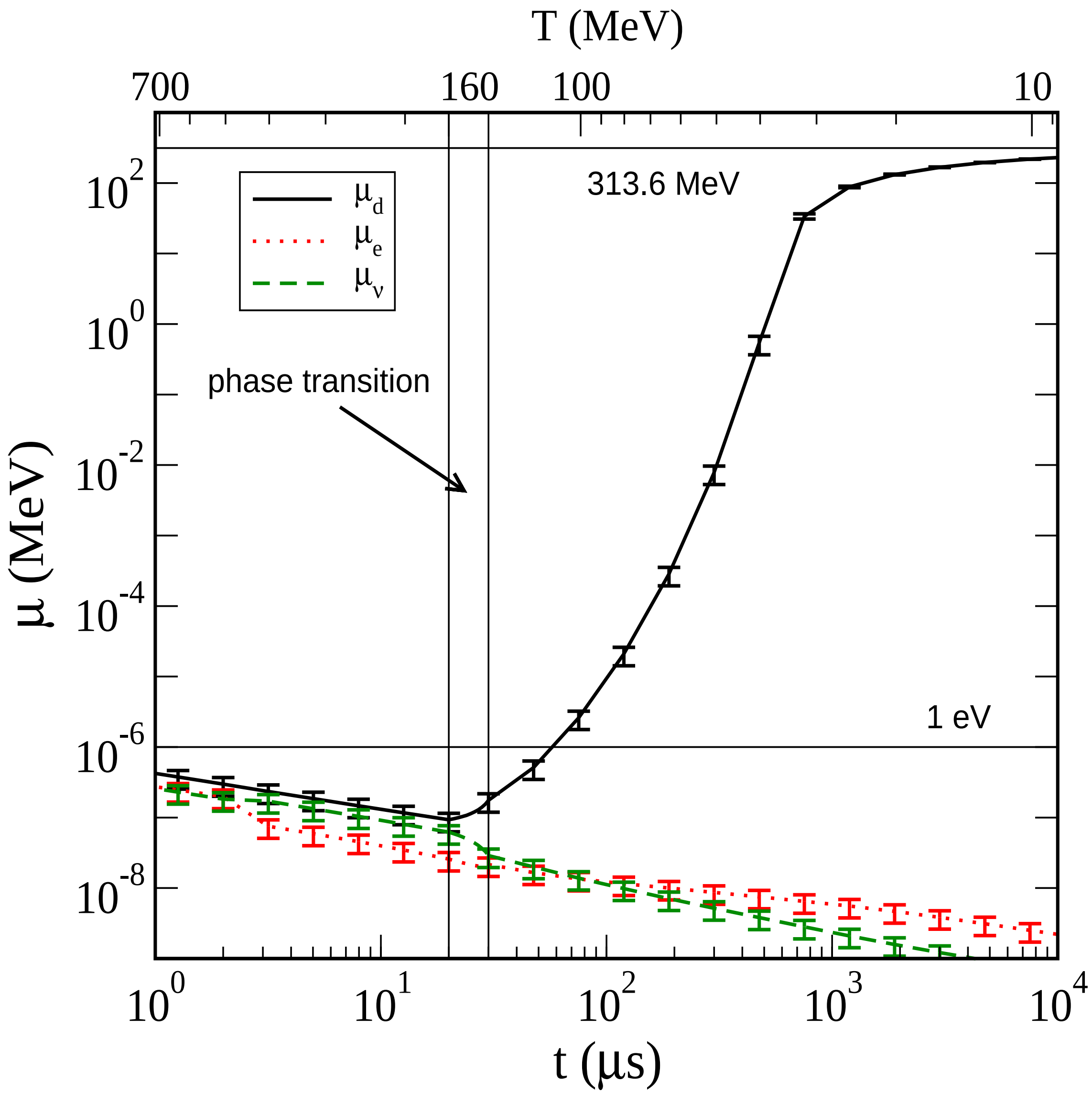
This can be easily generalized. As long as imbalance is not competing with large late photon to baryon ratio, it is hidden in slight neutrino-antineutrino asymmetry.

iii. *The Universe evolves adiabatically, i.e. Fixed value of entropy-per-baryon* **(S/B)**

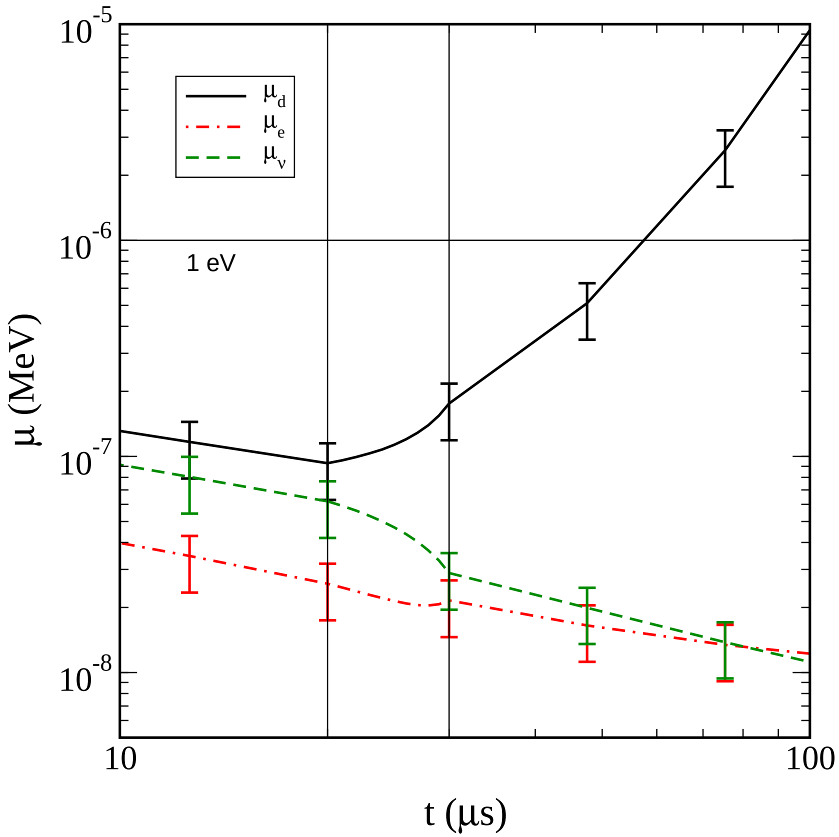
$$\frac{\sigma}{n_B} \equiv \frac{\sum_i \sigma_i(\mu_i, T)}{\sum_i B_i\, n_i(\mu_i, T)} = 3.2 \ldots 4.5 \times 10^{10}$$

Note, current value $S/B = 3.5 \times 10^{10}$ but results shown for older value 4.5×10^{10} See on-line *Hadronization of the quark Universe* **Michael J. Fromerth, Johann Rafelski (Arizona U.). Nov 2002. 4 pp. e-Print: astro-ph/0211346**

TRACING μ_d IN THE UNIVERSE



Minimum $\mu_b = 0.33^{+0.11}_{-0.08}$ eV.
μ_b relevant at final hadron $(\pi, \overline{N})$ freeze-out.



Mixed Phase – Case differs from RHI hadronization

Conserved quantum numbers (e.g. baryon and strangeness densities) of the Universe jump as one transits from QGP to Hadron Phase – 'contrast ratio'. Thus there must be mixed hadron-quark phase and parametrize the partition function during the phase transformation as

$$\ln Z_{\mathrm{tot}} = f_{\mathrm{HG}} \ln Z_{\mathrm{HG}} + (1 - f_{\mathrm{HG}}) \ln Z_{\mathrm{QGP}}$$

f_{HG} **represents the fraction of total phase space occupied by the HG phase. This is true even if and when energy, entropy, pressure smooth (phase transformation rather than transition).**

We resolve the three constraints by using e.g. for $Q = 0$:

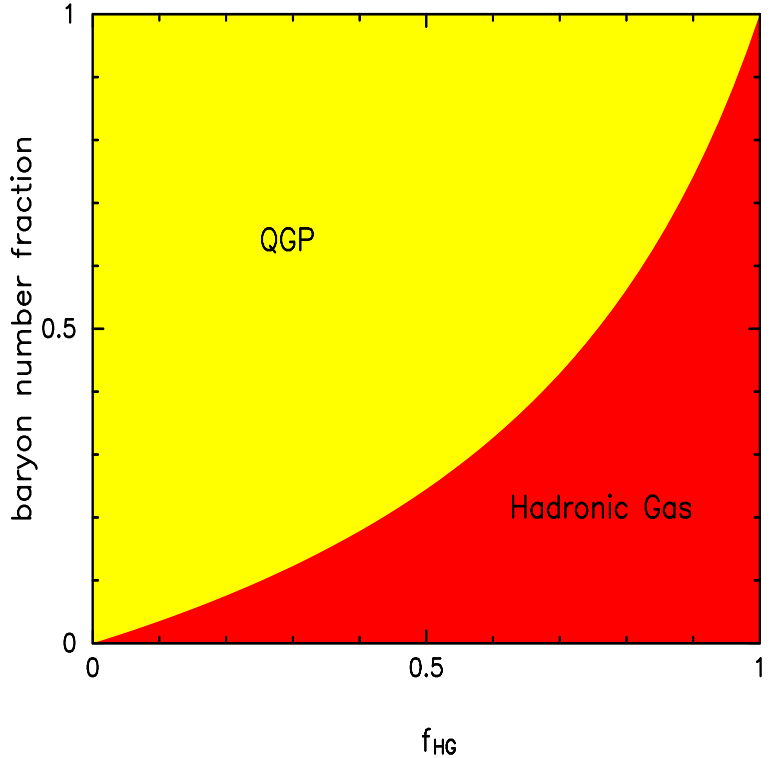
$$Q = 0 = n_Q^{\mathrm{QGP}}\, V_{\mathrm{QGP}} + n_Q^{\mathrm{HG}}\, V_{\mathrm{HG}} = V_{\mathrm{tot}} \left[(1 - f_{\mathrm{HG}})\, n_Q^{\mathrm{QGP}} + f_{\mathrm{HG}}\, n_Q^{\mathrm{HG}} \right[$$

where the total volume V_{tot} is irrelevant to the solution. Analogous expressions are used for $L - B$ and S/B constraints. Note that $f_{\mathrm{HG}}(t)$ is result of dynamics of nucleation, assumed not generated here

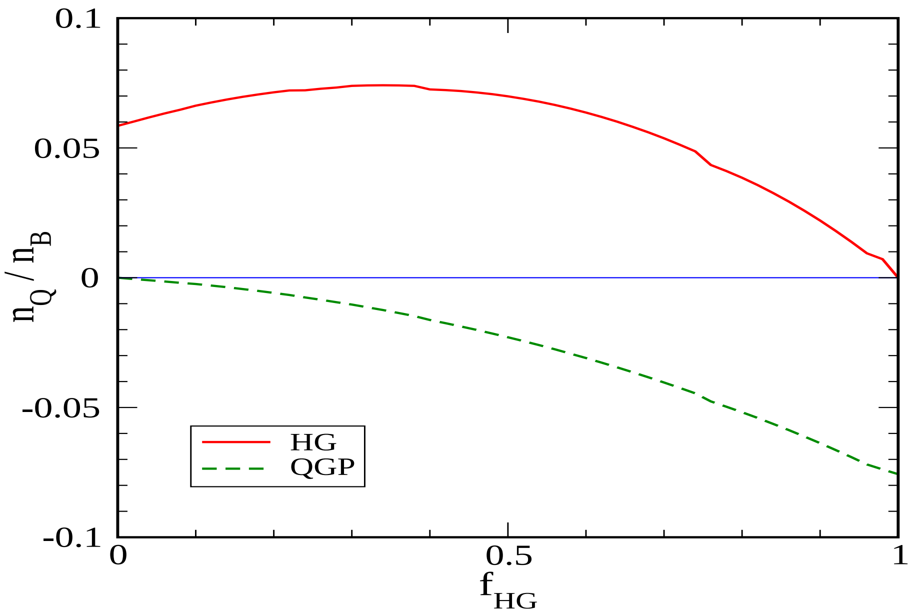
We assume that mixed phase exists $10\,\mu s$ and that f_{HG} changes linearly in time. Actual values will require dynamic nucleation transport theory description.

Charge and baryon number distillation

Initially at $f_{\rm HG} = 0$ all matter in QGP phase, as hadronization progresses with $f_{\rm HG} \to 1$ the baryon component in hadronic gas reaches 100%.



The constraint to a charge neutral universe conserves sum-charge in both fractions. Charge in each fraction can be finite. SAME for baryon number and strangeness: distillation!



A small charge separation introduces a finite non-zero Coulomb potential and this amplifies the existent baryon asymmetry. This mechanism noticed by Witten in his 1984 paper, and exploited by Angela Olinto for generation of magnetic fields.

MECHANISM OF HADRO-CHEMICAL EQUILIBRATION

Inga Kuznetsova and JR

1002.0375, Phys. Rev. C 82, 035203 (2010) and 0803.1588, Phys.Rev. D78, 014027 (2008)

The question is at which T in the expanding early Universe does the reaction

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

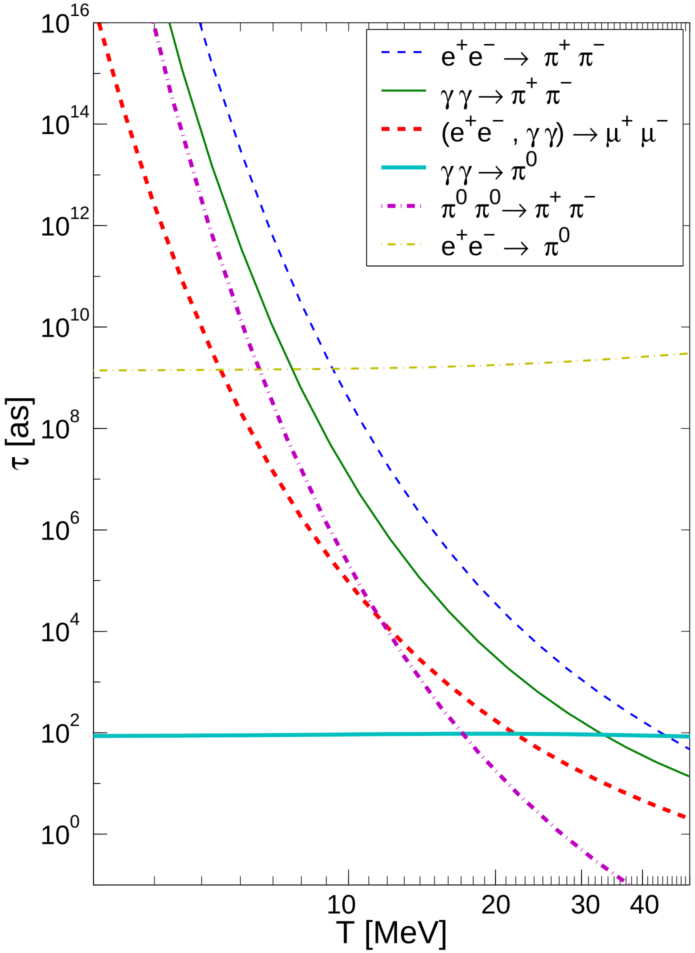
'freeze' out, that is the π^0 decay overwhelms the production rate and the yield falls out from chemical equilibrium yield. Since π^0 lifespan ($8.4\,10^{-17}$ s) is rather short, one is tempted to presume that the decay process dominates. However, there must be at sufficiently high density a detailed balance in the thermal bath

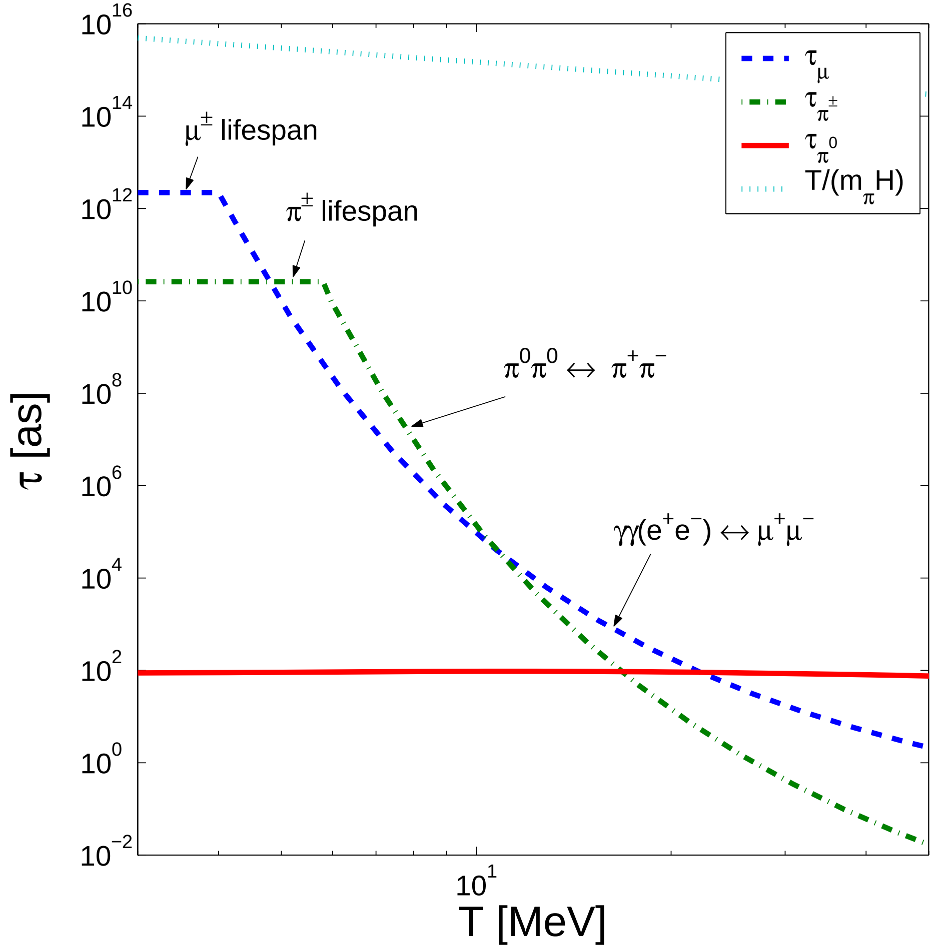
Presence of one type of pion implies presence of $\pi^{\pm}$, those can be equilibrated by the reaction:

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

All hadrons will be present: the π^0 creates the doorway.

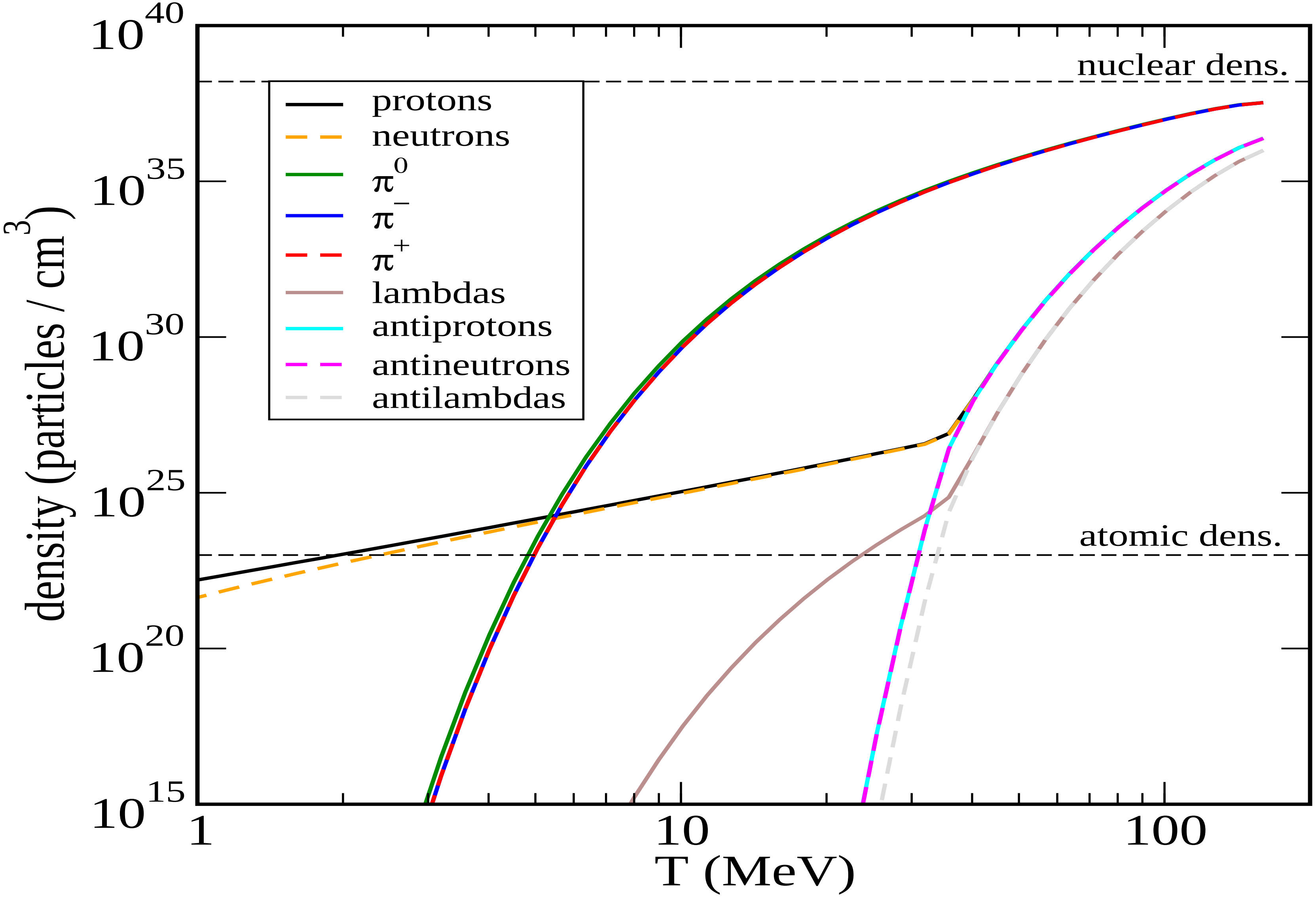
We develop kinetic theory for reactions involving three particles (two to one, one to two). We find that the expansion of the Universe is slow compared to pion equilibration, which somewhat surprisingly (for us) implies that π^0 is at all times in chemical equilibrium – at sufficiently low temperatures e.g. below e.g. 1 MeV, the local density of π^0 maybe too low to apply the methods of statistical physics.

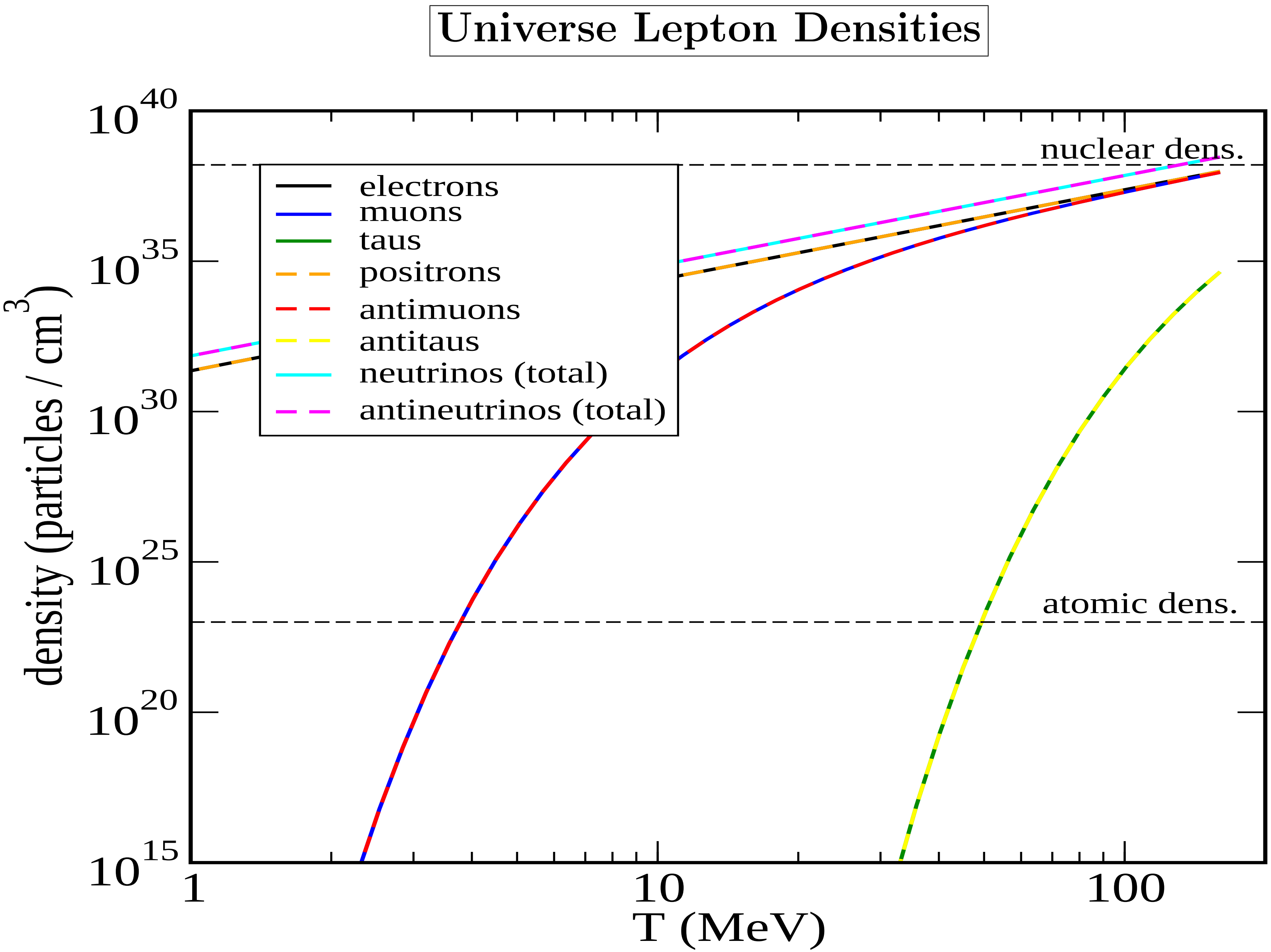




Relaxation times for dominant reactions for pion (and muon) equilibration. At small temperatures $T < 10$ MeV relaxation times for $\mu^{\pm}$ and $\pi^{\pm}$ equilibration becomes constant and much below Universe expansion rate and τ_T (dotted turquoise line on right).

Hadronic Universe Hadron Densities




Universe Lepton Densities
10^{40}
10^{35}
10^{30}
10^{25}
10^{20}
10^{15}
density (particles / cm^3)
1
10
100
T (MeV)
nuclear dens.
atomic dens.
electrons
muons
taus
positrons
antimuons
antitaus
neutrinos (total)
antineutrinos (total)

Did we find something worth continuing?

- **Cosmic evolution fully defined and constrained by current laboratory experiments from today back to Electro-Weak phase transition,**
- **and we have a pretty good view how the QGP Universe looks [This is the system that lattice QCD addresses, not RHI!],**
- **many details of cosmic evolution remain in investigation:**

1. **equilibrated flavor physics in QGP**
2. **equilibrium hadronization of u, d, s, c, b-QGP**
3. **There is without doubt strong local inhomogeneity at QGP hadronization**
4. **Strangeness present in a significant abundance in early Universe down to $T = 10$ MeV, potential for production of strange nuclearites**
5. **period of antimatter annihilation**
6. **neutrino decoupling, presence or not of light undiscovered particles**
7. **BBN in presence of dense e^+e^--plasma: unsettling.**