Near the beginning...there was Quark-Gluon Plasma

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BNL Physics Colloquium, January 21, 2014

Journey in time through the universe from a visit to the quark-gluon plasma era:

Matter surrounding us arose from the primordial phase of matter, Quark-Gluon Plasma (QGP). QGP was omni-present up to when the Universe was 13 microseconds old, just the time it takes for heavy ions to travel around the BNL-RHIC ring. As the universe expands and cools QGP hadronizes, forming abundant matter and antimatter. Only a nano-fraction surplus of nuclear matter survives annihilation process. A dense electron-positron-photon-neutrino plasma remains. The description of neutrino chemical and kinetic freeze-out dynamics requires use of the methods we developed in study of hadron freeze-out in QGP hadronization. Electrons and positrons begin to annihilate nearly at the same time when neutrinos decouple. Electron-positron-annihilation process lasts through the big-bang nucleo-synthesis (BBN) period. In the background of free streaming dark matter and neutrino fluids the visible matter evolves till ion-electron recombination completes, and the Universe becomes transparent to free-steaming light we observe as the cosmic microwave background.

The next hour is about

- **In depth look why we do relativistic heavy ion physics and:**
- **Applying this to the understanding of the Quark-Hadron Universe**
- **Applying non-equilibrium methods developed in RHI to other time epochs**

Past decade primary contributors: (former) students were ($\alpha\beta$'ic):
Jeremey Birrell, Michael Fromerth, Inga Kuznetsowa, Lance Labun Michal Petran, Giorgio Torrieri

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

Outline

- **The intellectual and historical pillars of RHI-QGP physics - extended version**
- **The beginning: Experimental HI Program**
- **The beginning: Introduction to cosmology and survey of three epochs of cosmic evolution: QGP, ν-decoupling – BBN, Ion-electron Recombination**
- **Differences to QGP in laboratory: time scale, baryon content, size scale**

TIME PERMITTING

- **Quark-lepton Chemistry**
- **Universe with mixed quark-hadron phase**
- **Hadron Universe emerges**

Intellectual Pillars of QGP/RHI Collisions Research Program

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 13 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.

INVESTIGATE STRUCTURED QUANTUM VACUUM (Einsteins 1920+ Aether)

The vacuum state determines prevailing fundamental laws of nature. Demonstrate by changing the vacuum to the color conductive deconfined ground state.

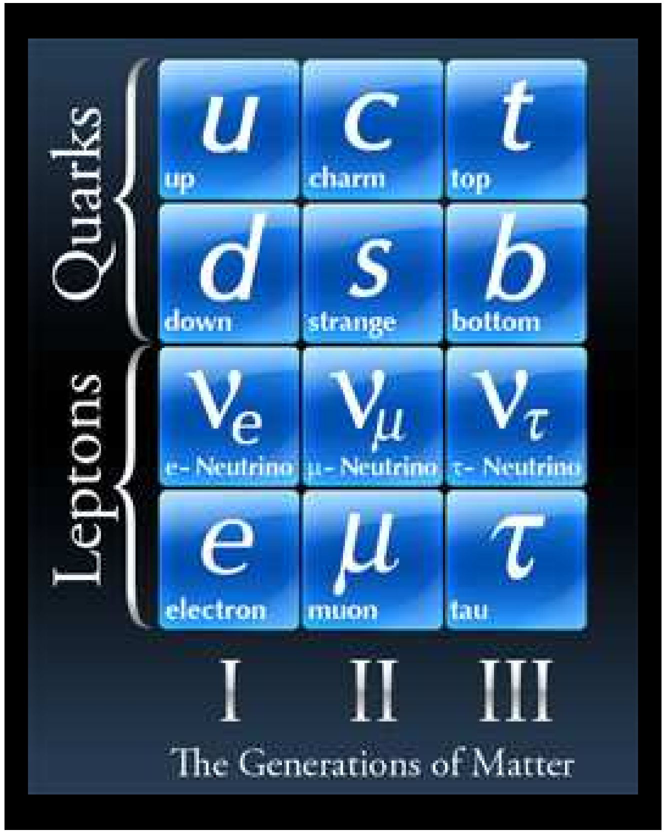
STUDY ORIGIN OF THE INERTIA OF MATTER

The confining vacuum state is the origin of 95% of inertial mass, the Higgs mechanism applies to the remaining few%. We want to: i) confirm the new paradigm; ii) explore the connection between charge and inertia; iii) understand how when we 'melt' the vacuum structure setting quarks free the energy locked in the mass of nucleons is transformed.

SEARCH FOR THE ORIGIN AND MEANING OF FLAVOR

Normal matter made of first flavor family $(u, d, e, [\nu_e])$. Strangeness and charm [at LHC] 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 family.

The Riddle of Three Generations of Matter



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

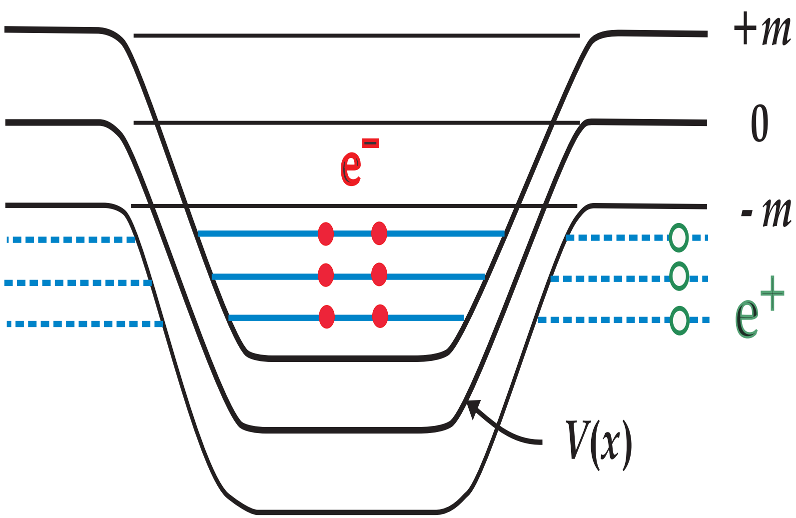
Vacuum Structure: Origin of Physics Laws

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 created in laboratory is a ponderable fragment of the early Universe: is this possible? Berndt Muller and I worked on this in early '70s:

Formation of Local Domain of Charged Vacuum



Pair production across (nearly) constant field fills the 'dived' states available in the localized domain. 'Positrons' are emitted. Hence a localized charge density builds up in the vacuum reducing the field strength - back reaction.

Charged vacuum ground state observable by positron emission.

Rate W per unit time and volume of positron (pair) production in presence of a strong electric field $|\vec{E}|$ first made explicit by J. Schwinger, PRD82, 664 (1950).

$$W = \mathcal{I}m\mathcal{L}_{\rm eff} = \frac{c}{8\pi^3}\frac{(eE)^2}{(\hbar c)^4}\sum_{n=1}^{\infty}\frac{1}{n^2}e^{-\pi E_s/E}, \qquad E_s = m_e^2c^3/e\hbar$$

What is special about E_s? **For $E \to E_s$ vacuum unstable, pair production very rapid, field cannot be maintained.**

Quantum physics allows local changes in the aether

Strong Fields and Charged Vacuum

Nuclear Physics B68 (1974) 585–604. North-Holland Publishing Company

THE CHARGED VACUUM IN OVER-CRITICAL FIELDS*

J. RAFELSKI, B. MÜLLER and W. GREINER
Institut für Theoretische Physik der Universität Frankfurt, Frankfurt am Main, Germany

Received 4 June 1973
(Revised 17 September 1973)

Abstract: The concept of over-critical fields, i.e. fields in which spontaneous, energy-less electron-position pair creation may occur, is discussed. It is shown that only a charged vacuum can be a stable ground state of the overcritical field. The time-dependent treatment confirms previous results for the cross sections for the auto-ionizing positrons. The questions in connection with the classical Dirac wave functions in over-critical fields are extensively discussed in the frame of the self-consistent formulation of QED including the effects of vacuum polarization and self-energy.

34, NUMBER 6 PHYSICAL REVIEW LETTERS 10 FEBRUARY 1975

Stabilization of the Charged Vacuum Created by Very Strong Electrical Fields in Nuclear Matter*

Berndt Müller
Department of Physics, University of Washington, Seattle, Washington 98195

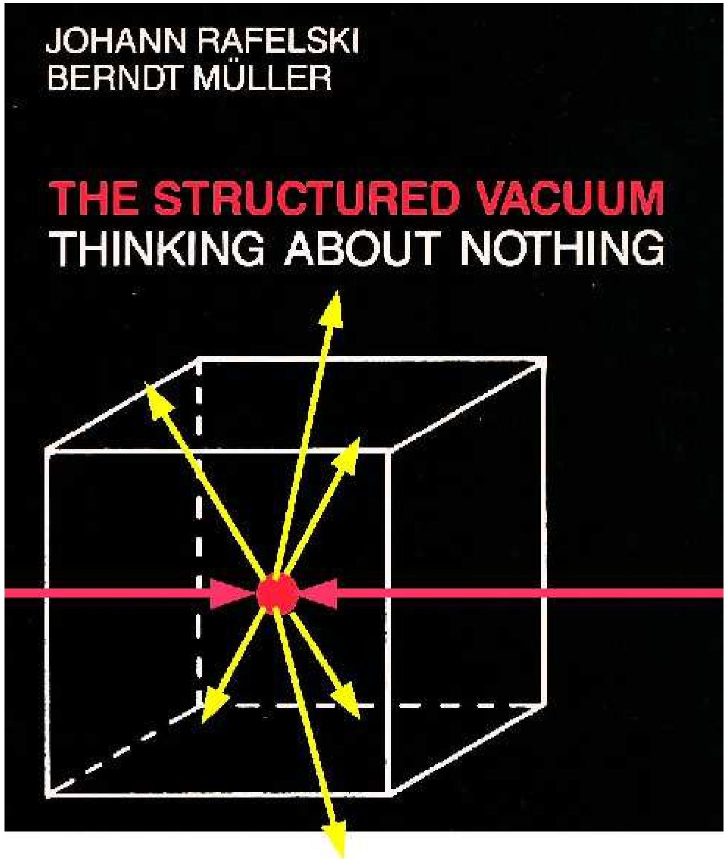
and

Johann Rafelski
Argonne National Laboratory, Argonne, Illinois 60439

(Received 2 December 1974)

The expectation value of electrical charge in charged vacuum is calculated utilizing the Thomas-Fermi model. We find almost complete screening of the nuclear charge. For any given nuclear density there is an upper bound for the electrical potential. For normal nuclear densities this value is -250 MeV. This suggests that the vacuum is stable against spontaneous formation of heavy, charged particles.

The Structured Vacuum 1985 booklet



We constructed interdisciplinary relation between Strong Fields–Casimir–High T–Deconfinement–Higgs vacuum

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
a 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-
ably the scope of the experimental program. In Table 1 are given the
present considered realistic for the PS and the ISR for fully stripped
is 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]	
t, 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

I was told that I am too young without track record and was denied access to the 'Bear Mountain' meeting set-up to advance RHI program. Of all participants as far as I can see only TD Lee had published on vacuum structure at that time. No wonder the US community kept on 10y long discussion of what and how to do. Phase transition at the "Quark Matter" meeting in September 1983 at BNL! This happened since:

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 $\bar{d}$):

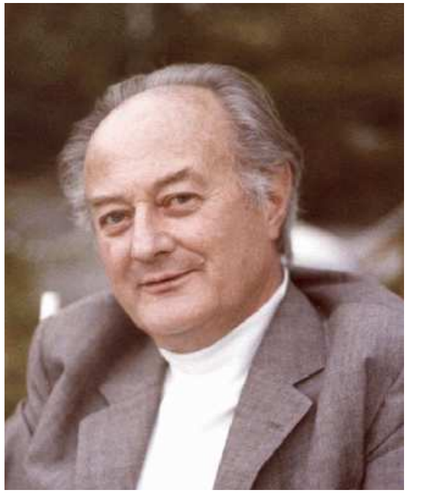
$$\frac{\bar{q}}{V} \simeq 6\int \frac{d^3p}{(2\pi)^3} e^{-|p|/T-\mu_q/T} = e^{-\mu_q/T}\cdot T^3\frac{6}{\pi^2} \qquad (27)$$

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.



⟸ 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 ⇒ 1985/6, Phys. Reports.

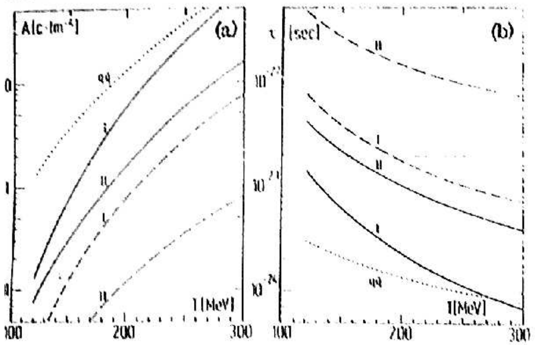


FIG. 2. (a) Rates A. (b) Time constants τ as func-
ns of temperature T. Full lines, $q\bar{q}\to s\bar{s}$ *and* $gg\to s\bar{s}$;
shed lines, $q\bar{q}\to s\bar{s}$; dotted lines, $gg\to q\bar{q}$ ($M = 15$
eV). Curves marked I are for $\alpha_s = 2.2$ and $M = 280$
eV; those marked II are for $\alpha_s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

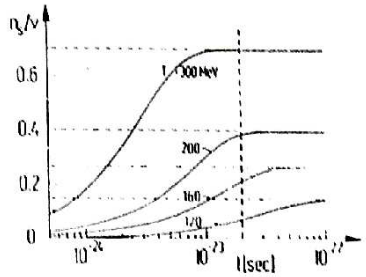


FIG. 3. Time evolution of the relative strange-quark to baryon-number abundance in the plasma for various temperatures

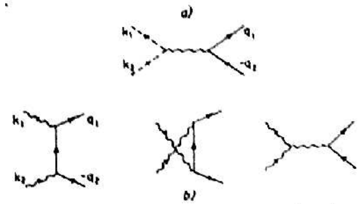


FIG. 1. Lowest-order QCD diagrams for $s\bar{s}$ production (a) $q\bar{q}\to s\bar{s}$, (b) $gg\to s\bar{s}$.

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 $T \gtrsim 160$ 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

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.

RHI Strangeness signature of QGP and Deconfinement

PHYSICS REPORTS (Review Section of Physics Letters) 142, No. 4 (1986) 167–262. North-Holland, Amsterdam

STRANGENESS IN RELATIVISTIC HEAVY ION COLLISIONS

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Received March 1986

Contents:

Move forward decades of RHI work ⇒ quark-hadron Universe

Today we are ready to explore setting the beginning at Electro-Weak vacuum freeze:

- **The expansion of the QGP Universe,**
- **The conversion of Quark Universe into hadrons,**
- **The dynamics of matter-antimatter annihilation and hadron disappearance in the range $300 < T < 3$ MeV and,**
- **The emergence of particle content as seen today.**
- **Connecting the evolution of plasma Universe towards neutrino decoupling to era of disappearance of e^+e^--pairs and BBN**

For most part we journey back to the quark-hadron Universe

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

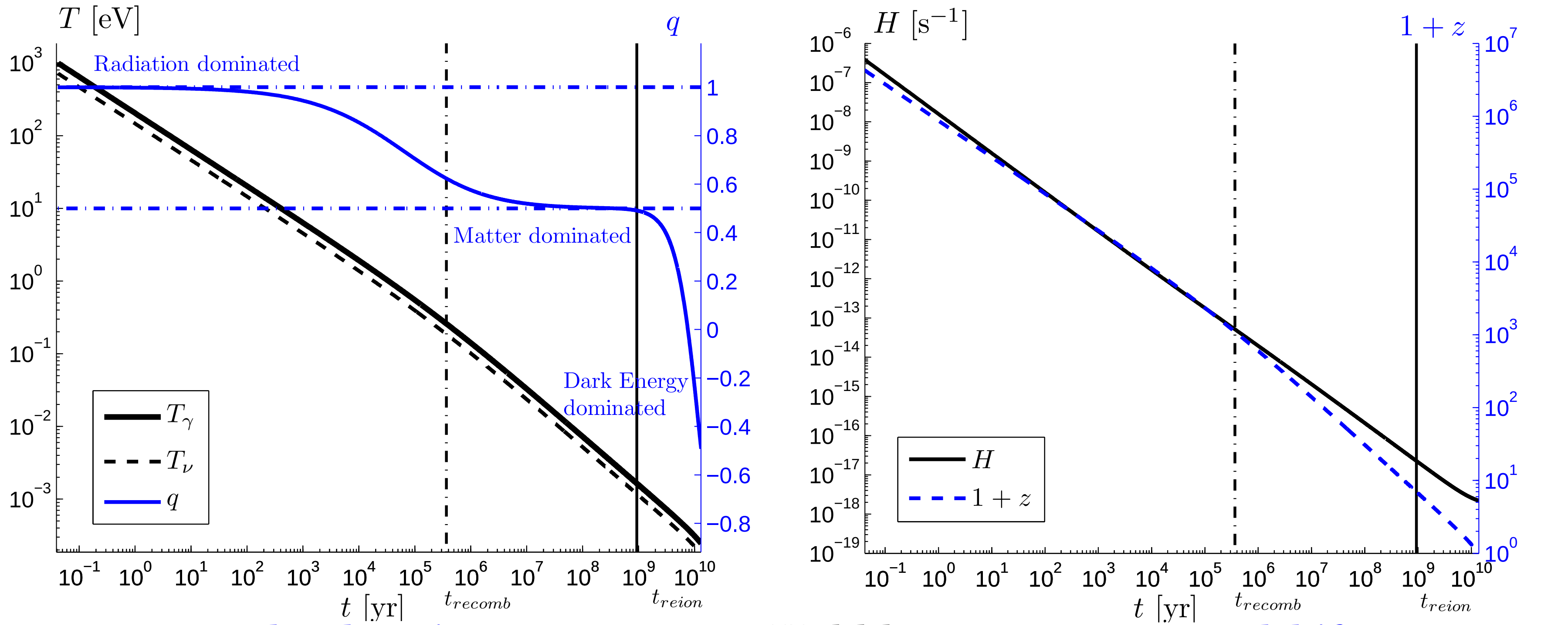
$$T^{\mu\nu}||_\nu = 0 \Rightarrow -\frac{\dot{\varepsilon}}{\varepsilon + P} = 3\frac{\dot{a}}{a} = 3H,$$

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 e.g. $M = 1$ TeV is 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.

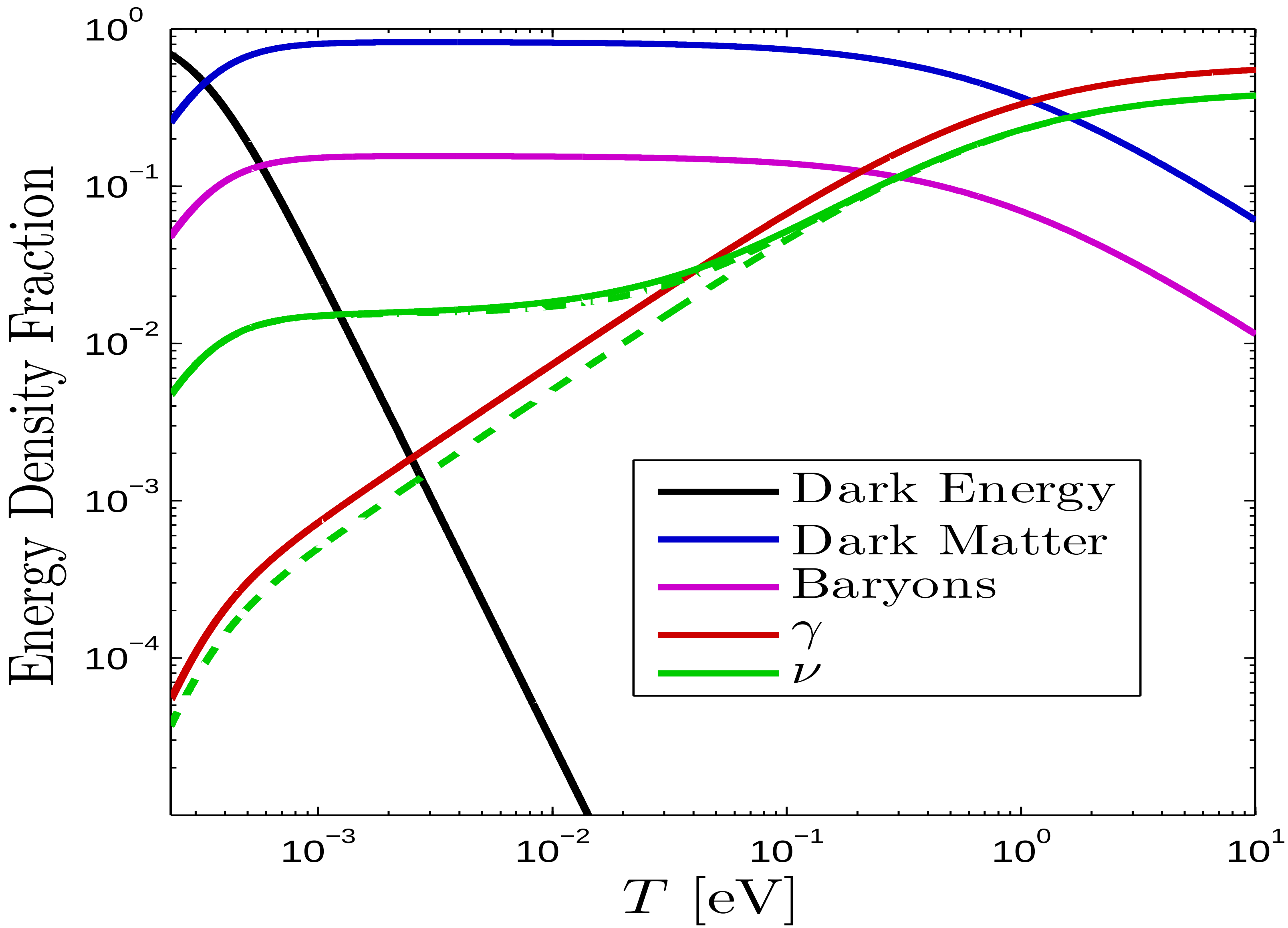
From the present day back beyond ion recombination: the almost 'visible universe'



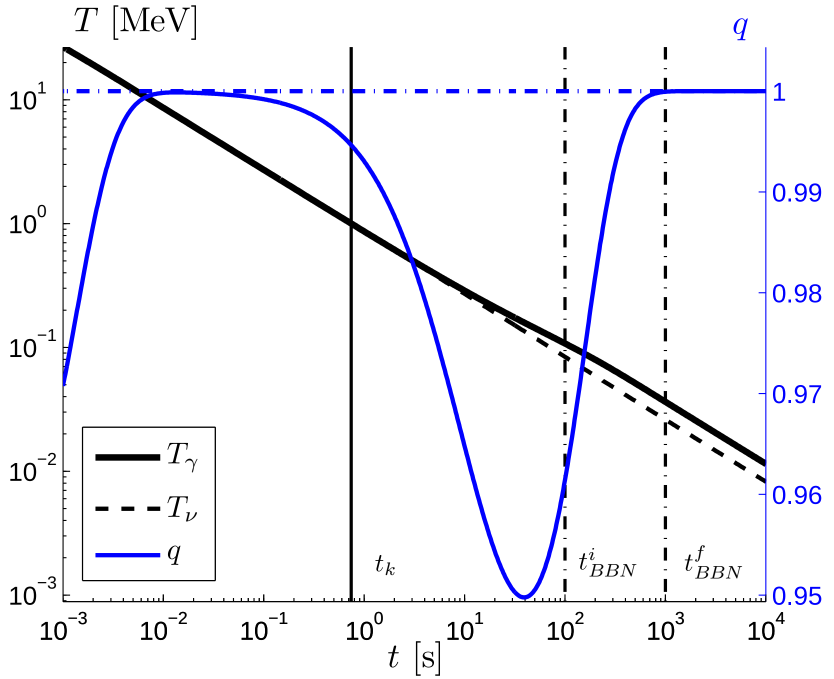
Temperature T, deceleration parameter q; Hubble parameter H, redshift $z+1$.

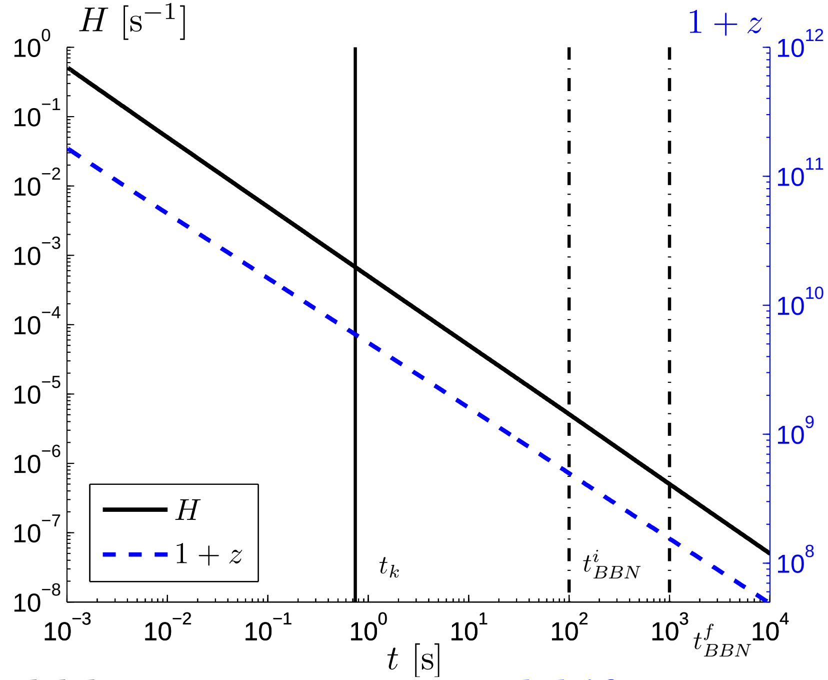
NOTE: this is in essence reproduction of the 'Planck' study of the connection of cosmic microwave background fluctuations, SN-standard candles which we employed. Started with Planck value $H_{\rm now}$

Composition of the 'present day' Universe



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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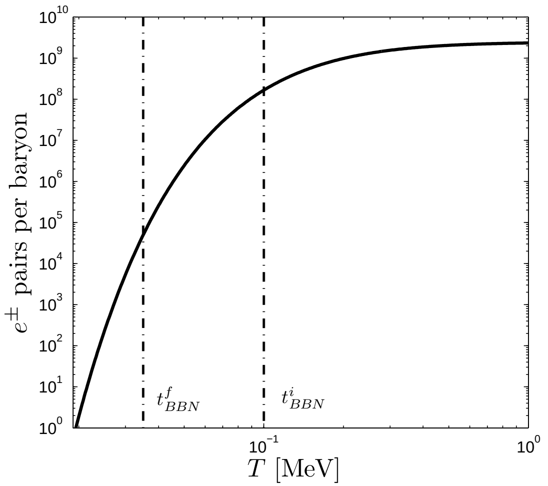
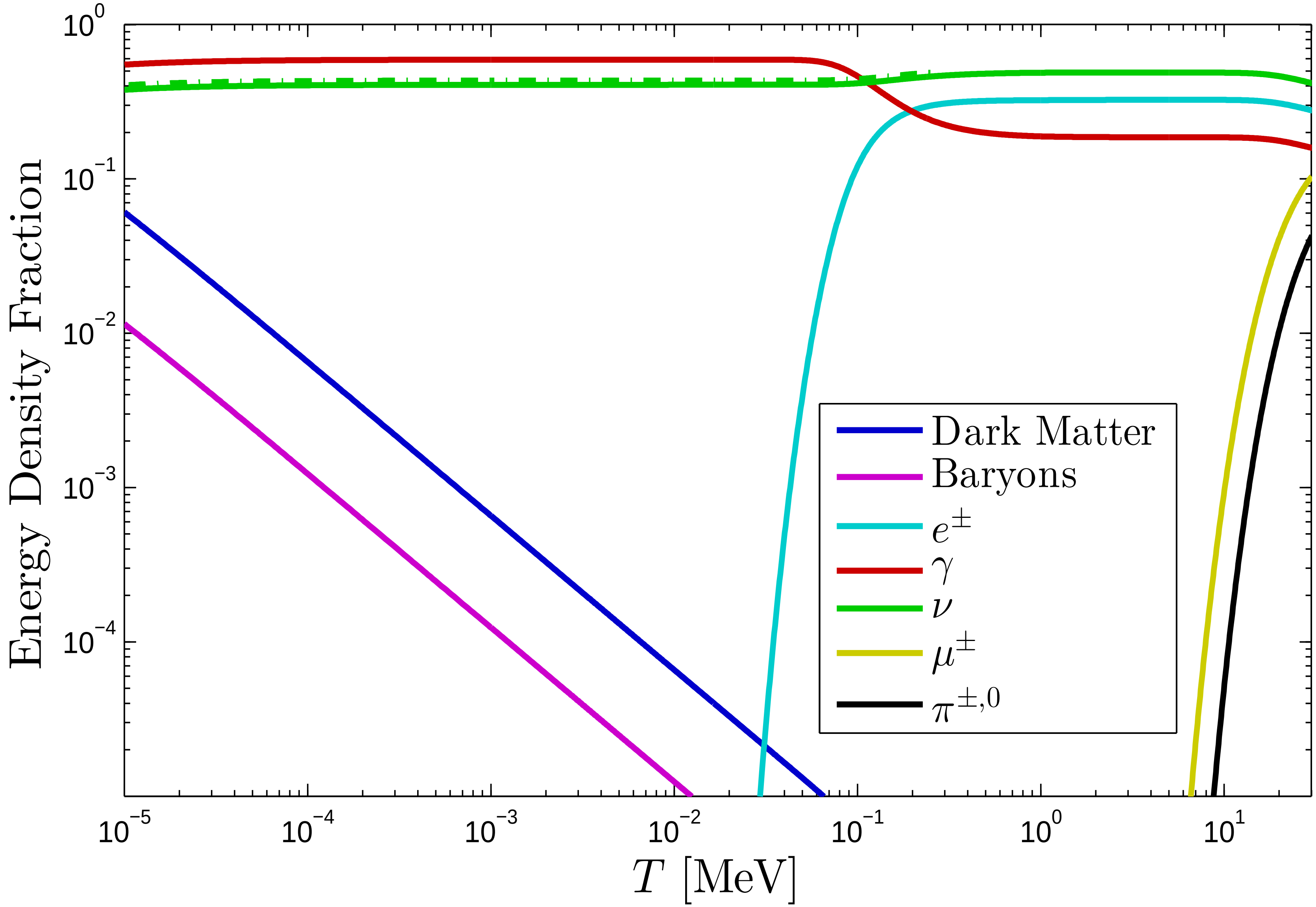


Number of e^+e^--pairs per baryon through BBN. e^+e^- pairs dominates largely the number of baryons through the BBN period, a fact which deserves more thought.

Composition of the 'recent' Universe



A few words about neutrinos: decoupling and degrees of freedom

Chemical (particle number changing reactions) decoupling at a few MeV, exact point of no concern as it happens in a very bland Universe.

Kinetic decoupling at lower T as all scattering process matter, now near beginning of e^+e^- annihilation time period.

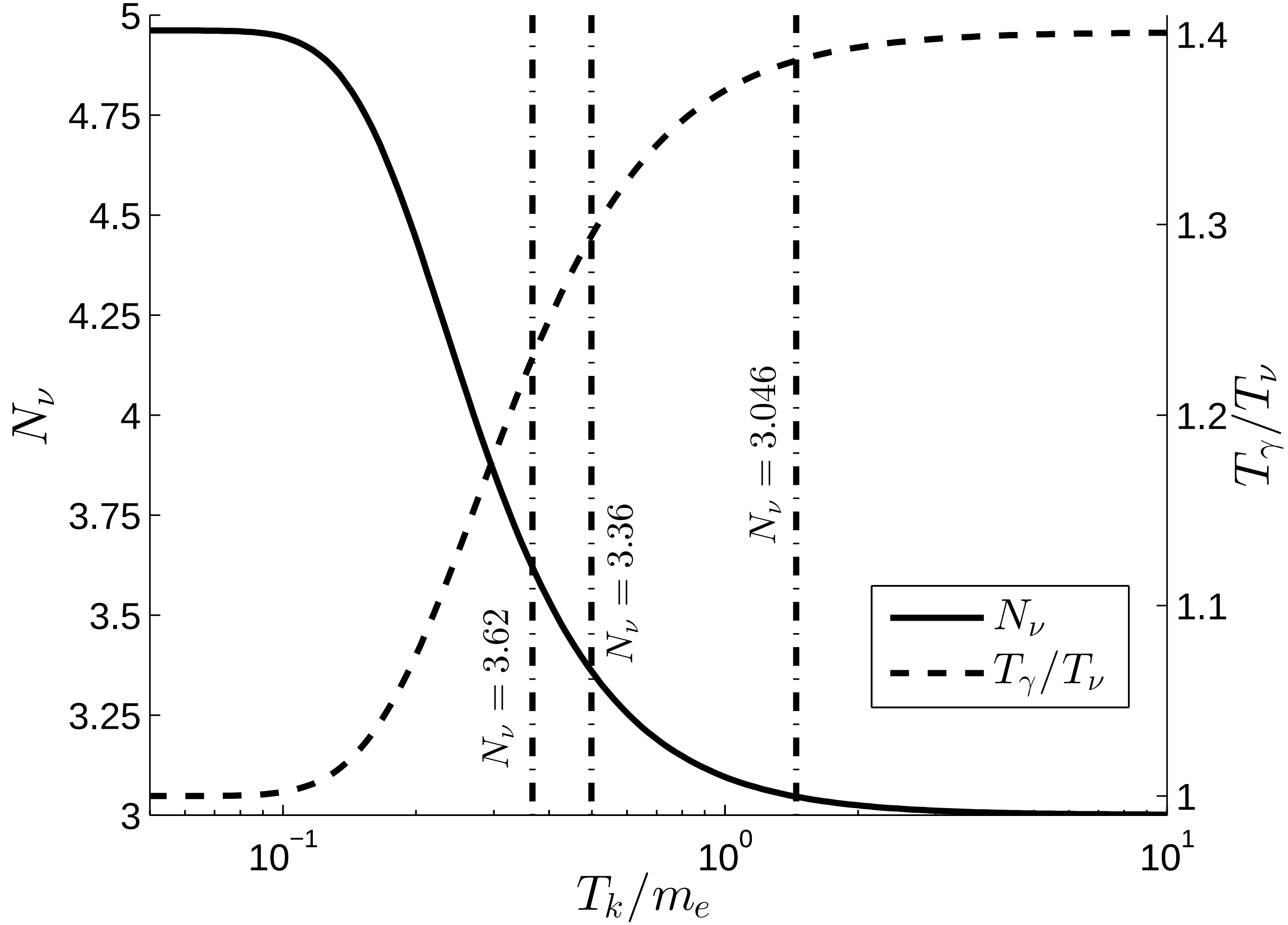
Problem: Some of energy from e^+e^- can flow to neutrinos. We compare the total neutrino energy density to the energy density of a massless fermion with two degrees of freedom and standard photon reheating (all e^+e^- entropy flows into photons):

$$N_\nu \equiv \frac{\varepsilon_\nu}{\frac{7}{120}\pi^2\left(\left(\frac{4}{11}\right)^{1/3}T_\gamma\right)^4}.$$

Remember: the cosmological effective number of neutrinos is distinct from the number of neutrino flavors, $N_\nu^f = 3$, though the latter certainly would impact the former should there be any doubt about the value of N_ν^f.

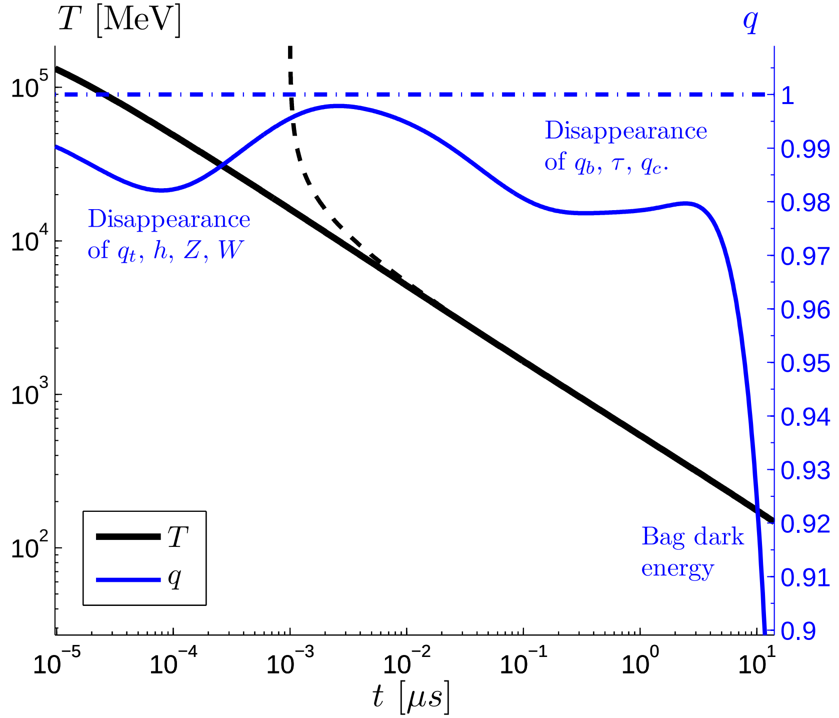
After decoupling neutrino free-stream with regard to scattering but interact gravitationally and impact expansion speed of the Universe to a degree that one can see the value N_ν both at BBN and at ion recombination. There is bias towards a value $N_\nu \simeq 3.5$.

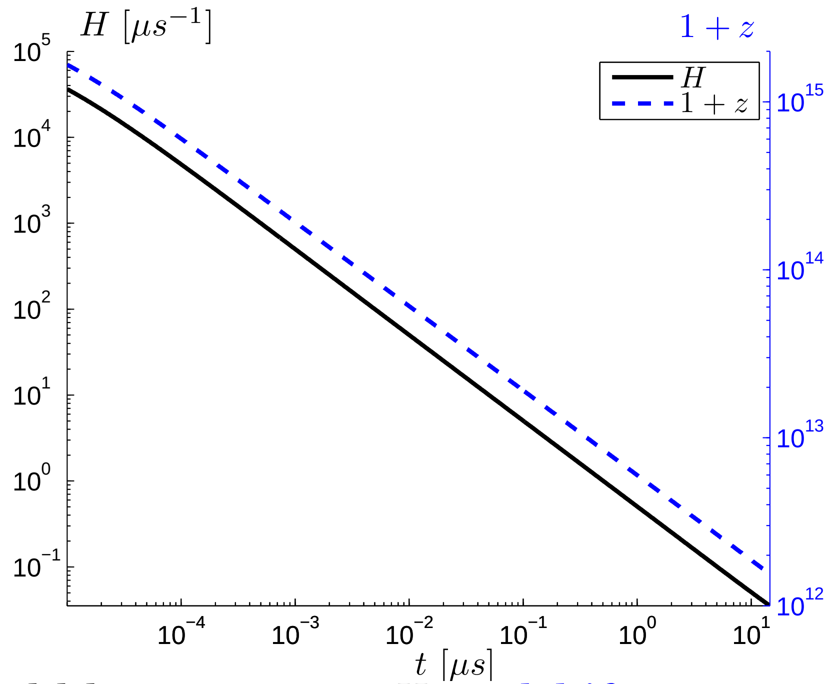
Kinetic decoupling and degrees of freedom in detail



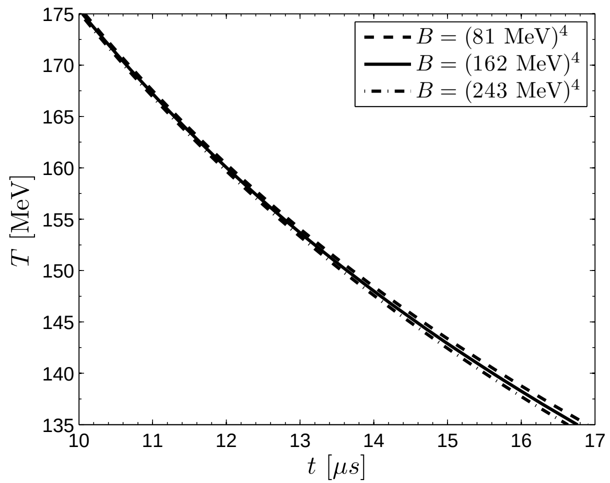
J. Birrell et al "Relic neutrinos: Physically consistent treatment of effective number of neutrinos and neutrino mass" PRD in press, arXiv:1212.6943

Forward: from EW symmetric world to QGP hadronization



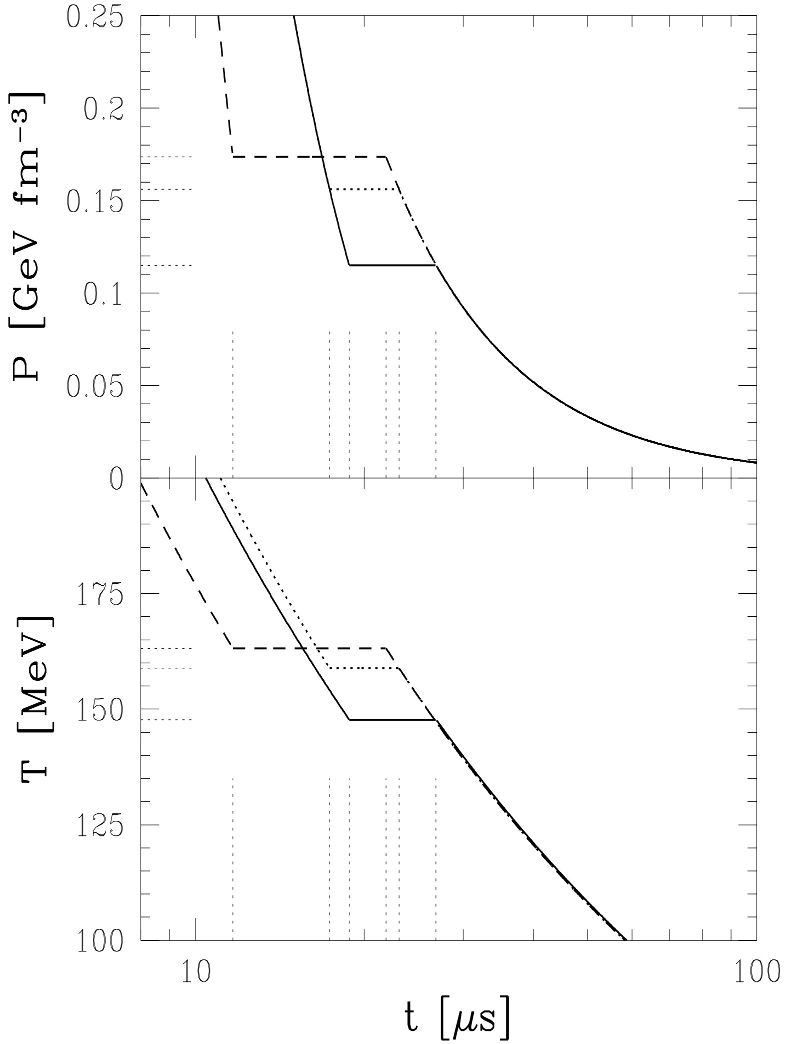


Temperature T, deceleration parameter q; Hubble parameter H, redshift $z+1$.



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:

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

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:

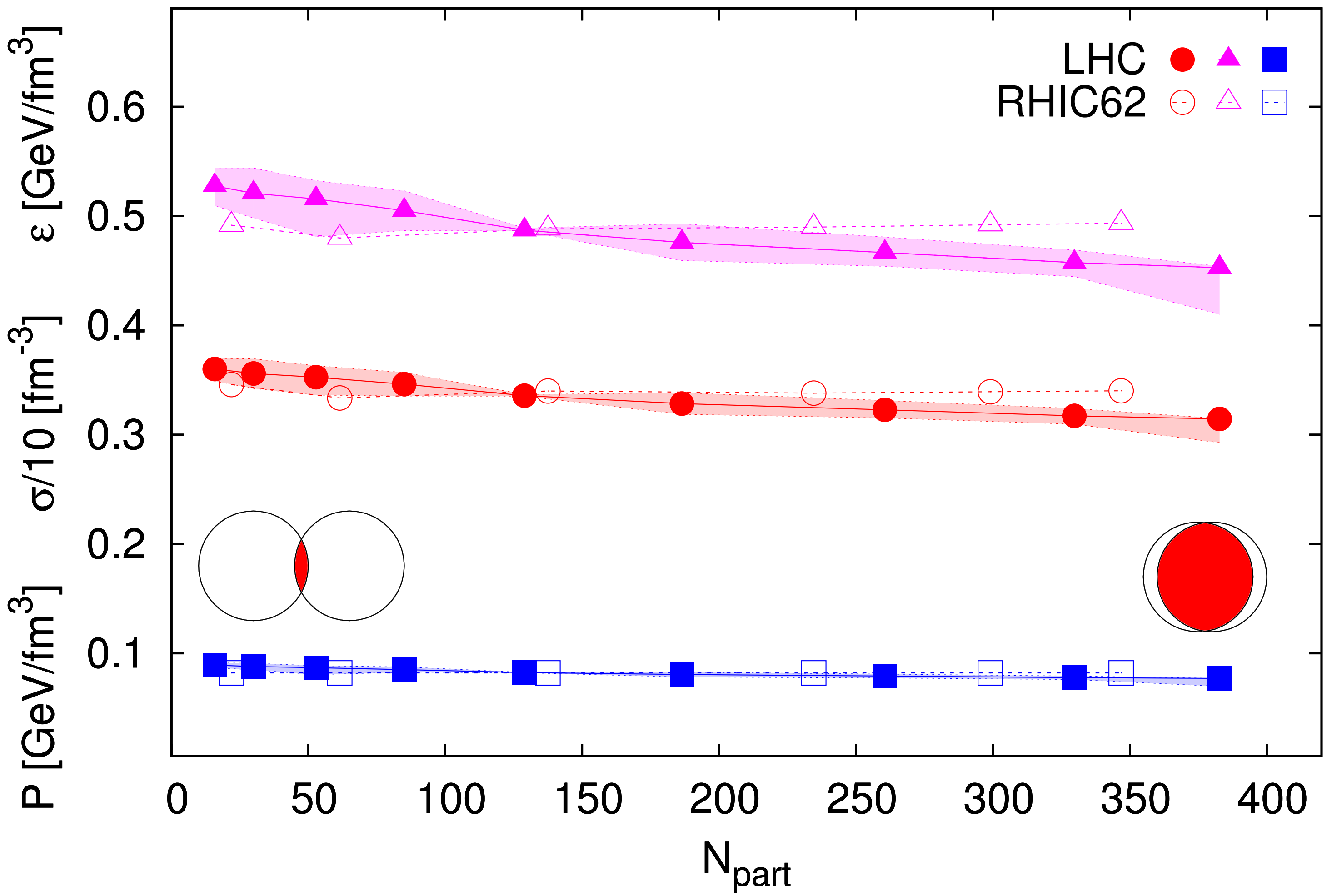
$$\epsilon = \frac{3}{32\pi G}\frac{1}{(t_0 + t)^2}$$

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.

Is QGP Hadronization in the Lab the Same as in Early Universe?



Open Symbols: RHIC-62, Filled Symbols LHC-2.76.
Analysis of data by Michal Petran et al:
Phys. Rev. C 88, 034907 (2013), DOI:10.1103/PhysRevC.88.034907 .

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:**

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

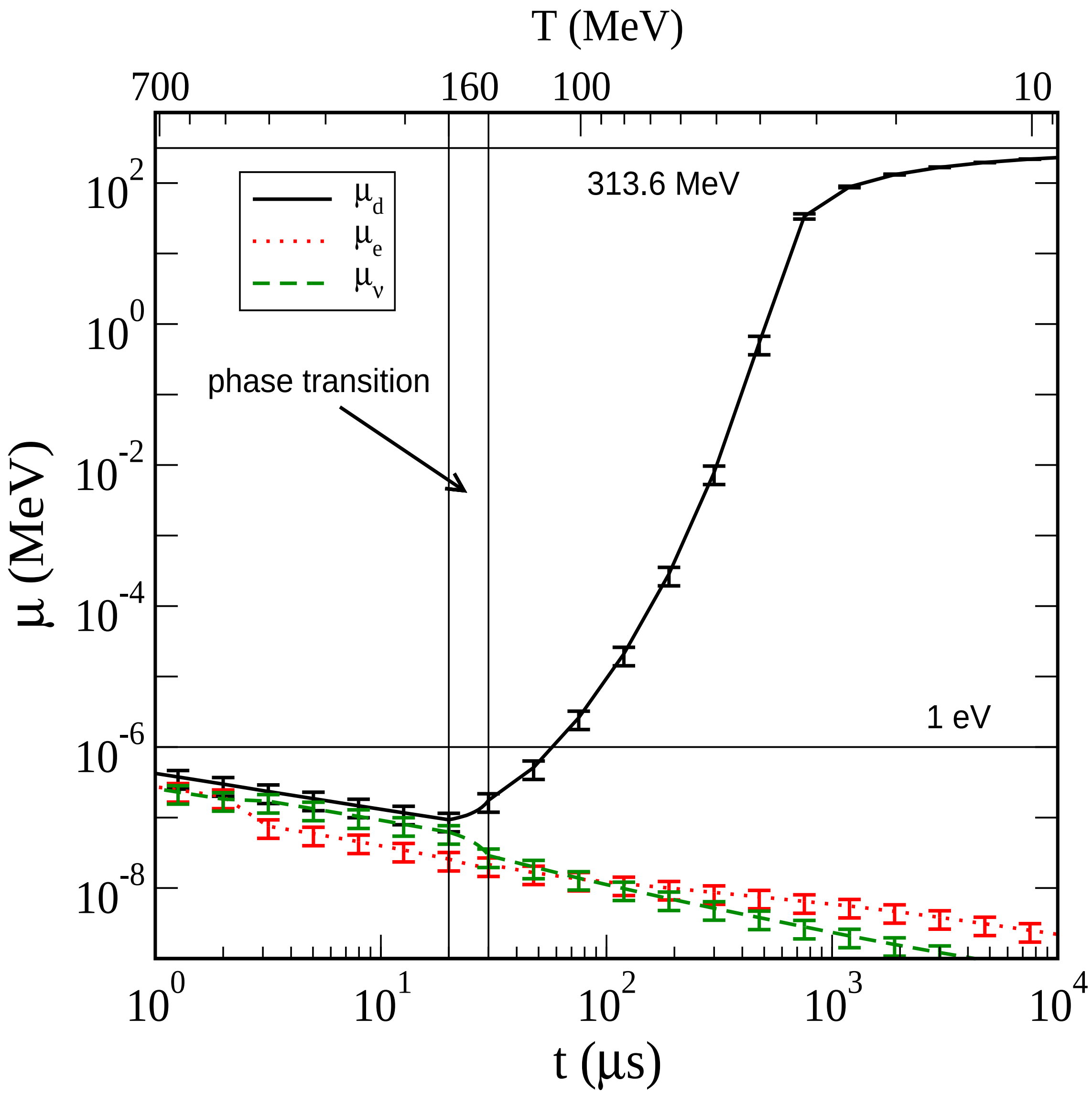
This can be easily generalized. As long as imbalance is not competing with large late photon to baryon ratio, it is hidden in slight neutrino-antineutrino asymmetry.

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

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

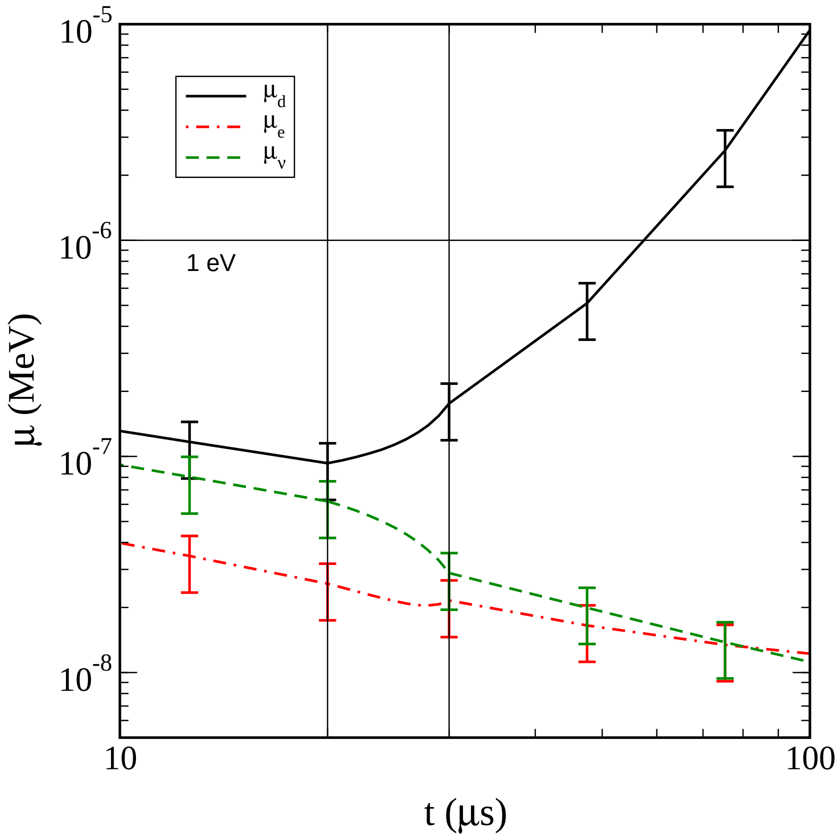
Note, current value $S/B = 3.5 \times 10^{10}$ but results shown for older value 4.5×10^{10} See on-line *Hadronization of the quark Universe* **Michael J. Fromerth, Johann Rafelski (Arizona U.). Nov 2002. 4 pp. e-Print: astro-ph/0211346**

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

2 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

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

$f_{\rm HG}$ 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 $Q = 0$:

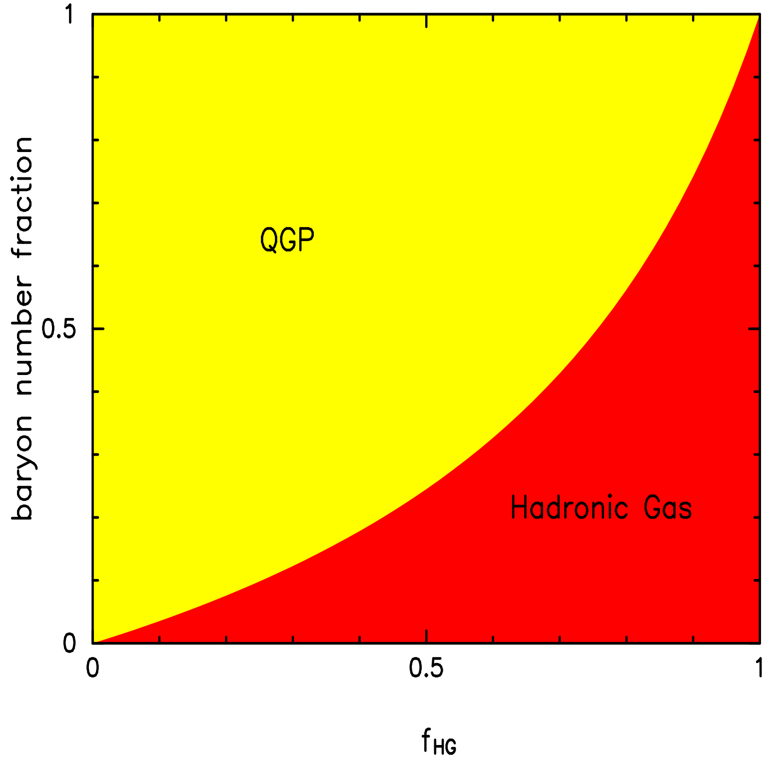
$$Q = 0 = n_Q^{\rm QGP} V_{\rm QGP} + n_Q^{\rm HG} V_{\rm HG} = V_{\rm tot} \left[(1 - f_{\rm HG})\, n_Q^{\rm QGP} + f_{\rm HG}\, n_Q^{\rm HG} \right[$$

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

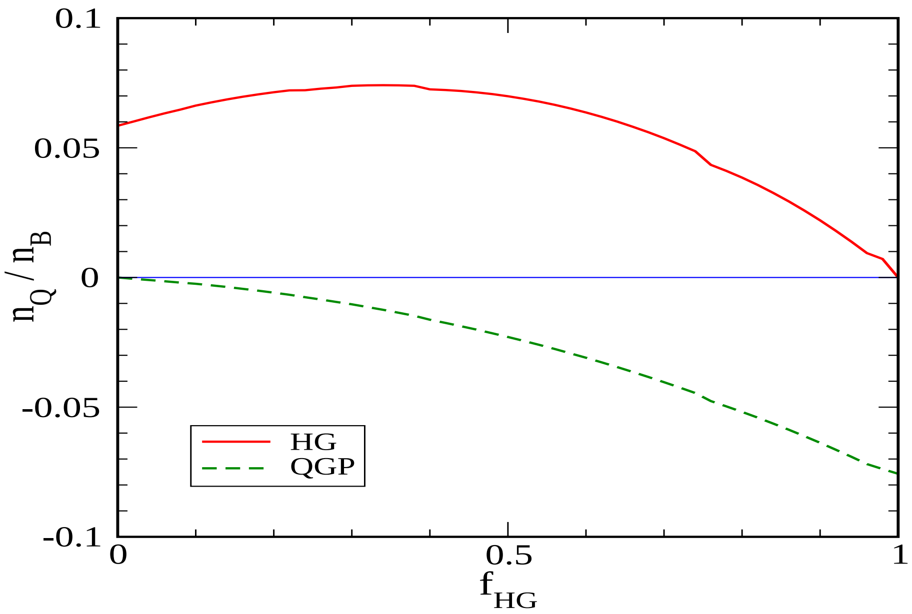
We assume that mixed phase exists $10\,\mu s$ and that $f_{\rm HG}$ changes linearly in time. Actual values will require dynamic nucleation transport theory description.

Charge and baryon number distillation

Initially at $f_{HG} = 0$ all matter in QGP phase, as hadronization progresses with $f_{HG} \to 1$ 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

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

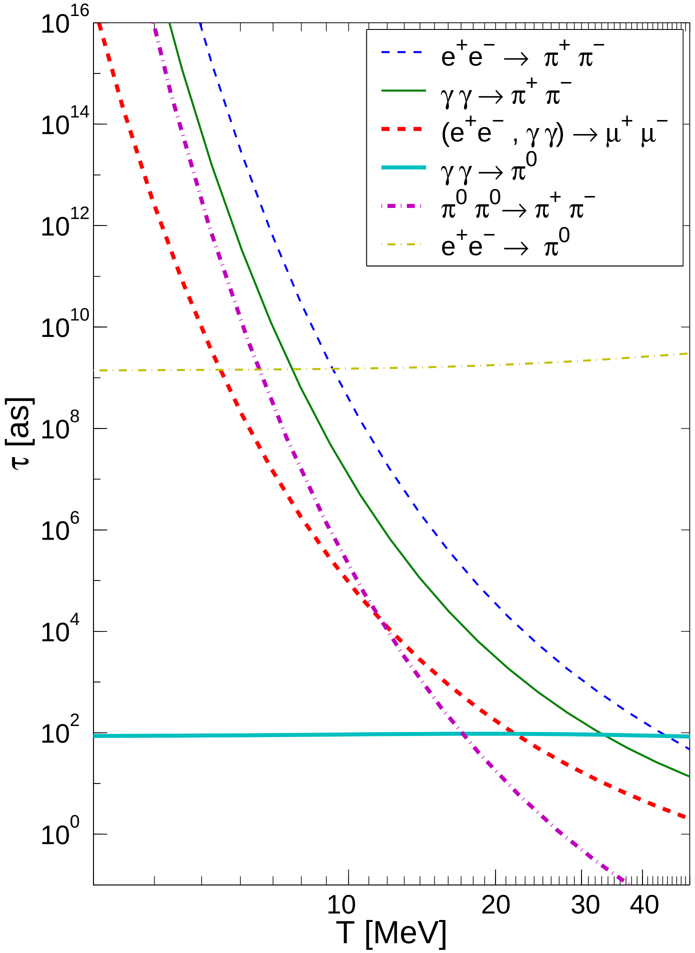
'freeze' out, that is the π^0 decay overwhelms the production rate and the yield falls out from chemical equilibrium yield. Since π^0 lifespan ($8.4\, 10^{-17}$ s) is rather short, one is tempted to presume that the decay process dominates. However, there must be at sufficiently high density a detailed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

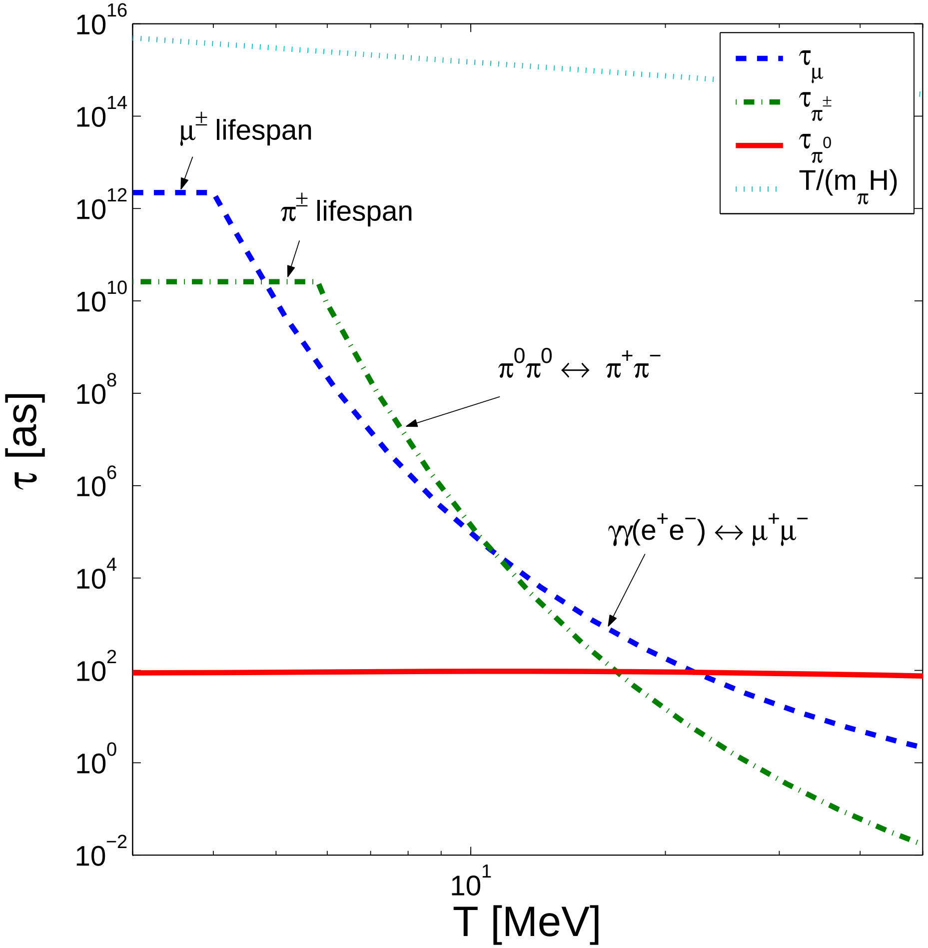
Presence of one type of pion implies presence of $\pi^\pm$, those can be equilibrated by the reaction:

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

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

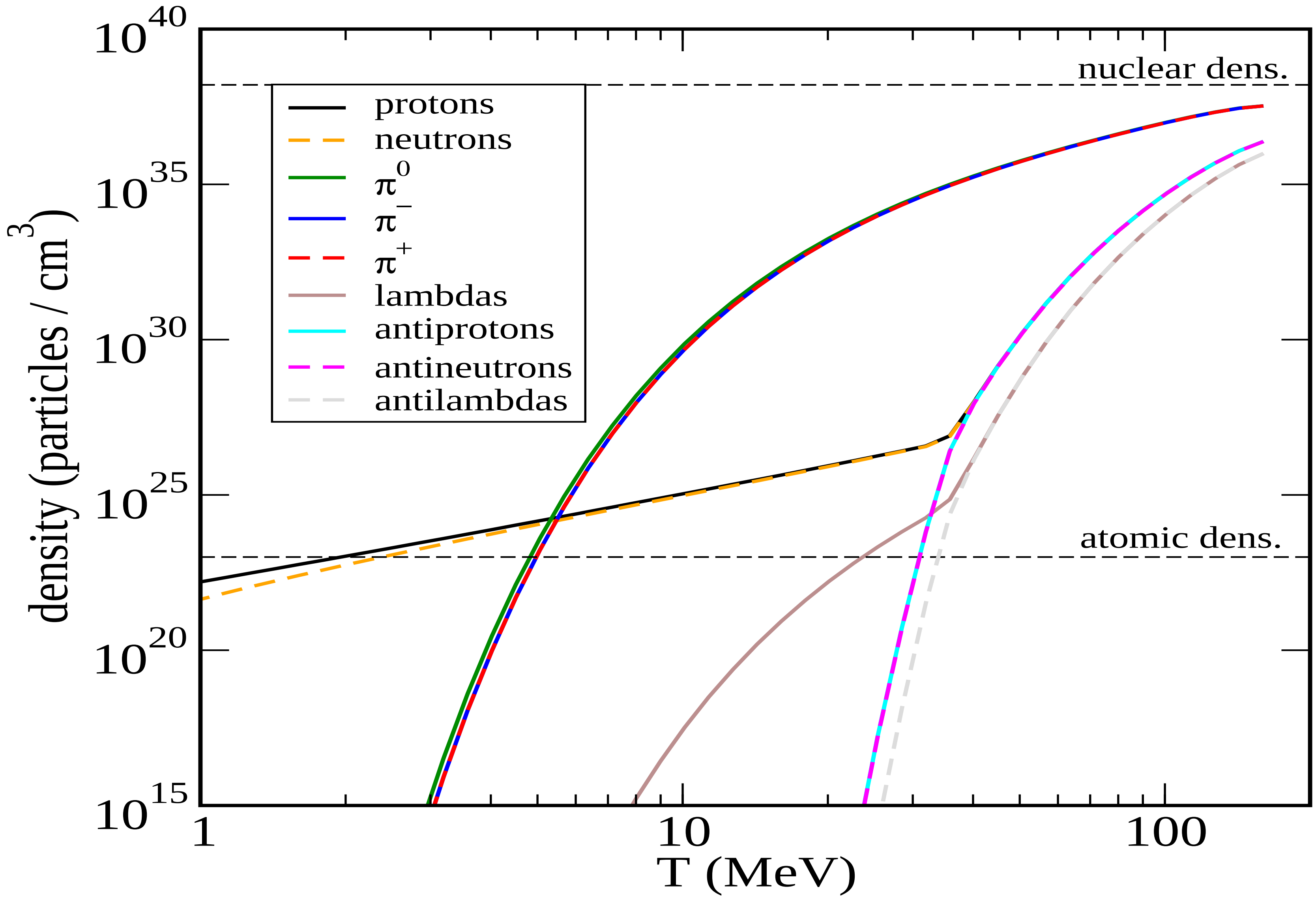
We develop kinetic theory for reactions involving three particles (two to one, one to two). We find that the expansion of the Universe is slow compared to pion equilibration, which somewhat surprisingly (for us) implies that π^0 is at all times in chemical equilibrium – at sufficiently low temperatures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



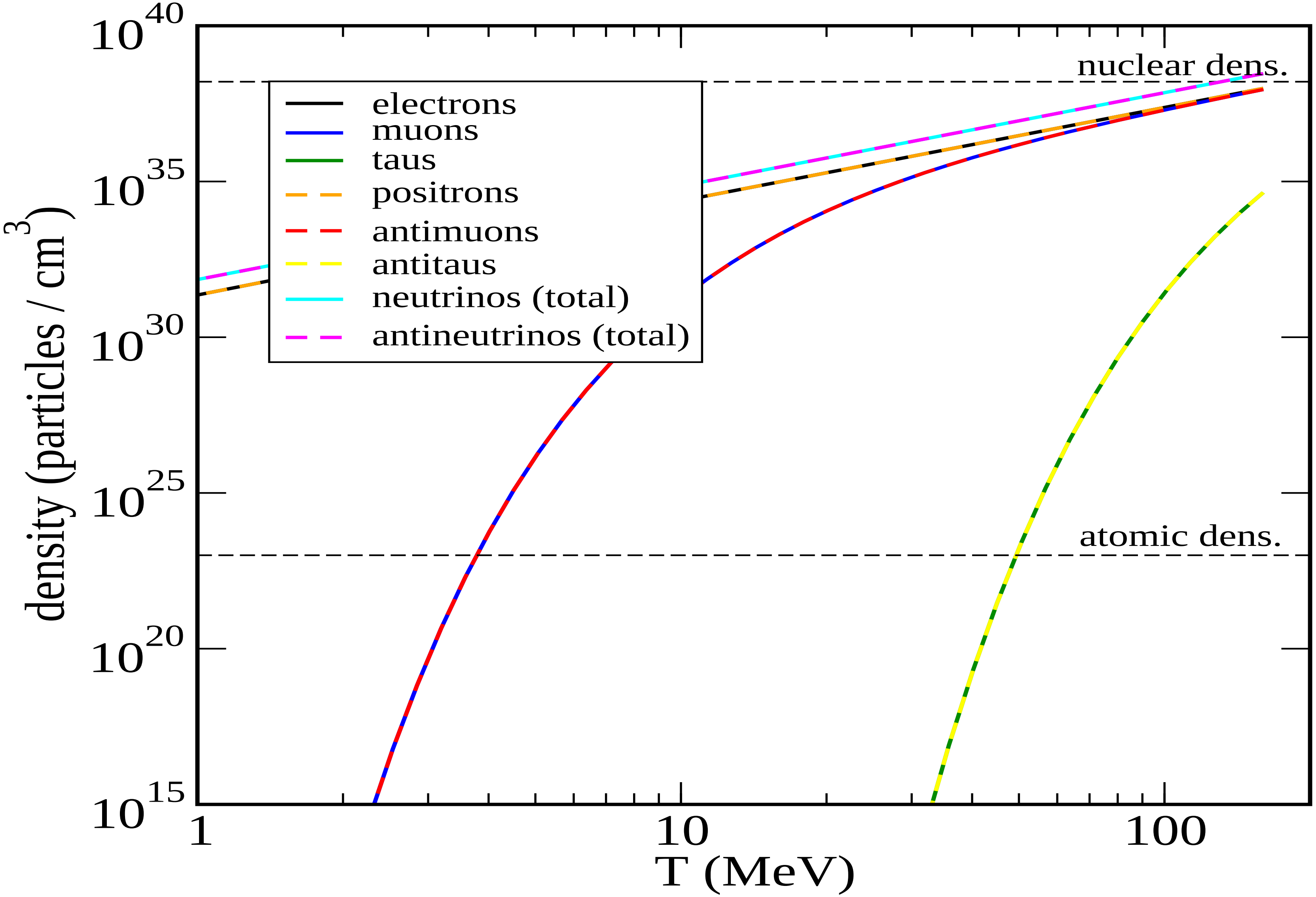


Relaxation times for dominant reactions for pion (and muon) equilibration. At small temperatures $T < 10$ MeV relaxation times for $\mu^{\pm}$ and $\pi^{\pm}$ equilibration becomes constant and much below Universe expansion rate and τ_T (dotted turquoise line on right).

Hadronic Universe Hadron Densities



Universe Lepton Densities



Did we find something worth continuing?

- **Cosmic evolution in principle fully defined and constrained by current laboratory experiments from today back to Electro-Weak phase transition,**
- **We understand qualitatively the QGP Universe [This is the system that lattice QCD addresses directly, RHIC indirectly],**
- **Interesting details of cosmic evolution remain in investigation:**
  1. **Strong local inhomogeneity at QGP hadronization**
  2. **Strangeness present in a significant abundance in early Universe down to $T = 10$ MeV, potential for production of strange nuclearites**
  3. **Period of antimatter annihilation**
  4. **Neutrino kinetic decoupling**
  5. **BBN in presence of dense e^+e^--plasma: unsettling yet scales seperate**