Connecting QGP-RHI physics to the Early Universe

The first three seconds

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Birmingham, SQM2013, July 24, 2013

The next 30min is about

- **The first 3 seconds of the relativistic heavy ion program**
- **The first 3 seconds of QGP/matter in the Universe**
- **Including Universe hadronization = creation of matter**
- **Including annihilation of antimatter**

See on-line *Hadronization of the quark Universe* **Michael J. Fromerth, JR, e-Print: astro-ph/0211346 and two recent contributions: Michael J. Fromerth, et al, Acta Phys.Polon. B43 (2012) 12, 2261-2284, e-Print: arXiv:1211.4297; JR, arXiv:1306.2471**

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

WHY? – Four 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 30 μs after big bang.

QGP-Universe hadronization led to nearly matter-antimatter symmetric state, the later ensuing matter-antimatter annihilation leaves behind as our world the tiny 10^{-10} matter asymmetry.

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

ORIGIN OF MASS OF MATTER –(DE)CONFINEMENT
The confining quark vacuum state is the origin of 99.9% of mass, the Higgs mechanism applies to the remaining 0.1%. 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.

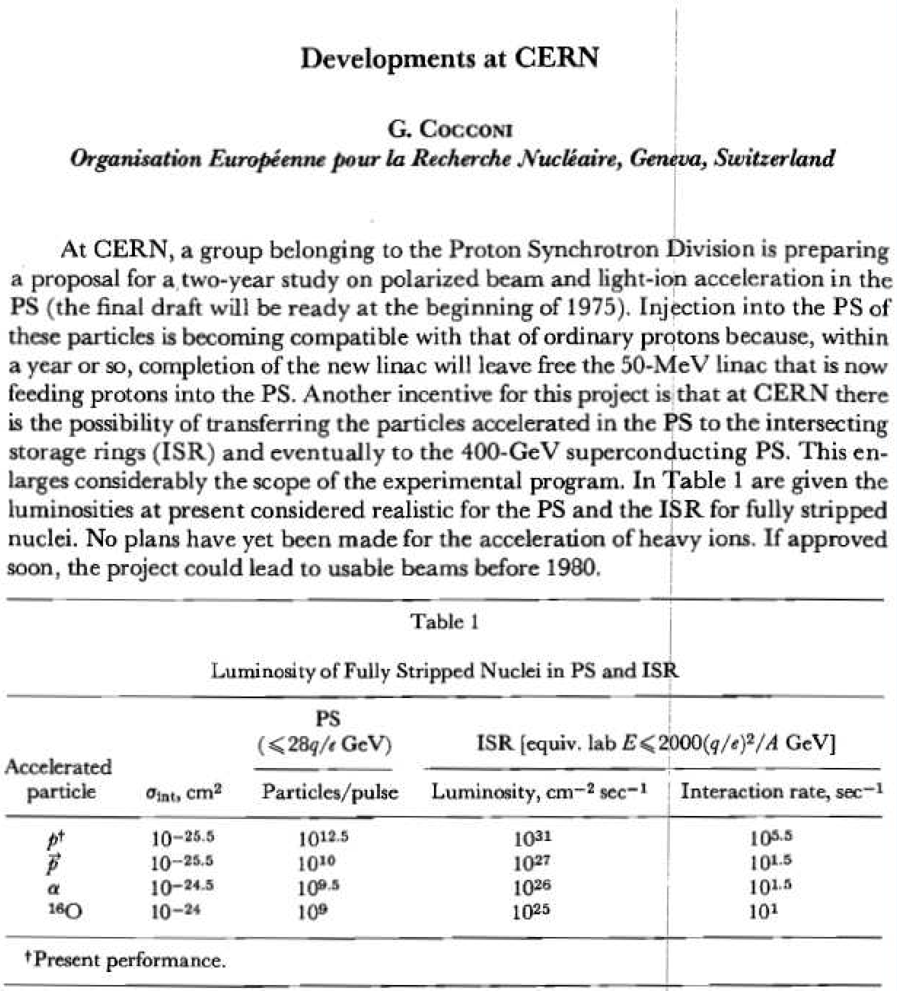
ORIGIN OF FLAVOR
Normal matter made of first flavor family (u, d, e, ν_e). Strangeness rich quark-gluon plasma the sole laboratory environment filled with 2nd family matter (s, c, μ, ν_μ) – arguable the only experimental environment where we could unravel the secret of flavor.

Relativistically Invariant Aether 1920: Albert Einstein at first rejected æther as unobservable when formulating special relativity, but eventually changed his initial position, re-introducing what is referred to as the 'relativistically invariant' æther. In a letter to H.A. Lorentz of November 15, 1919, see page 2 in *Einstein and the Æther*, **L. Kostro, Apeiron, Montreal (2000). Einstein writes:**
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.

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 conclusion:
. . . 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 (NOT) consisting of parts which may be tracked through time. The idea of motion may not be applied to it.

Note, the QGP in laboratory is a ponderable fragment of the early Universe: quantum physics makes this possible, in 1920 structured quantum vacuum was not yet invented.

Relativistic Heavy Ions - the Beginning I



Developments at CERN

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

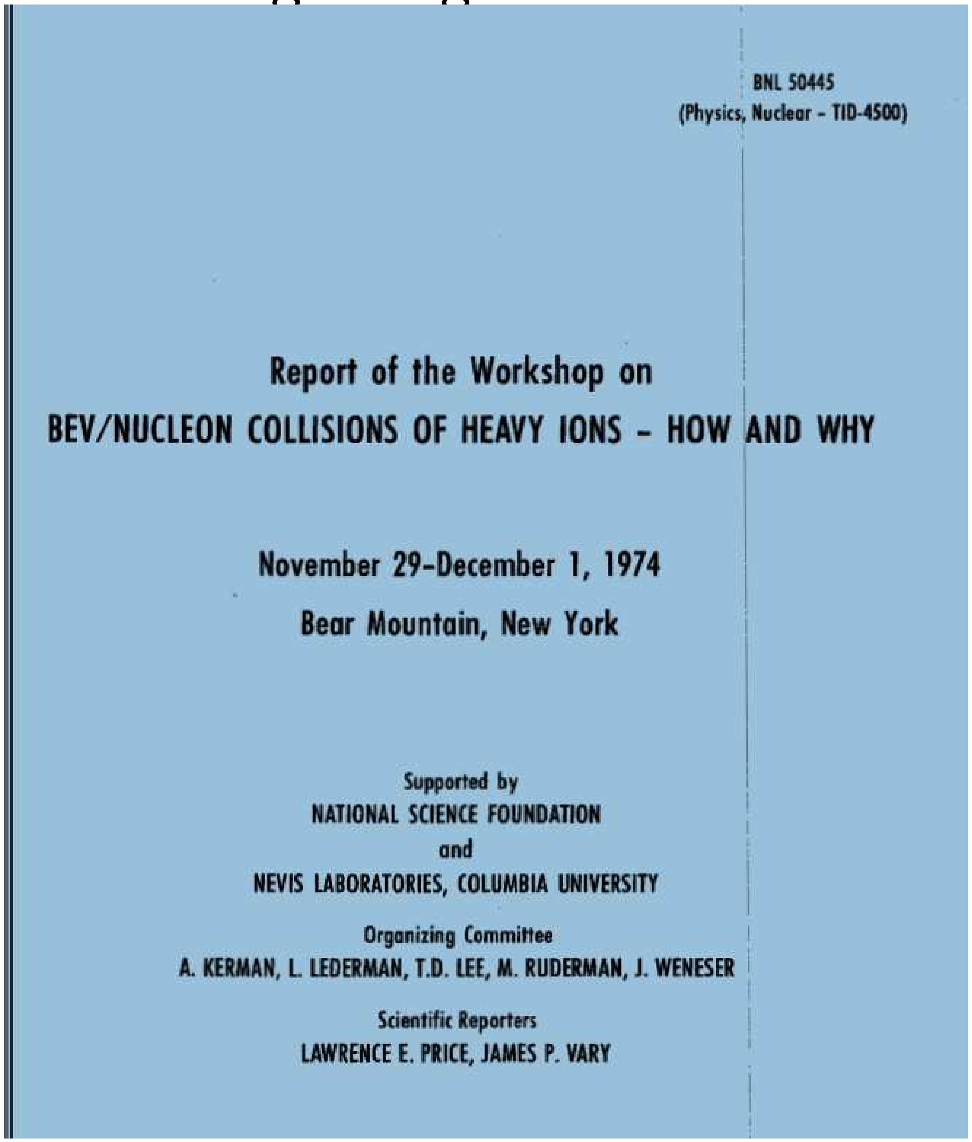
At CERN, a group belonging to the Proton Synchrotron Division is preparing a proposal for a two-year study on polarized beam and light-ion acceleration in the PS (the final draft will be ready at the beginning of 1975). Injection into the PS of these particles is becoming compatible with that of ordinary protons because, within a year or so, completion of the new linac will leave free the 50-MeV linac that is now feeding protons into the PS. Another incentive for this project is that at CERN there is the possibility of transferring the particles accelerated in the PS to the intersecting storage rings (ISR) and eventually to the 400-GeV superconducting PS. This enlarges considerably the scope of the experimental program. In Table 1 are given the luminosities at present considered realistic for the PS and the ISR for fully stripped nuclei. No plans have yet been made for the acceleration of heavy ions. If approved soon, the project could lead to usable beams before 1980.

Table 1

Luminosity of Fully Stripped Nuclei in PS and ISR

Accelerated particle	σ_{int}, cm^2	PS ($\leqslant 28q/e$ GeV) Particles/pulse	ISR [equiv. lab $E \leqslant 2000(q/e)^2/A$ GeV] Luminosity, cm^{-2} sec^{-1}	 Interaction rate, sec^{-1}
$p^\dagger$	$10^{-25.5}$	$10^{12.5}$	10^{31}	$10^{5.5}$
$\vec{p}$	$10^{-25.5}$	10^{10}	10^{27}	$10^{1.5}$
α	$10^{-24.5}$	$10^{9.5}$	10^{26}	$10^{1.5}$
^{16}O	10^{-24}	10^{9}	10^{25}	10^{1}

†Present performance.



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

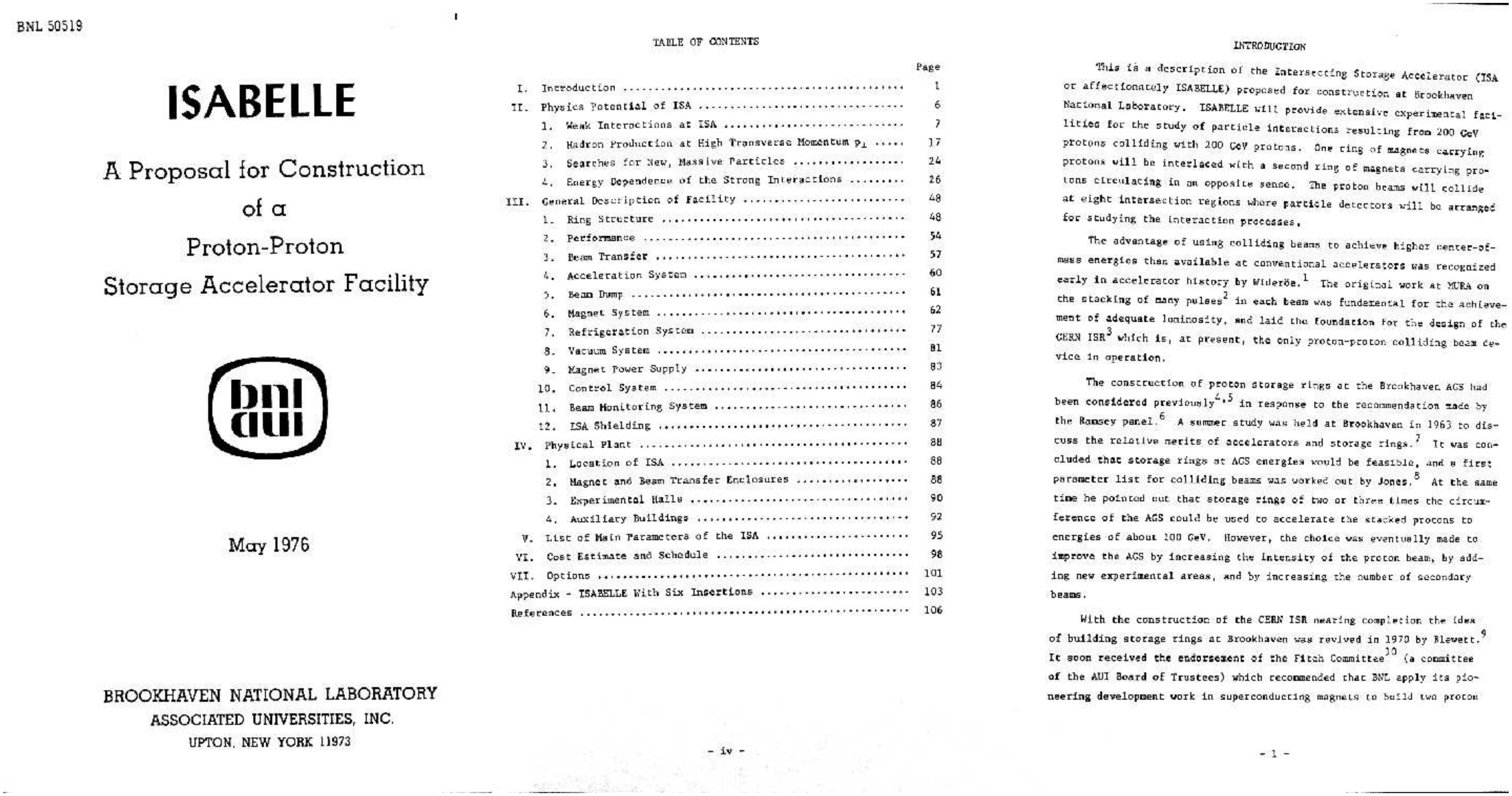
Supported by
NATIONAL SCIENCE FOUNDATION
and
NEVIS LABORATORIES, COLUMBIA UNIVERSITY

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

Scientific Reporters
LAWRENCE E. PRICE, JAMES P. VARY

CERN attracted soon after the theorists interested in quark deconfinement, and ultimately, much of the experimental Relativistic Heavy Ion Program.

Relativistic Heavy Ions - the Beginning II



BNL 50519

ISABELLE

A Proposal for Construction
of a
Proton-Proton
Storage Accelerator Facility

May 1976

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
UPTON, NEW YORK 11973

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INTRODUCTION

This is a description of the Intersecting Storage Accelerator (ISA or affectionately ISABELLE) proposed for construction at Brookhaven National Laboratory. ISABELLE will provide extensive experimental facilities for the study of particle interactions resulting from 200 GeV protons colliding with 200 GeV protons. One ring of magnets carrying protons will be interlaced with a second ring of magnets carrying protons circulating in an opposite sense. The proton beams will collide at eight intersection regions where particle detectors will be arranged for studying the interaction processes.

The advantage of using colliding beams to achieve higher center-of-mass energies than available at conventional accelerators was recognized early in accelerator history by Wideröe.[1] The original work at MURA on the stacking of many pulses[2] in each beam was fundamental for the achievement of adequate luminosity, and laid the foundation for the design of the CERN ISR[3] which is, at present, the only proton-proton colliding beam device in operation.

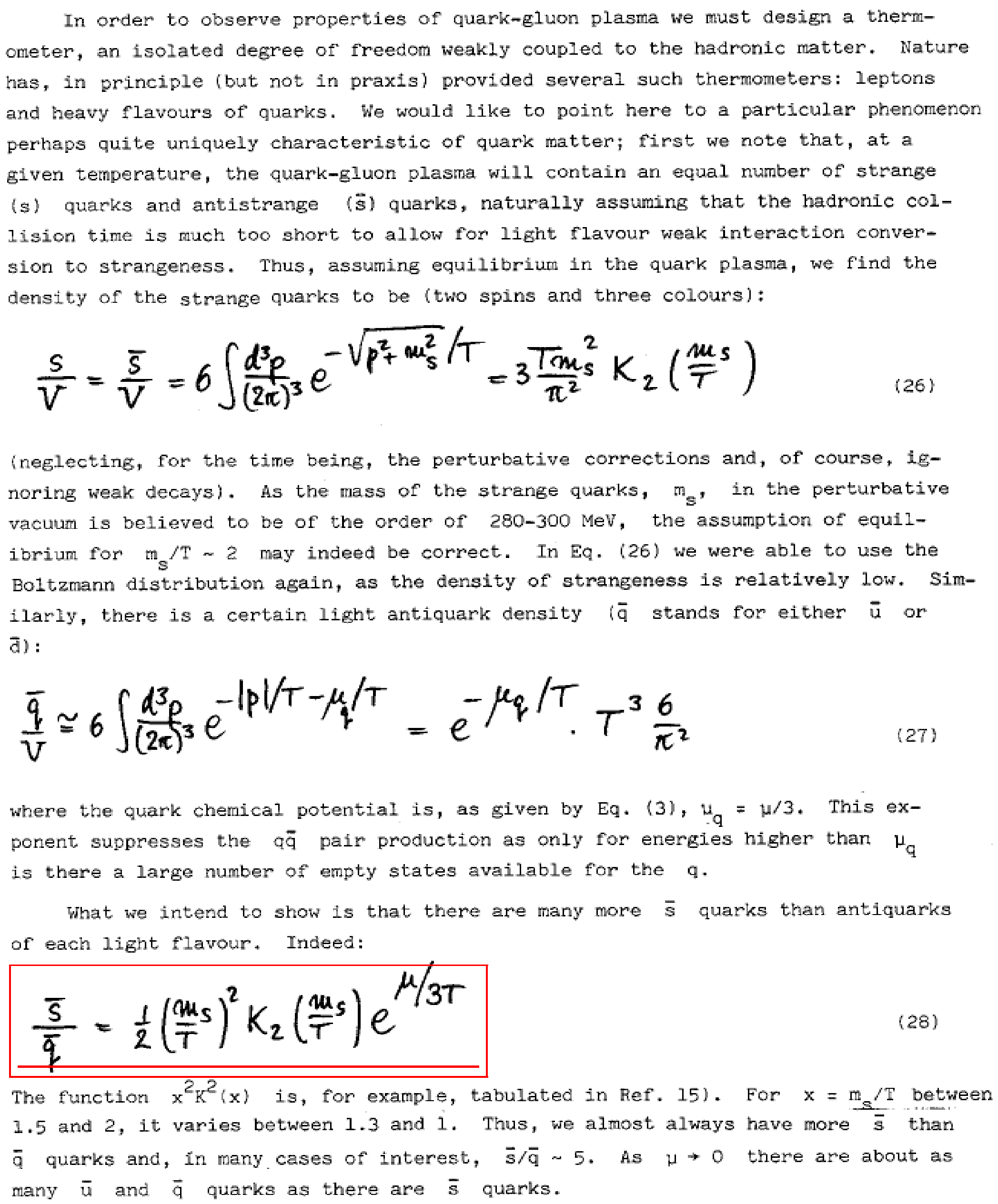
The construction of proton storage rings at the Brookhaven AGS had been considered previously[4,5] in response to the recommendation made by the Ramsey panel.[6] A summer study was held at Brookhaven in 1963 to discuss the relative merits of accelerators and storage rings.[7] It was concluded that storage rings at AGS energies would be feasible, and a first parameter list for colliding beams was worked out by Jones.[8] At the same time he pointed out that storage rings of two or three times the circumference of the AGS could be used to accelerate the stacked protons to energies of about 100 GeV. However, the choice was eventually made to improve the AGS by increasing the intensity of the proton beam, by adding new experimental areas, and by increasing the number of secondary beams.

With the construction of the CERN ISR nearing completion the idea of building storage rings at Brookhaven was revived in 1970 by Blewett.[9] It soon received the endorsement of the Fitch Committee[10] (a committee of the AUI Board of Trustees) which recommended that BNL apply its pioneering development work in superconducting magnets to build two proton

- 1 -

BNL-Isabelle rendered obsolete by CERN S$p\bar{p}$S was reborn as RHIC: the original 1976 proposal did not have one word about heavy ions in Isabelle.

To pass committees 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):

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

(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:

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

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.

⇐ J. R. & R. Hagedorn, CERN-TH-2969, Oct.1980 ***From Quark Matter to Hadron gas*** **in “Statistical Mechanics of Quarks and Hadrons”, H. Satz, editor, Elsevier 1981.**

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

In December, 1980 we published canonical suppression and we submitted kinetic strangeness production to PRL in December 1981. In March 1982 we reported on multistrange antibaryons reprinted in Phys. Rep. same year. Hadronization developed 1982-5, pubs with P.Koch, PhD thesis ⇒ 1985/6, Phys. Reports.

Move forward 20+y of RHI work ⇒ quark-hadron Universe

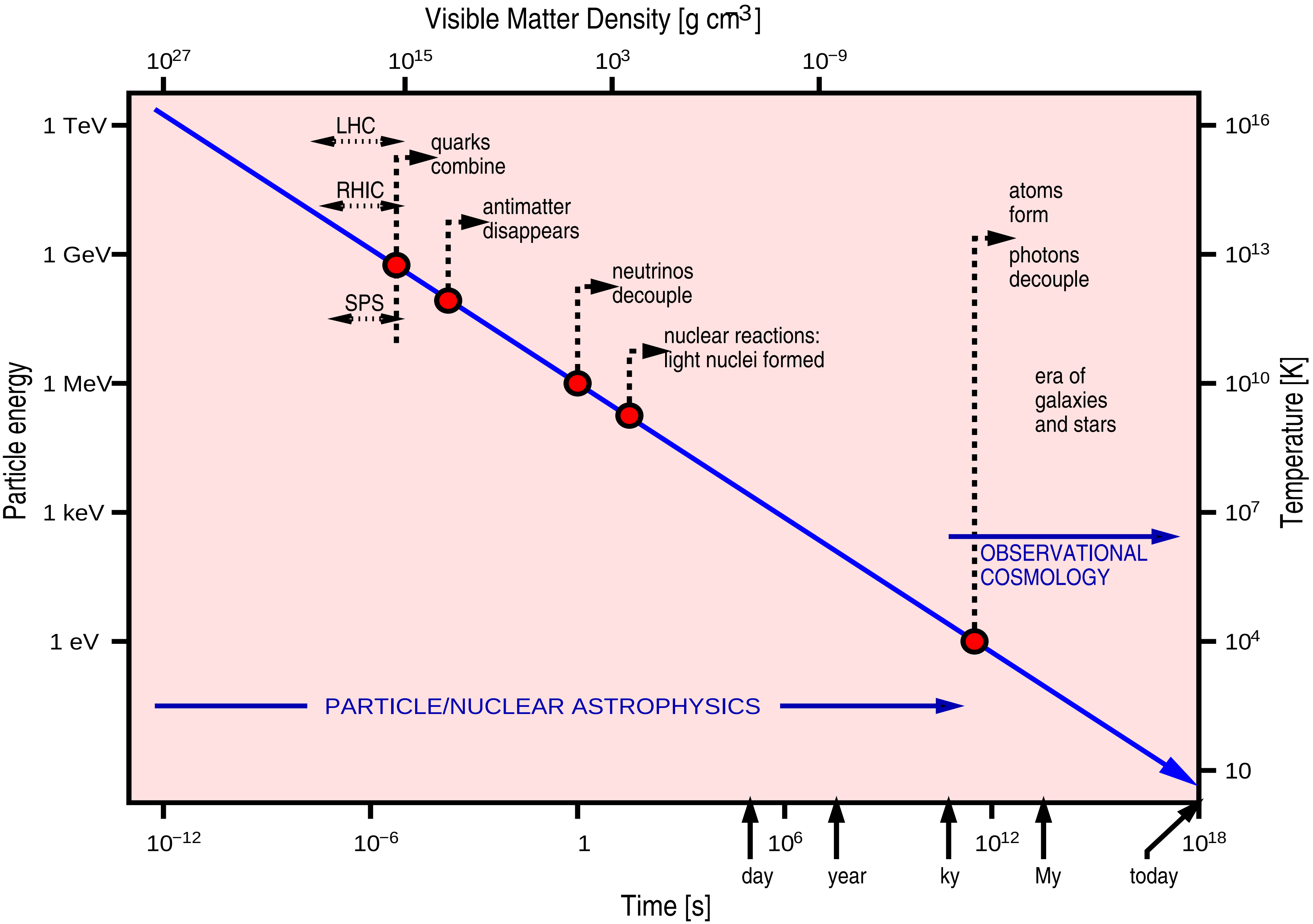
Today we are ready to explore

- 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.

There are a few tacit assumptions not to be mentioned again:

1. The dark energy is practically just like Einstein's cosmological term Λ, dominant energy form today yet entirely negligible in the early Universe;
2. The dark matter decay and/or annihilation is mostly complete before QGP hadronization and does not impact the inventory of visible matter.
3. Dark matter mass scale is outside energy range of our study,
   e.g. outside 300–3 MeV
4. There are three flavors of neutrinos and antineutrinos which have each only left/right-handed dynamic components.

Overview of the evolution of the Universe



Basics of QGP Universe Evolution

Einstein equations

$$\mathcal{R}_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu}\mathcal{R} + \Lambda_{\rm v} g_{\mu\nu} = 8\pi G T_{\mu\nu},$$

for

$$\mathrm{diag}(g_{\mu\nu}) = (1, -R^2, -R^2, -R^2) \quad \text{and} \quad \mathrm{diag}(T^{\mu\nu}) = (\epsilon, P, P, P)$$

lead to two dynamical equations:

1. **Entropy conserving expansion, also from 1st law:**

$$dE + P\,dV = T\,dS = 0, \quad \frac{3dR}{R} = -\frac{d\epsilon}{\epsilon + P}: \quad \boxed{\dot\epsilon = -3H(\epsilon + P)} \quad \frac{\dot R}{R} \equiv H$$

where $dE = d(\epsilon V)$, $dV/V = D\,dR/R$ **and** $D \to 3$ **is the number of expanding dimensions.**

2. **Friedmann-Lemaître-Robertson-Walker Universe Dynamics**

$$\boxed{H^2 = \tfrac{8\pi G}{3}\epsilon} + \frac{\Lambda}{3} - \frac{k}{R^2}$$

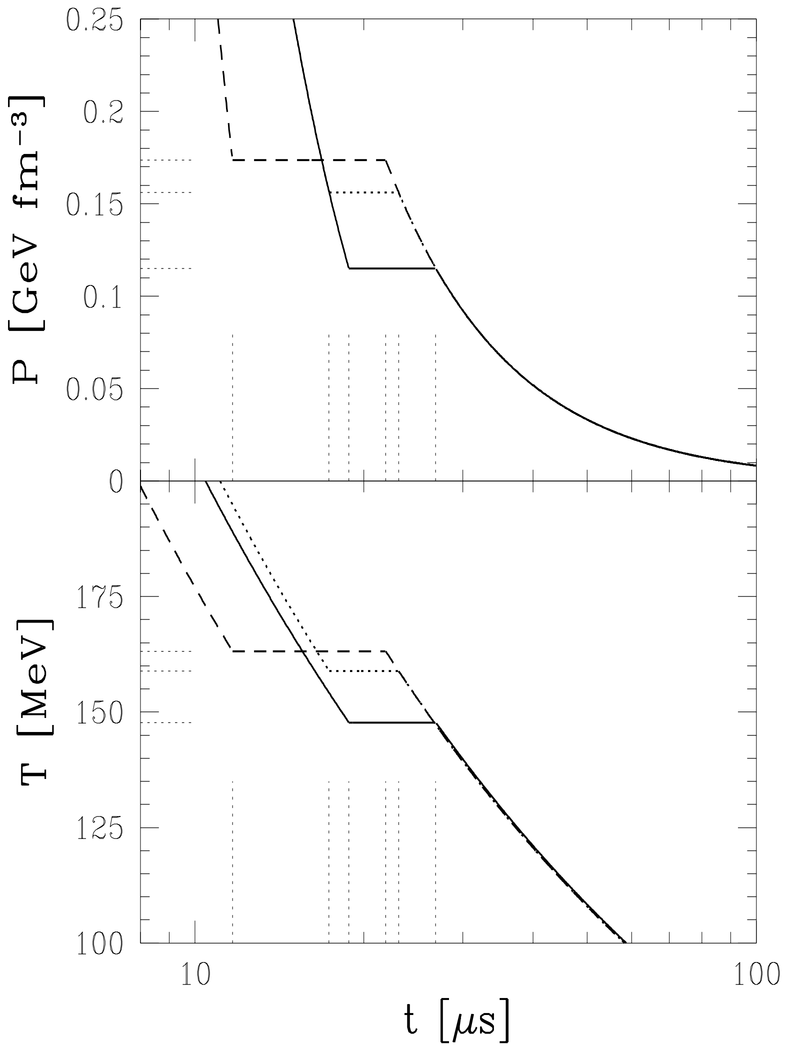
$\Lambda \to 8\pi G\mathcal{B}$ **absorbed into** ϵ**; experiment favors a flat** $k = 0$ **universe.**

Given equation of state $P = f(\epsilon)$ **this is an integrable equation system allowing to obtain the time dependence of the Hubble 'constant'** $H(t)$**, and the energy density** $\epsilon(t) \to T(t)$**.**

In the early Universe almost always radiation dominance: $P = \epsilon/3$**. However, to describe the transformation of vacuum structure we introduce** $\Lambda = 8\pi G\mathcal{B}$**:**

$$\epsilon_p = \epsilon - \mathcal{B} = 3P_p = 3P + 3\mathcal{B}, \Rightarrow \boxed{\epsilon + P = \tfrac{4}{3}(\epsilon - \mathcal{B})}$$

Hadronization is when? – Time scales



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

Combine both dynamical equations

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

for $\mathcal{B} \to 0$ and massless particles:

$$\epsilon = \frac{3}{32\pi G}\frac{1}{(t_0+t)^2} \Rightarrow \frac{T}{T_0} = \sqrt{\frac{t_0}{t_0+t}}$$

Analytic solution also with $\mathcal{B}$:

$$\epsilon_{\mathrm{QGP}} = \mathcal{B}\coth^2 x, \qquad x = \frac{\tau_0}{\tau_{\mathrm{U}}}\left(\frac{t_0+t}{\tau_0}\right),$$

With time constant:

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

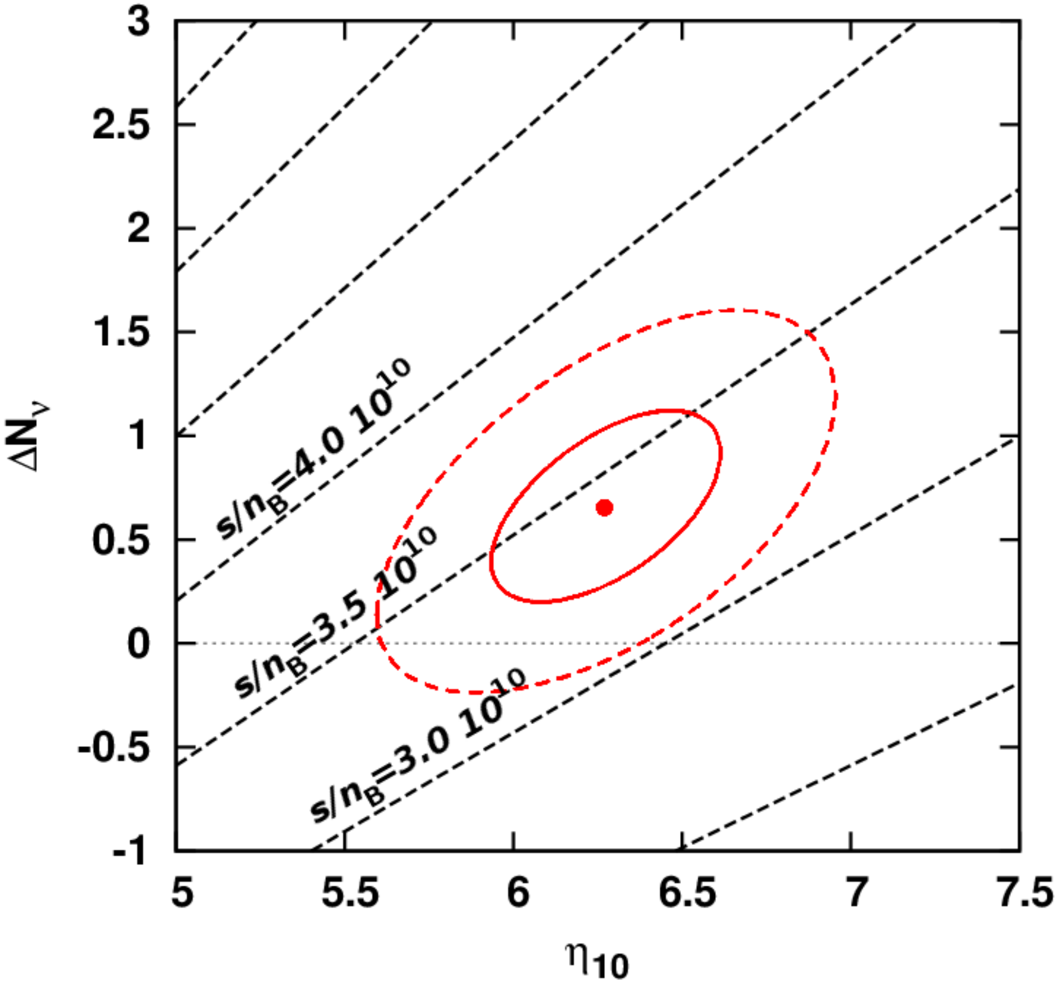
τ_0: **time of prior latent heat jump at electro-weak transition 1000 times greater T as compared to QGP:** $\tau_0 \simeq 30\,\mathrm{ps}$

Transition time at $\Delta t \simeq \tau_{\mathrm{U}}/3 \simeq 10\mu\mathrm{s}$, $\Delta R = 3\mathrm{km}$.

The QGP Universe expands,

$$H = \frac{\coth x}{2\tau_{\mathrm{U}}}, \qquad R = R_0\sqrt{\frac{\sinh x}{\sinh(t_0/\tau_{\mathrm{U}})}} < 10^4 R_0$$

Characteristic parameter: entropy per baryon in the Universe



$\eta_{10} = 10^{10} n_B/n_\gamma$, **red circles from Fig 4 of G. Steigman, 1208.0032 - WMAP is consistent with BBN introducing a dynamic neutrino excess** ΔN_ν **(not necessarily extra neutrinos expresses reheating of neutrinos). In the Universe** $S/B = 3.5 \pm 0.5\, 10^{10}$, **at LHC** $S/B \simeq 10^4$ **(Thursday 9:30AM, M. Petran on LHC)**

Size of the Quark Universe

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

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

Where we used entropy density at hadronization $\sigma = S/V$ composed of hadronic (Thursday lecture by M. Petran at 9:30AM) and leptonic component, both of comparable magnitude, so $\sigma \simeq 10/{\rm fm}^3$. We have $S/B = 3.5 10^{10}$

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

The baryon content of the Universe is estimated from the models estimating unseen galaxies, leading to $N_{\rm galaxie} = 5 10^{11}$, thus the total baryon number bound in stars within the current horizon of the Universe is given as $B_{\rm all\ \ stars} \simeq 0.5 10^{80}$. Astrophysicists fight about how much is in interstellar dust. We simply take a round number $B_{\rm Universe} \simeq 10^{80}$

To make all stars in the Universe we need 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, which renders the Universe 10^{11} bigger. Keep in mind 2nd big difference to RHI: time and size scale.

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. Keep in mind 3rd big difference to RHI: equilibrium!

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 decoupling

$$T \simeq 2\,\mathbf{MeV} \qquad t \simeq 3\,s$$

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:**

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

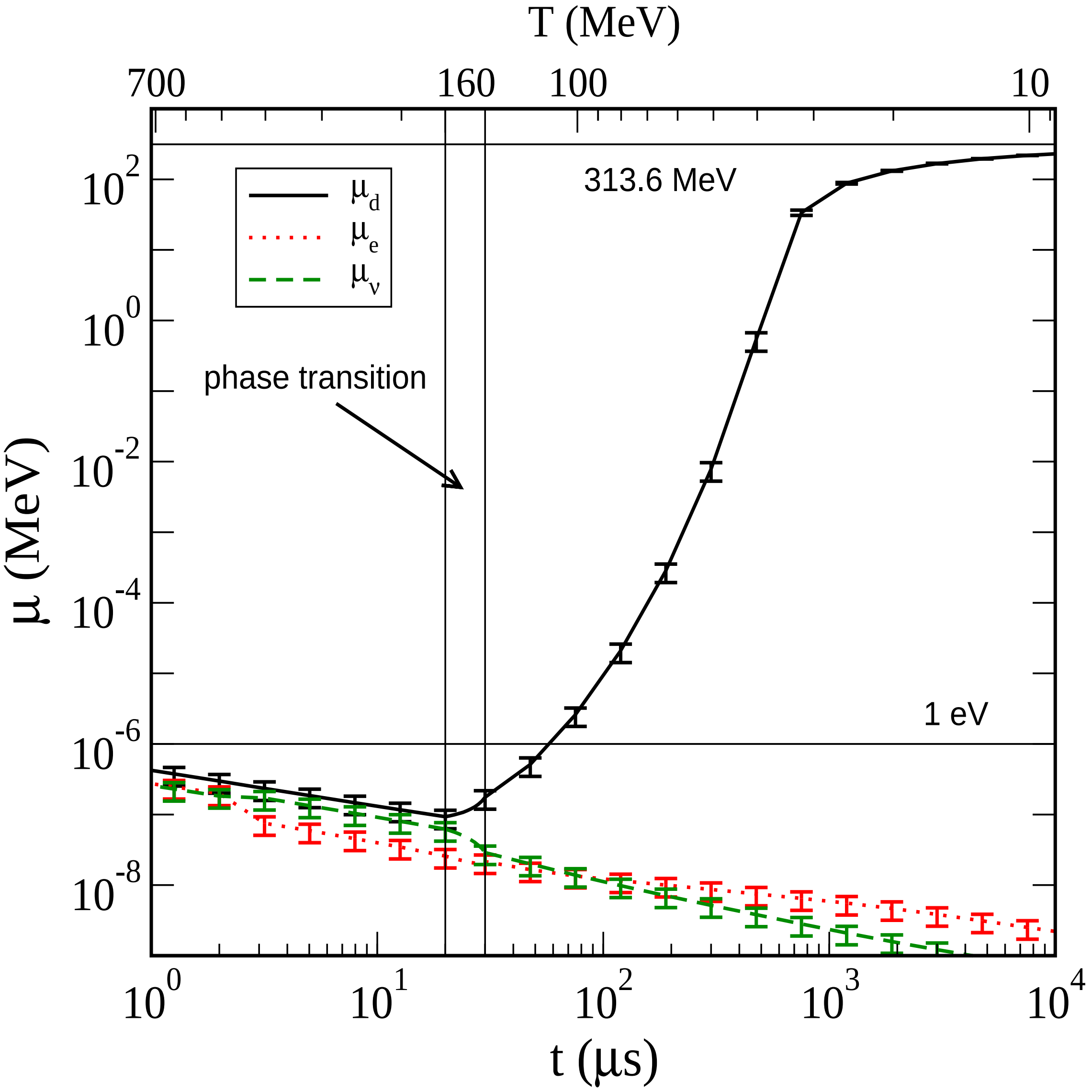
This can be easily generalized. As long as imbalance is not competing with large late photon to baryon ratio, it is hidden in slight neutrino-antineutrino asymmetry.

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

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

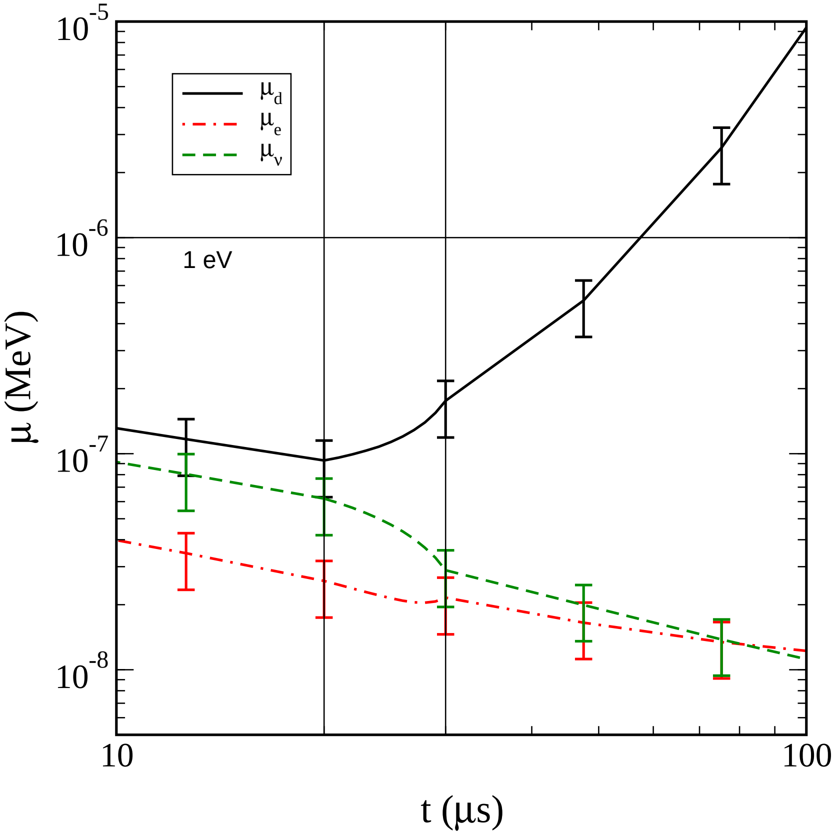
Note, current value $S/B = 3.5 \times 10^{10}$ but results shown for older value 4.5×10^{10} See on-line *Hadronization of the quark Universe* **Michael J. Fromerth, Johann Rafelski (Arizona U.). Nov 2002. 4 pp. e-Print: astro-ph/0211346**

TRACING μ_d IN THE UNIVERSE

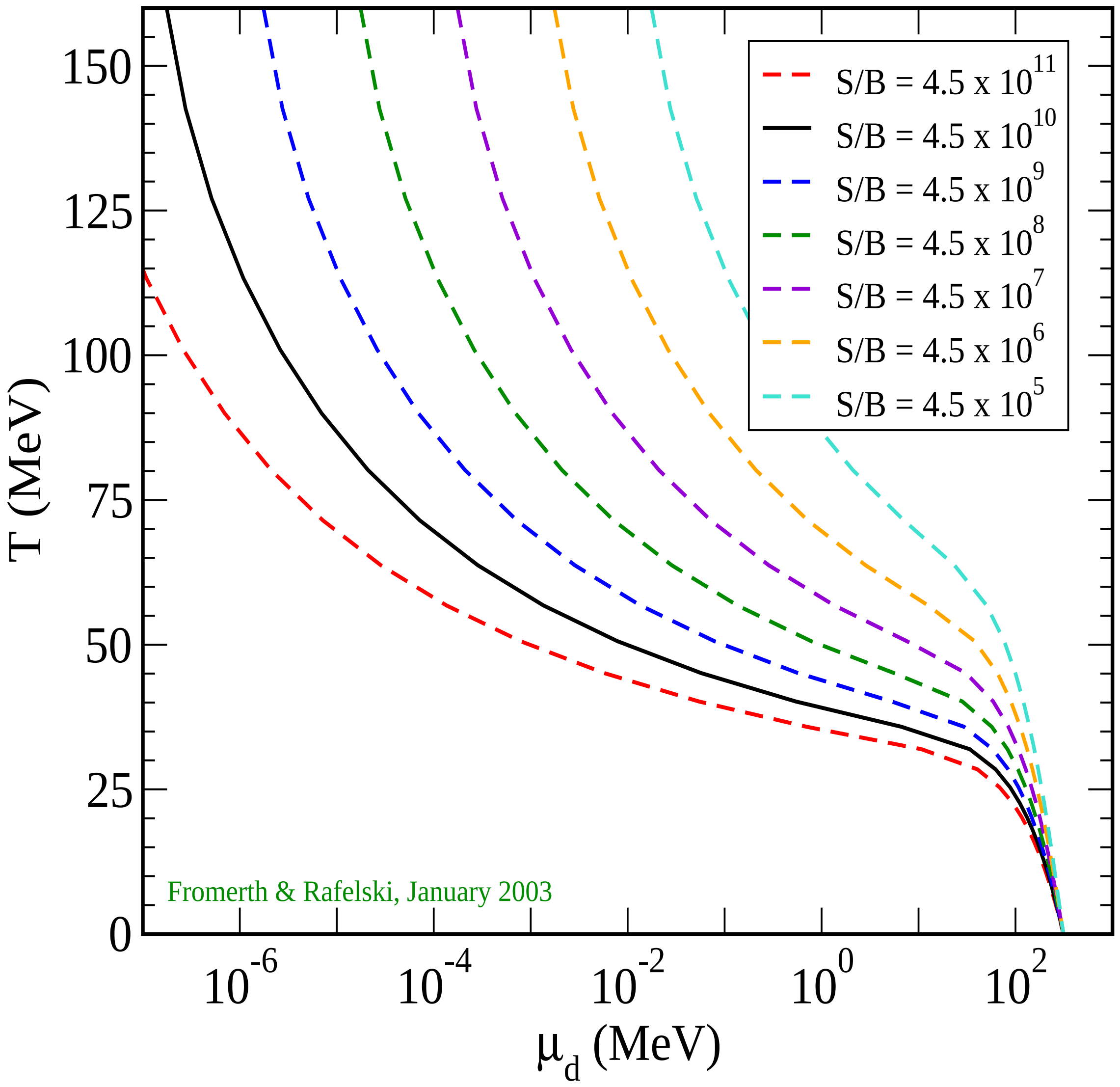


Minimum $\mu_b = 0.33^{+0.11}_{-0.08}$ eV.

μ_b relevant at final hadron $(\pi, \overline{N})$ freeze-out.



TRACING μ_d IN A UNIVERSE



Mixed Phase – This differs from LHC heavy Ions

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 $Q = 0$:

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

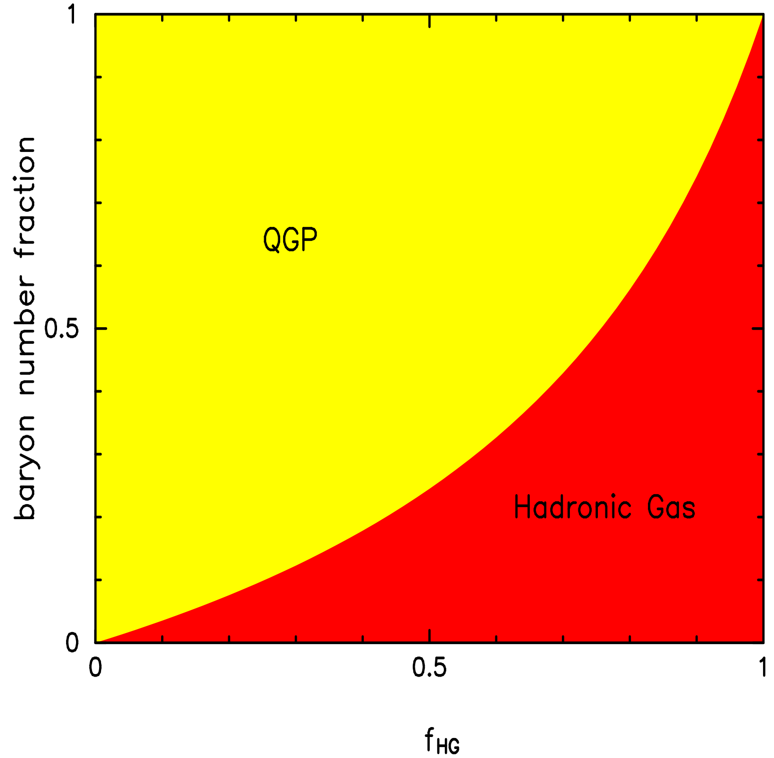
where the total volume $V_{\rm tot}$ is irrelevant to the solution. Analogous expressions are used for $L - B$ and S/B constraints. Note that $f_{\rm HG}(t)$ is result of dynamics of nucleation, assumed not generated here

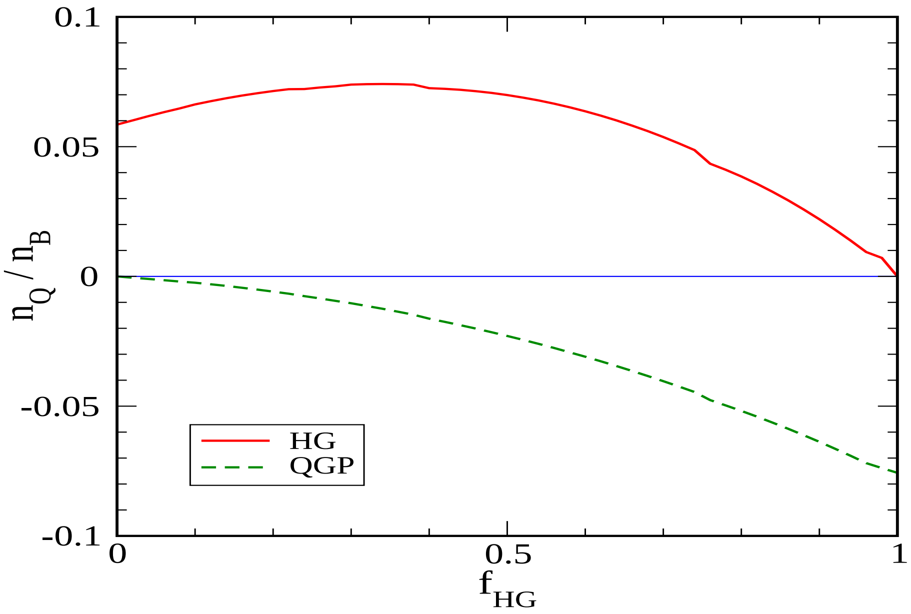
We assume that mixed phase exists $10\,\mu s$ and that $f_{\rm HG}$ changes linearly in time. Actual values will require dynamic nucleation transport theory description.

Charge and baryon number distillation

Initially at $f_{\mathrm{HG}} = 0$ all matter in QGP phase, as hadronization progresses with $f_{\mathrm{HG}} \to 1$ 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,⇐ T. Kodama refused to be co-author

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

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

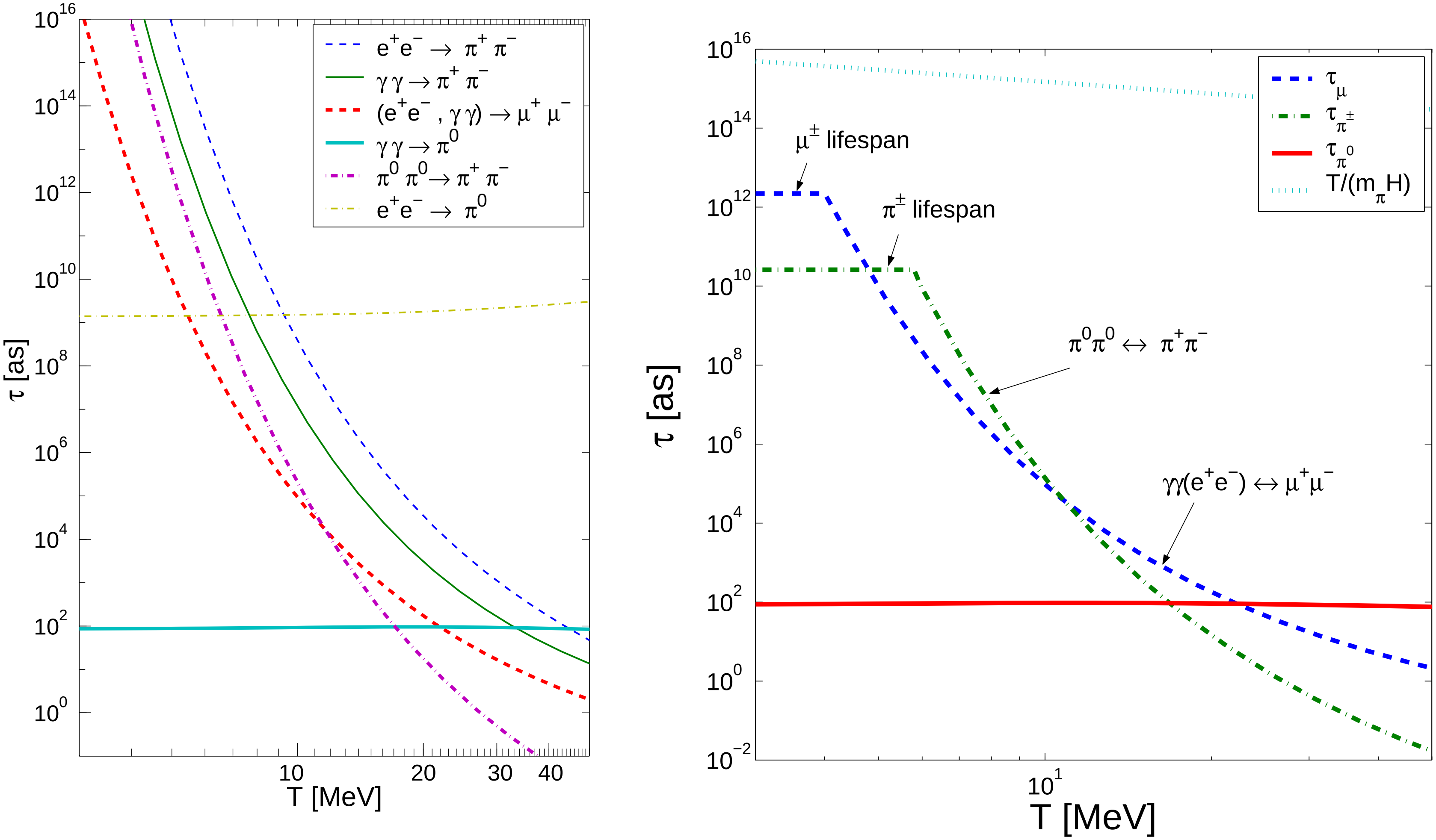
'freeze' out, that is the π^0 decay overwhelms the production rate and the yield falls out from chemical equilibrium yield. Since π^0 lifespan (8.4 10^{-17} s) is rather short, one is tempted to presume that the decay process dominates. However, there must be at sufficiently high density a detailed balance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

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

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

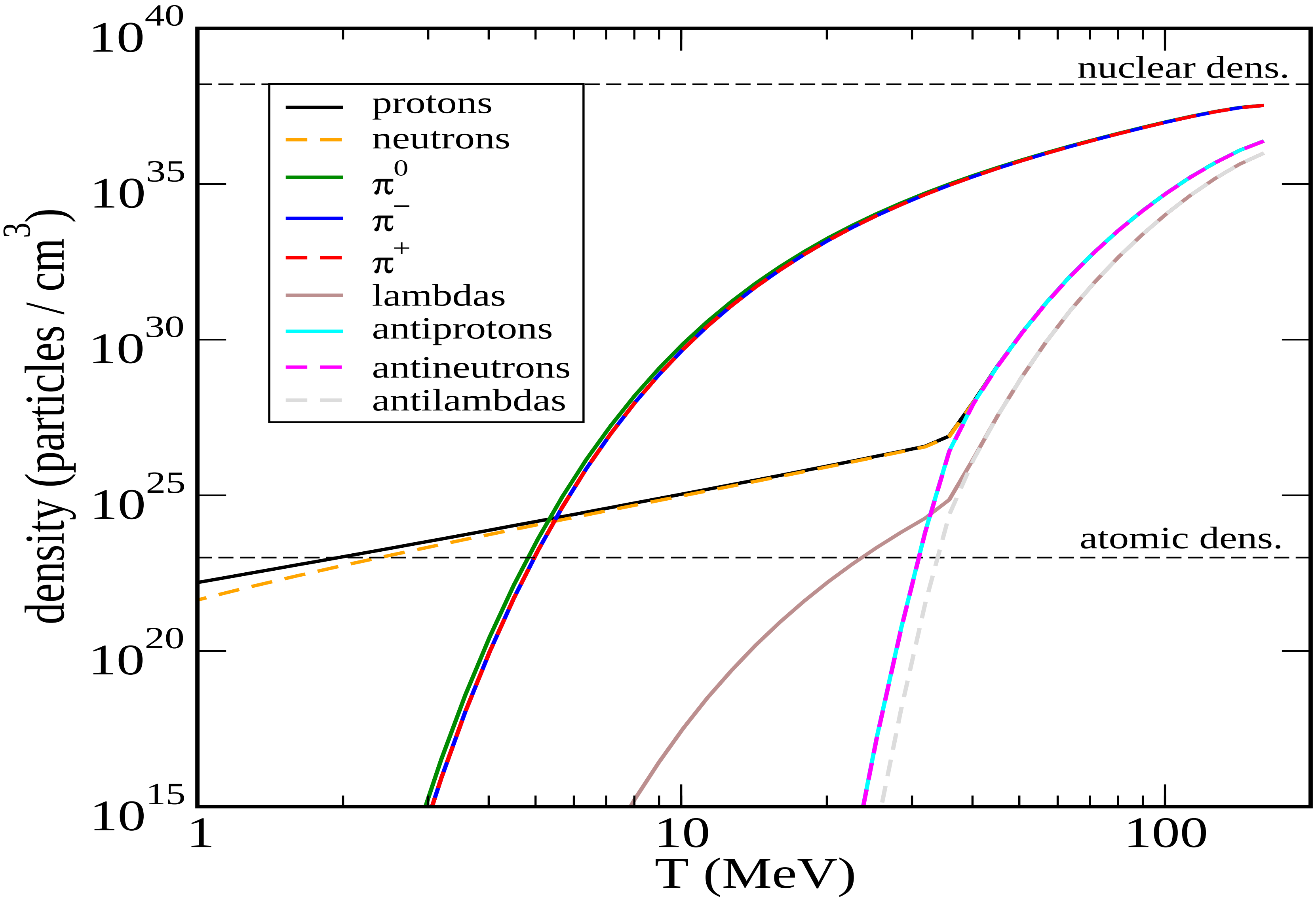
All hadrons will be present: the π^0 creates the doorway.

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.

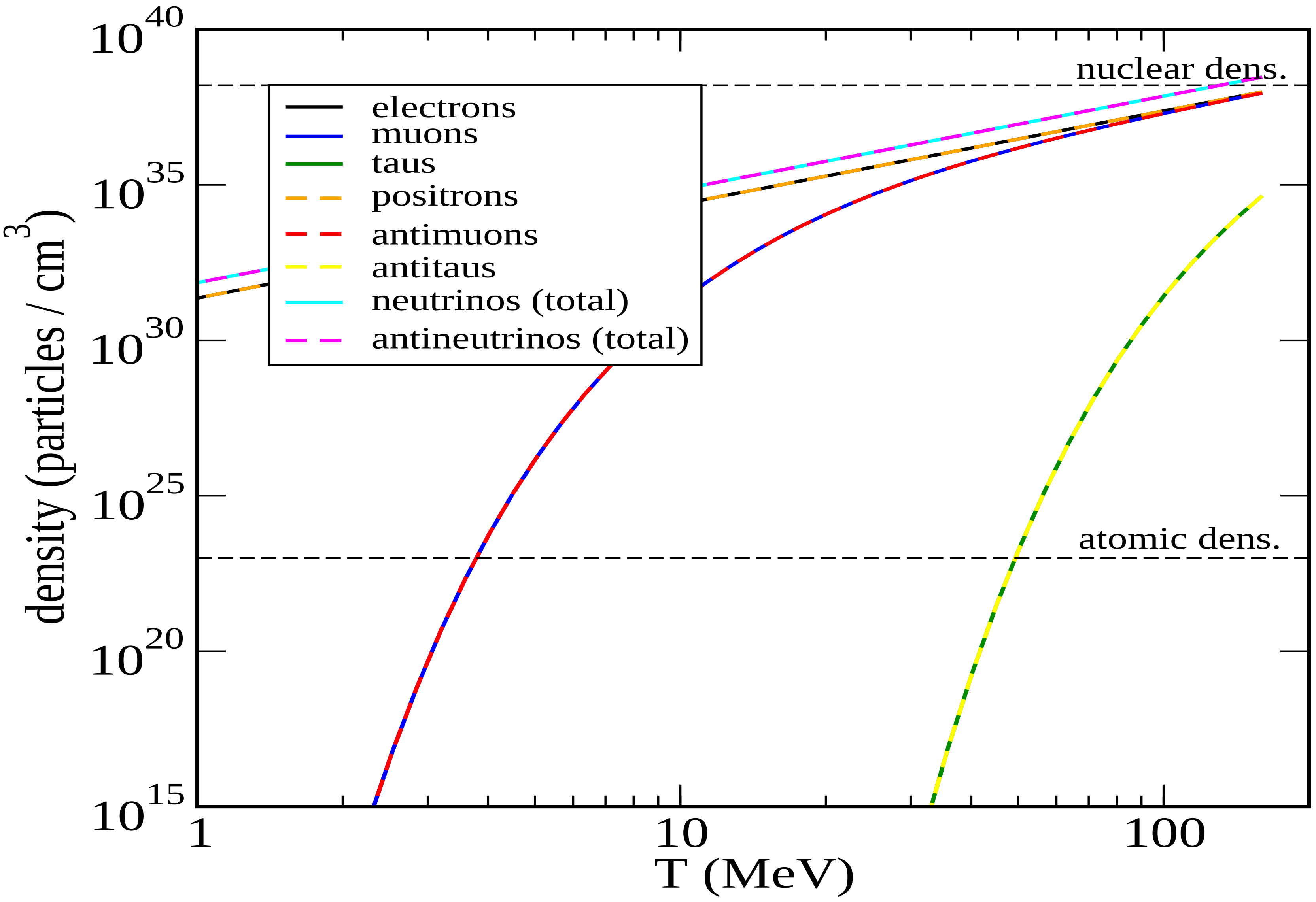


Relaxation times for dominant reactions for pion (and muon) equilibration. At small temperatures $T < 10$ MeV relaxation times for $\mu^\pm$ and $\pi^\pm$ equilibration becomes constant and much below Universe expansion rate and τ_T (dotted turquoise line on right).

Hadronic Universe Hadron Densities



Universe Lepton Densities



Did we learn anything useful?

- **We have a pretty good view how the average Universe looks when it was $30\,\mathrm{ps} < t < 3\,\mathrm{s}$ old. This is the system that lattice QCD addresses, not RHI!**
- **Is there global homogeneity? Probably not, much more work is needed on domains – we laid first foundation stone for this.**
- **Strangeness in a significant abundance down to $T = 10$ MeV, potential for production of strange nuclearites**
- **We found fantastically precise fine tuning: hadrons disappear just in time, neutrinos decouple and free stream just (or not) before e^+e^- annihilation. The Hadron/Neutrino/Nuclear Universe with barely seperate eras. If non-uniform, physics of early Universe could become exciting.**