Connecting QGP-RHI physics to the Early Universe

Today: From QGP to $T = 1$ MeV prior to $e^-e^+ \to \gamma's$

Johann Rafelski

Department of Physics, The University of ARIZONA, Tucson

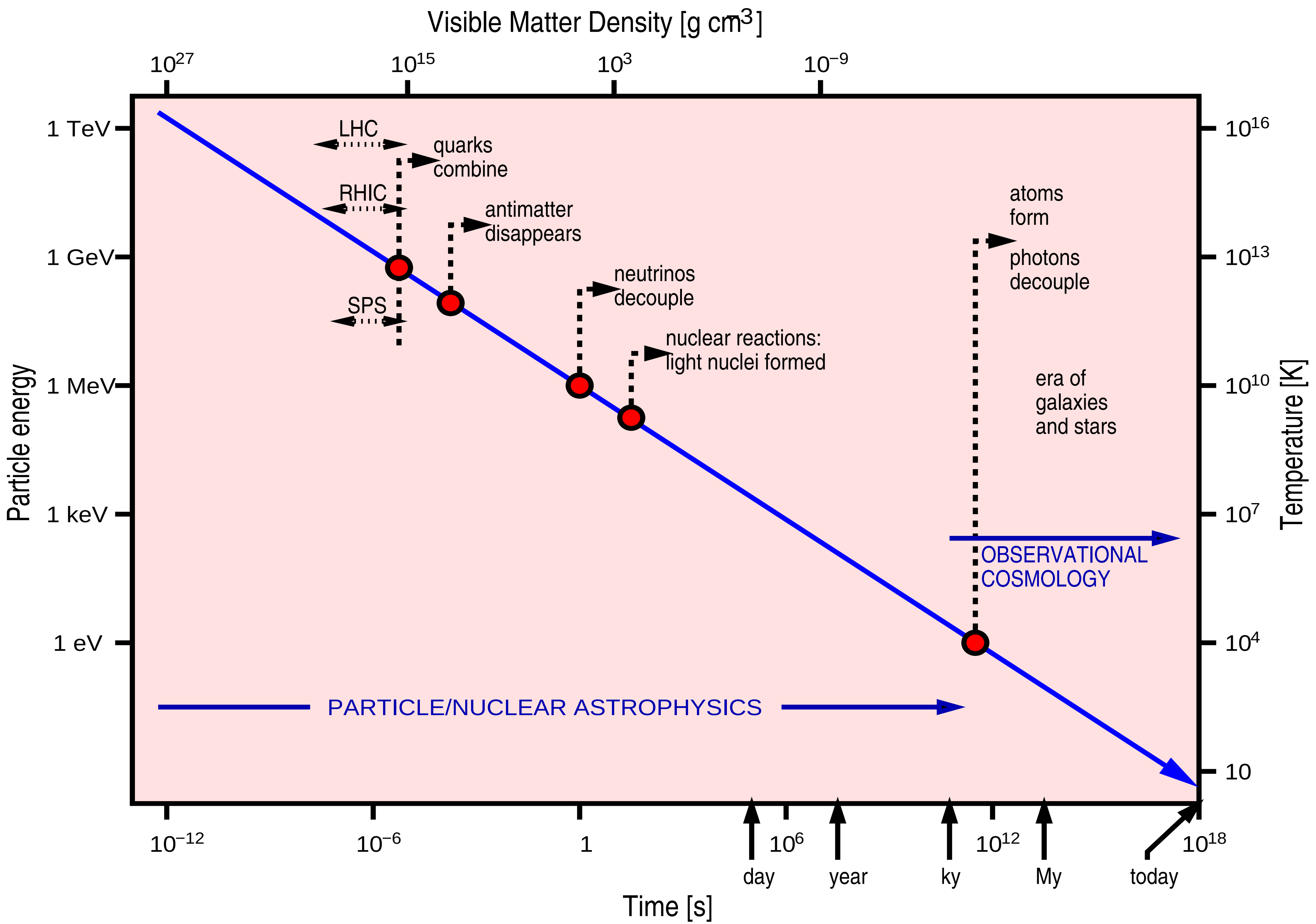
SpacePart at CERN, 5-7, November, 2012

Report on work with

Mike Fromerth, *astro-ph/0211346 Hadronization of the Quark Universe*
Inga Kuznetsova, *1002.0375, Phys. Rev. C 82, 035203 (2010)*
Unstable hadrons in hot hadron gas: In the laboratory and in the early Universe
and *0803.1588, Phys.Rev. D78, 014027 (2008)*
Pion and muon production in e-, e+, gamma plasma
Lance Labun, *1112.5765, Acta Phys.Polon.Supp. 5 (2012) 381-386*
Planetary Impacts by Clustered Quark Matter Strangelets
Jean Letessier *Hadrons from QGP (Cambridge Univ. Press, 2000)*,

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

Stages in the evolution of the Universe



Our objective is to understand

- **The conversion of Quark Universe into the hadronic phase,**
- **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.**

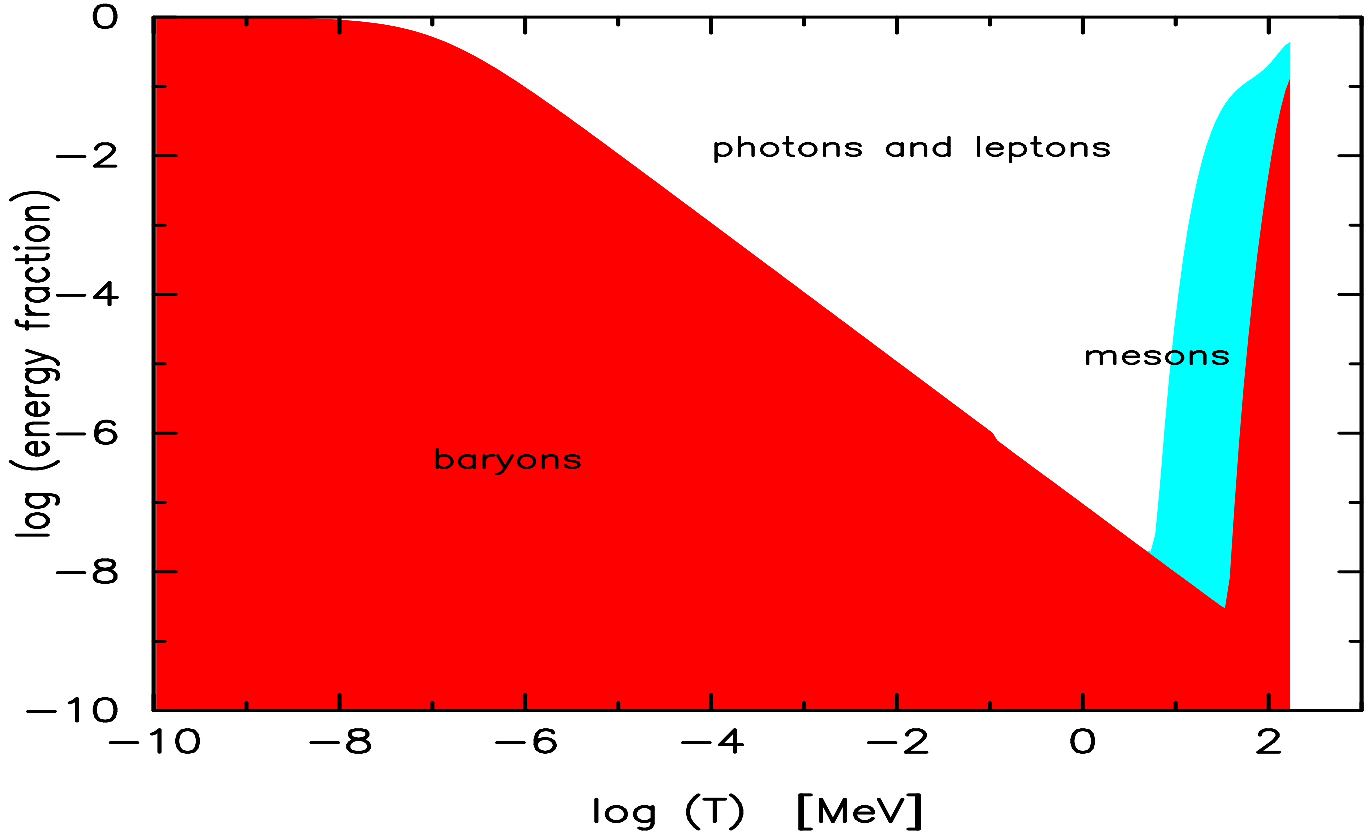
There are a few tacit assumptions:

1. **The dark energy does not matter in the early Universe, e.g. it is a constant like Einstein's Λ, and if variable, it has been not an important component at that time (prevailing view today);**
2. **The dark matter decays and annihilation are too slow to impact dynamics of the visible matter in the time interval $[20\mu\text{s} \equiv T = 200\text{MeV}, 0.1\text{s} \equiv T = 2.5$ MeV].**
3. **Dark matter is either 'cold' (prevailing view) or 'warm' (axionic exception) that is mass must be outside the range of our study (outside 200-1 MeV)**
4. **There are $3 + \delta\nu$ neutrinos and antineutrinos which have each only two components**

Direct Probe of the Early Universe: Heavy Ion Collisions at LHC

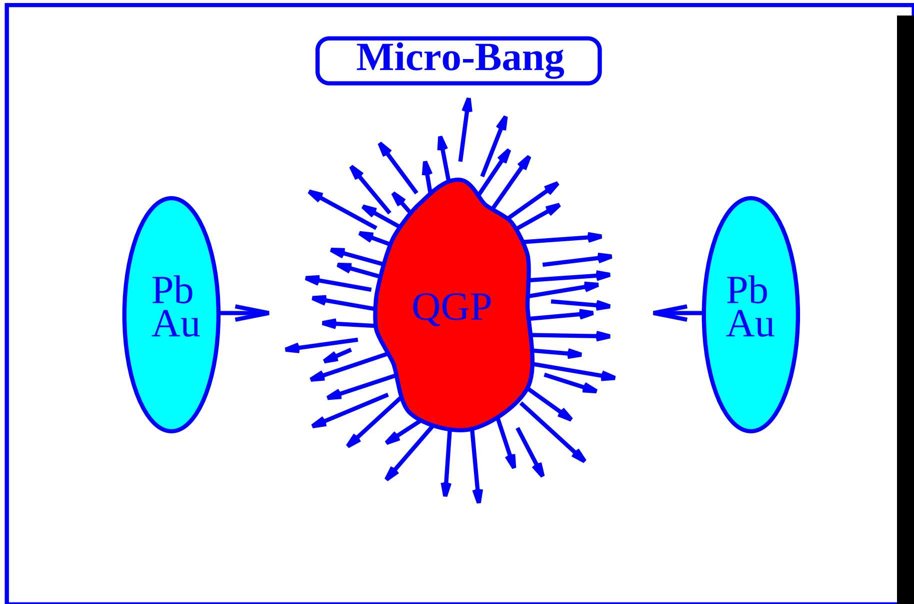
RECREATE THE EARLY UNIVERSE IN LABORATORY:
Recreate and understand the high energy density conditions prevailing in the Universe when matter formed from elementary degrees of freedom (quarks, gluons) at about 30 μs after big bang.

QGP-Universe hadronization led to nearly matter-antimatter symmetric state, ensuing matter-antimatter annihilation yields 10^{-10} *matter asymmetry, the world around us.*

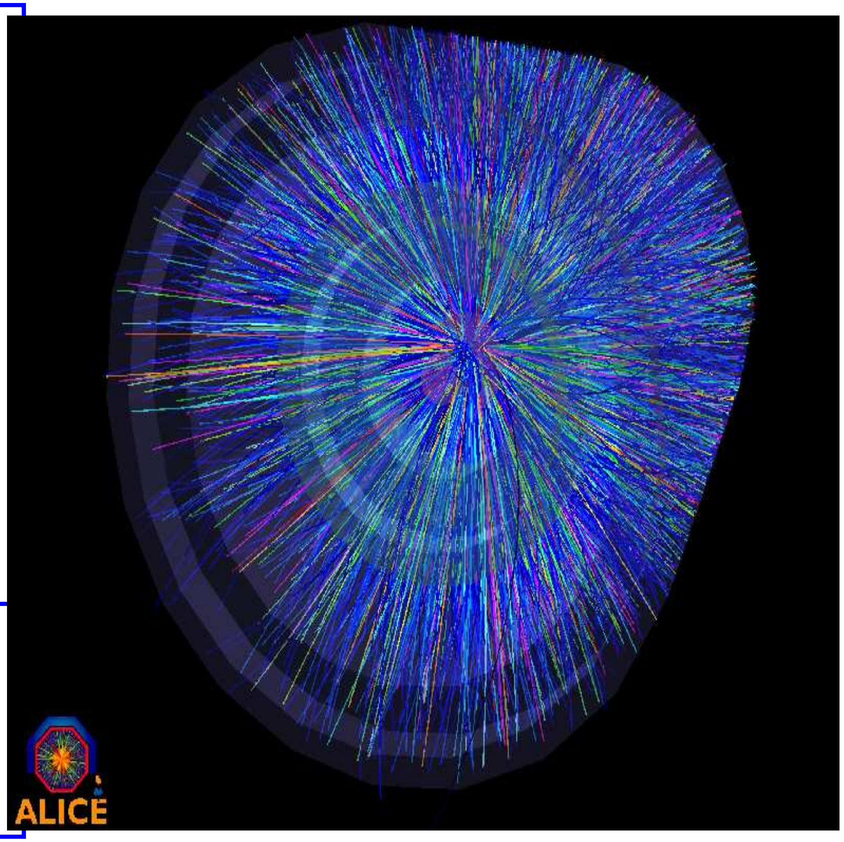


Note spike immediately following hadronization at T=160 MeV

RECREATING THE EARLY UNIVERSE: ENERGY TO MATTER



Big-Bang	Micro-Bang
$\tau \simeq 10\mu s$	$\tau \simeq 4\ 10^{-23}s$
$N_B / N \simeq 10^{-10}$	$N_B / N \simeq 0.1$



ALICE at LHC

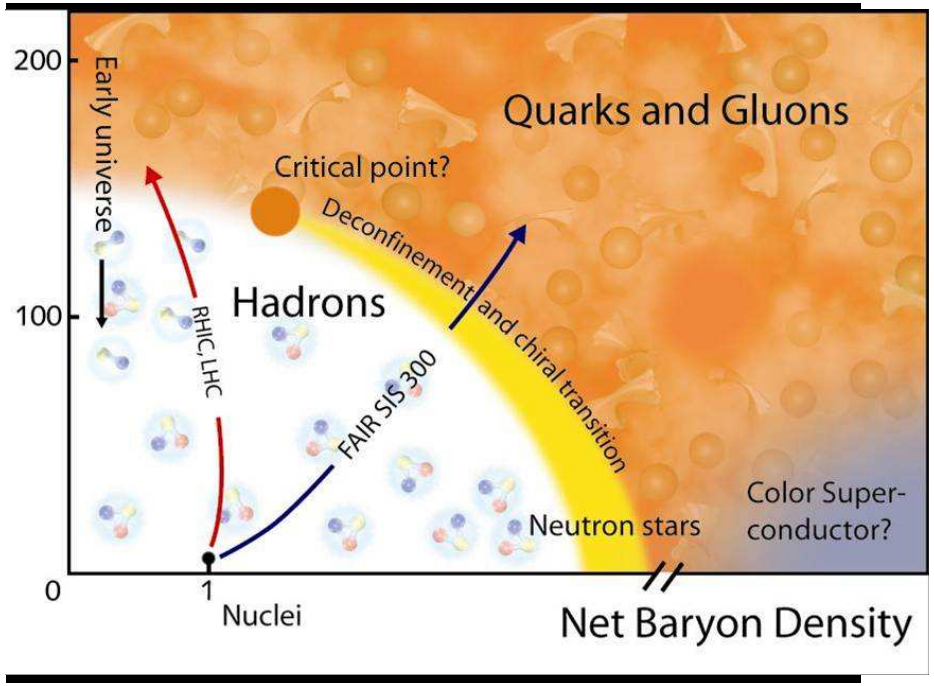
Orders of Magnitude

ENERGY/V	ϵ	$\simeq 1$–**50GeV/fm**^{3} $= 0.18$–$9\ 10^{16}$**g/cc**
Vacuum heat	B	$\simeq$**0.4GeV/fm**^{3} $= (234\text{MeV})^4 = 0.64\ 10^{29}$**J/cc**
Pressure	P	$= \frac{1}{3}\epsilon = (0.52 - 26)\ 10^{30}$ **bar**
Temperature	T_0, T_f	**500, 160 MeV;** **300MeV**$\simeq$**3.5** 10^{12}**K**

What and where is deconfinement?

A domain of (space, time) where matter as we know it does not exist. This is the early Universe strongly interacting phase of matter.

We expect a pronounced boundary in temperature and density between confined and deconfined phases of matter: phase diagram. Deconfinement expected at both: high temperature and at high matter density.

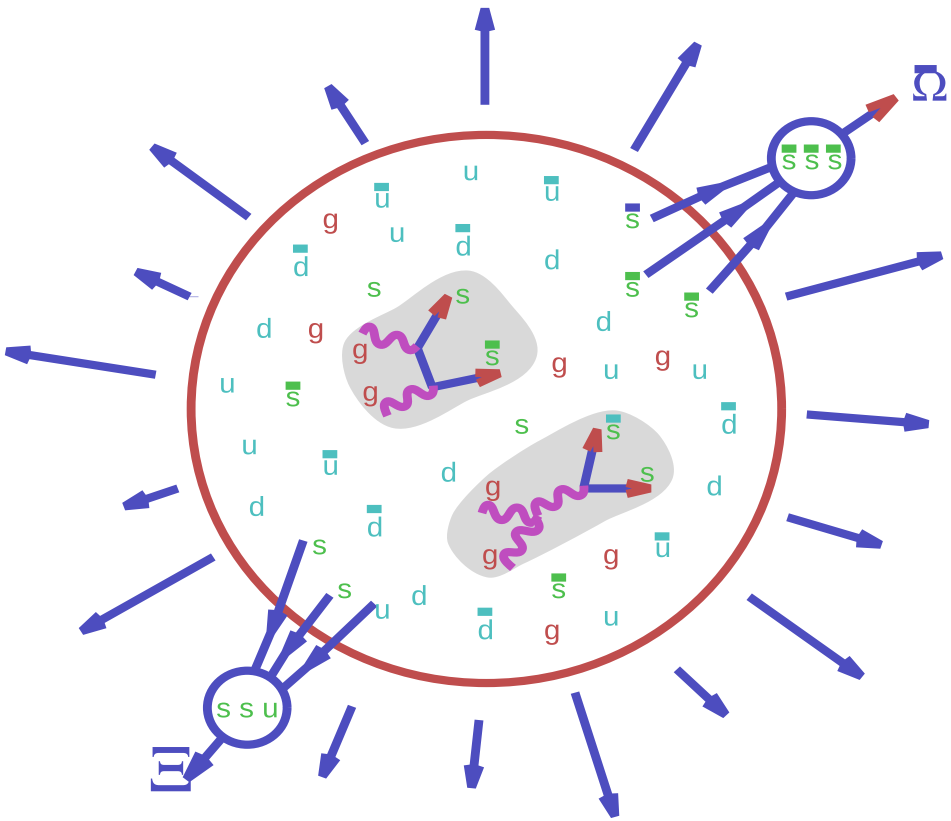


REMINDER: ORIGIN OF THE MASS OF MATTER IN (DE)CONFINEMENT

The confining quark vacuum state is the origin of 99.9% of GRAVITATING visible matter mass, the Higgs mechanism applies to the remaining 0.1%. Experiment to ascertain the quantum zero-point energy of confined quarks is the mass of matter: we 'melt' the vacuum structure setting quarks free.

From QGP to Hadrons: Statistical Hadronization Model

= recombinant quark hadronization, main consequence in laboratory experiments: strangeness enhancement leads to enhancement of multi 'heavy' flavored (strange, charm, bottom) antibaryons progressing with 'heavy flavor content – my QGP signature, see e.g. See: P. Koch, B. Muller and JR *Strangeness In Relativistic Heavy Ion Collisions,* **Phys. Rept. 142, 167 (1986), and references therein.**



Two step process:

1. **$GG \rightarrow s\bar{s}$ (thermal gluons collide)**
   $GG \rightarrow c\bar{c}$ (initial parton collision)
   $GG \rightarrow b\bar{b}$ (initial parton collision)
   gluon dominated reactions
2. **RECOMBINATION of pre-formed $s,\ \bar{s},\ c,\ \bar{c},\ b,\ \bar{b}$ quarks**

SHM is FERMI PHASE SPACE MODEL with QUARK CHEMISTRY

One transparency: QCD and QGP Quark-Gluon Gas

$$\frac{T}{V}\ln \mathcal{Z}_{QGP} = -\mathcal{B} + \frac{8}{45\pi^2}c_1(\pi T)^4 + \sum_{i=u,d,s}\frac{n_i}{15\pi^2}\left[\frac{7}{4}c_2(\pi T)^4 + \frac{15}{2}c_3\left(\mu_i^2(\pi T)^2 + \frac{1}{2}\mu_i^4\right)\right]$$

$$c_1 = 1 - \frac{15\alpha_s}{4\pi}, \quad c_2 = 1 - \frac{50\alpha_s}{21\pi}, \quad c_3 = 1 - \frac{2\alpha_s}{\pi}.$$

We recall that $\mu_b = 3\mu_q$ and $\lambda_q = e^{\mu_q/T}$. The temperature dependence $\alpha_s(T)$ is estimated to be $\mu = 2\pi T$ that is use $\alpha_s(2\pi T)$ with lowest order perturbative correction, which works well. At finite chemical potential $\mu = 2\sqrt{(\pi T)^2 + \mu_q^2} = 2\pi T\sqrt{1 + \frac{1}{\pi^2}\ln^2\lambda_q}$. A convenient way to obtain entropy and baryon density uses the thermodynamic potential $\mathcal{F}$:

$$\frac{\mathcal{F}(T,\mu_q,V)}{V} = -\frac{T}{V}\ln \mathcal{Z}(\beta,\lambda_q,V)_{QGP} = -P_{QGP}.$$

The entropy density is:

$$s_{QGP} = -\frac{d\mathcal{F}}{VdT} = \frac{32\pi^2}{45}c_1T^3 + \frac{n_f 7\pi^2}{15}c_2T^3 + n_f c_3\mu_q^2 T + A\frac{\pi^2 T}{\pi^2T^2 + \mu_q^2}.$$

Noting that baryon density is 1/3 of quark density, we have:

$$\rho_B = -\frac{1}{3}\frac{d\mathcal{F}}{Vd\mu_q} = \frac{n_f}{3}c_3\left\{\mu_q T^2 + \frac{1}{\pi^2}\mu_q^3\right\} + \frac{1}{3}A\frac{\mu_q}{\pi^2T^2 + \mu_q^2}.$$

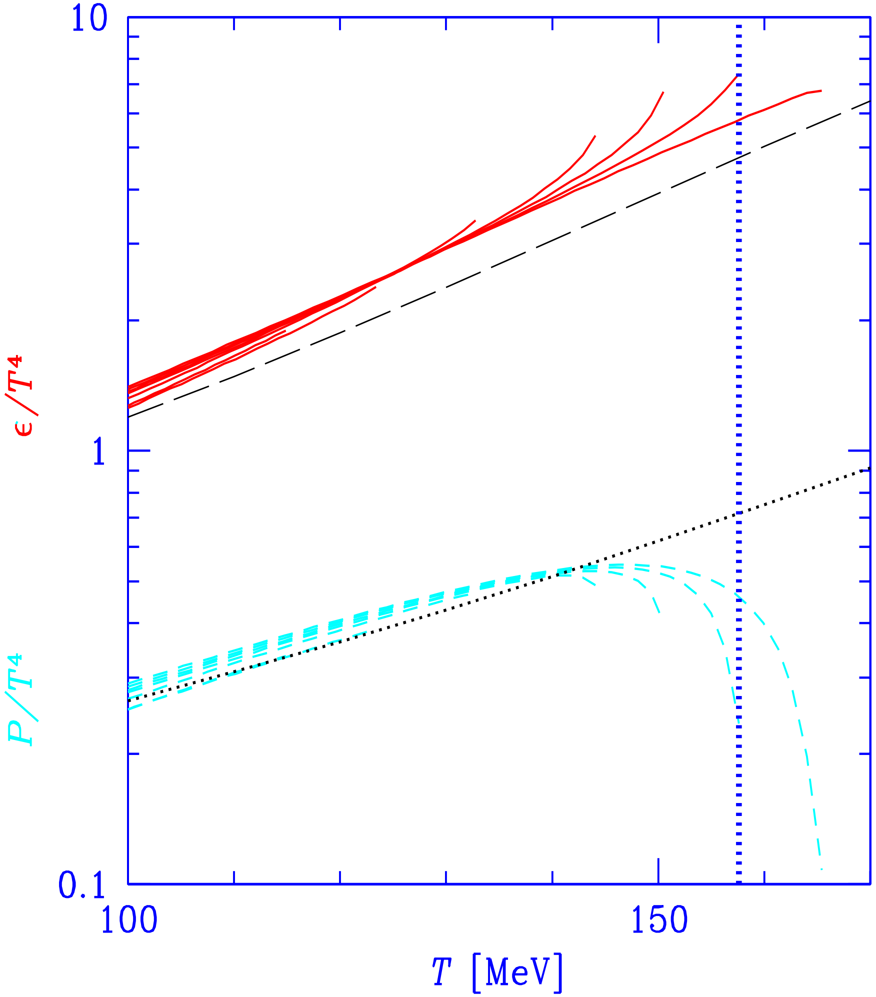
$$A = A_g + A_q + A_s; \quad A_g = (b_0\alpha_s^2 + b_1\alpha_s^3)\frac{2\pi}{3}T^4$$

$$A_{i=q,s} = (b_0\alpha_s^2 + b_1\alpha_s^3)\left[\frac{n_i 5\pi}{18}T^4 + \frac{n_i}{\pi}\left\{\mu_i^2T^2 + \frac{1}{2\pi^2}\mu_i^4\right\}\right].$$

One Transparency: Finite Volume Hadron Gas Model

The gas of finite size hadrons with exponential mass spectrum has nearly the same properties as a gas of point hadrons with today experimentally observed mass spectrum. That is why 'statistical hadronization works'.

Point hadron gas in free available volume Δ to have the properties of finite size hadron gas in total mean volume $\langle V\rangle$ (Hagedorn/JR 1978-82)



$$\ln \mathcal{Z}_{\rm pt}(T,\Delta,\lambda) \equiv \ln \mathcal{Z}(T,\langle V\rangle,\lambda)$$

Proper particle volume in the rest frame is assumed to be proportional to mass. For a gas of moving hadrons, in gas rest frame: $\langle V\rangle = \Delta + \langle E\rangle/4\mathcal{B}$.

$$\langle E\rangle = \langle V\rangle \epsilon(\beta,\lambda) = -\frac{\partial}{\partial\beta}\ln \mathcal{Z}(\beta,\langle V\rangle,\lambda) =$$

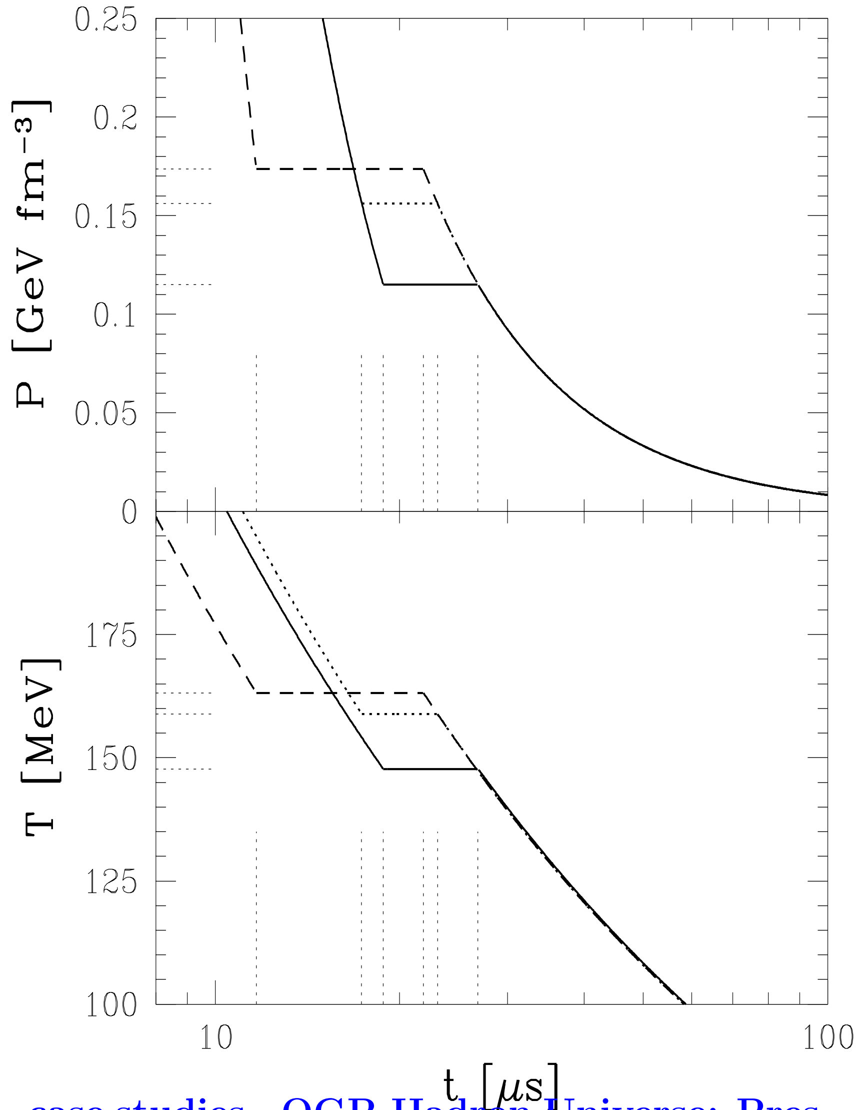
$$= -\frac{\partial}{\partial\beta}\ln \mathcal{Z}_{\rm pt}(\beta,\Delta,\lambda) = \Delta\epsilon_{\rm pt}(\beta,\lambda)$$

$$\langle V\rangle = \Delta\big(1+\epsilon_{\rm pt}(\beta,\lambda)/4\mathcal{B}\big),$$

$$\frac{\langle E\rangle}{\langle V\rangle} \equiv \epsilon(\beta,\lambda) = \frac{\epsilon_{\rm pt}(\beta,\lambda)}{1+\epsilon_{\rm pt}(\beta,\lambda)/(4\mathcal{B})},$$

$$P = \frac{P_{\rm pt}(\beta,\lambda)}{1+\epsilon_{\rm pt}(\beta,\lambda)/4\mathcal{B}}.$$

Universe Hadronization: Time Scales; When and How?



- case studies - QGP-Hadron Universe: Pressure (upper) and temperature (lower part) as function of time, in the vicinity of the phase transformation from the deconfined phase to the confined phase.

Einstein equations

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

lead to two dynamical equations:

Entropy conserving expansion:

$$\dot\epsilon = -3\frac{\dot R}{R}(\epsilon + P)$$

Friedmann-Lemaître-Robertson-Walker Universe Dynamics

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

$\Lambda = 0$ and flat $k = 0$ universe, combine, use latent heat, only massless particles count: EoS

$$\epsilon_p = \epsilon - \mathcal{B} = 3P_p = 3P + 3\mathcal{B},$$

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

GENERAL ANALYTIC Solution:

in QGP book, trivial,original, not seen published:

$$\epsilon_{\rm QGP} = \mathcal{B}\coth^2(t/\tau_{\rm U}),$$

With time constant:

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

Evolution of particle abundances

Follow conditions in which matter (protons, neutrons) formed and evolved QGP, hadronization , and hadron gas.

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

$$T \simeq 155\,\mathbf{MeV} \qquad t \simeq 30\mu s,$$

2) Understanding of the dynamics of quark-hadron phase transformation (preferably with nucleation dynamics) is limited, contrast rations cause baryon and strangeness number distillation;

3) Demonstrate that the Universe can be in chemical equilibrium during this period EXTRA SLIDES AT END OF LECTURE

4) Describe the composition and equilibration of the Universe during evolution towards and beyond the condition of neutrino decoupling

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

5) We use input from experimental anchor points and from lattice computation near QGP-Hadron boundary

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.

- **There are three chemical potentials which are 'free' and we choose to follow the following: μ_d, μ_e, and μ_ν.**

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

- **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. *Charge neutrality* **($Q = 0$) is required to eliminate Coulomb energy. This implies that:**

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

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 baryogenesis:**

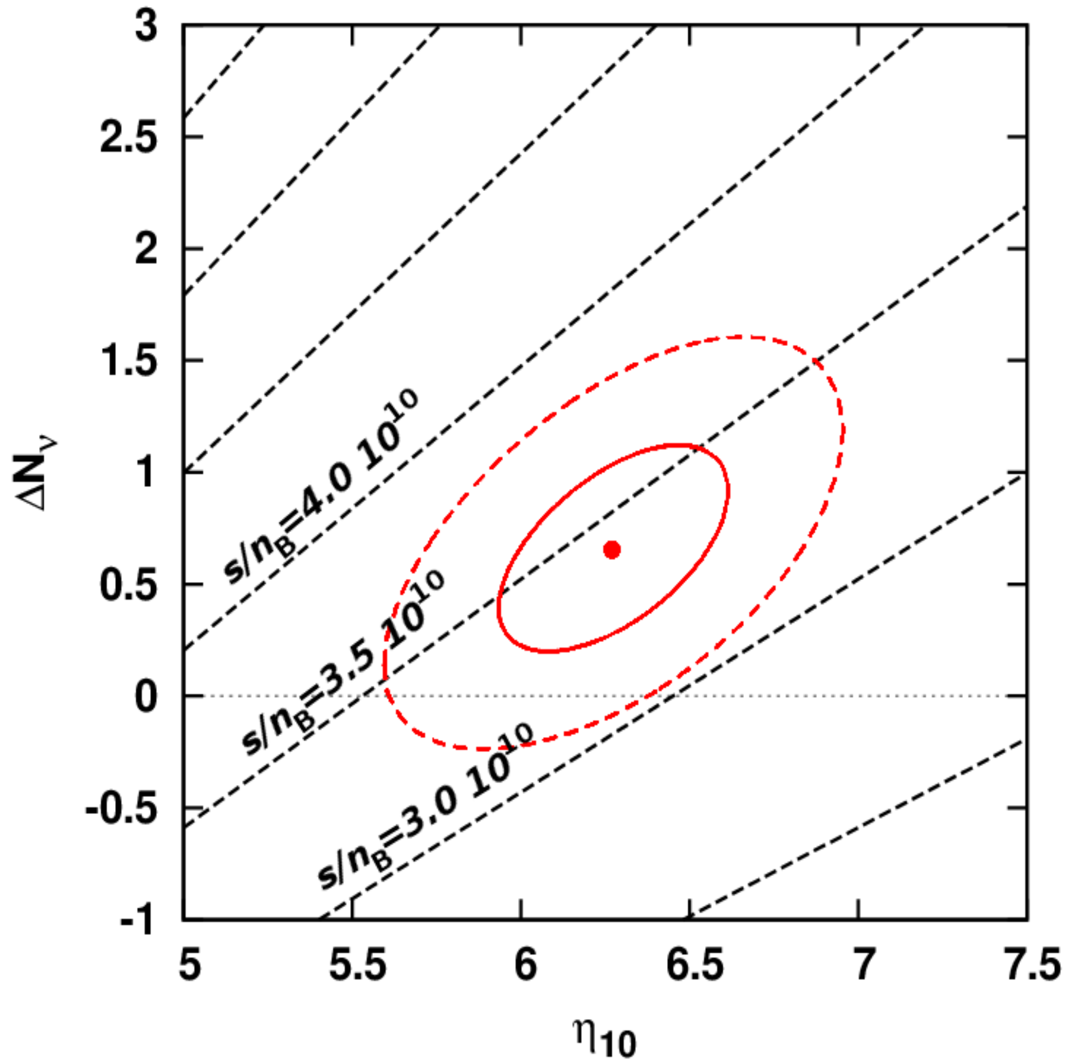
$$n_L - n_B \equiv \sum_i (L_i - B_i) \, n_i(\mu_i, T) = 0,$$

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)**

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

Entropy per Baryon in the Universe derived from $\eta_1 0 = 10^{10} n_B/n_\gamma$



For red circles see Fig 4 of G. Steigman, 1208.0032 - the desired value of WMAP is consistent with BBN introducing a neutrino excess ΔN_ν ; black lines This leads to entropy per baryon, $\rightarrow$

Counting entropy AFTER neutrino freeze-out at $T = 1$MeV

Present in Universe in large abundance:
a) equilibrated: photons, electrons, positrons,
b) potentially in non-equilibrium chemical abundance: neutrinos.

$$\frac{S_{\rm Universe}}{V} = \frac{S_\gamma}{V} + \frac{S_{e\bar e}}{V} + \frac{S_{\nu\bar\nu}}{V}$$

$$\frac{S_\gamma}{V} = \frac{S_\gamma}{N_\gamma}\frac{N_\gamma}{V} = 3.601\frac{N_\gamma}{V}, \qquad \frac{S_{e\bar e}}{V} = \frac{S_{e\bar e}}{N_{e\bar e}}\frac{N_{e\bar e}}{V} = 4.202\frac{N_{e\bar e}}{V}, \qquad \frac{S_{\nu\bar\nu}}{V} = \frac{S_{\nu\bar\nu}}{N_{\nu\bar\nu}}\frac{N_{\nu\bar\nu}}{V} = 4.202\frac{N_{\nu\bar\nu}}{V}$$

3.601 is the entropy per particle for bosons and 4.202 the entropy per particle for fermions;

$$\frac{S_{\rm Universe}}{V} = \frac{N_\gamma}{V}\left(3.601 + 4.202\frac{N_{e\bar e}}{N_\gamma} + 4.202\frac{N_{\nu\bar\nu}}{N_\gamma}\right)$$

$$\frac{N_{e\bar e}}{N_\gamma} = 2\frac{3}{4}, \qquad \frac{N_{\nu\bar\nu}}{N_\gamma} = (3+\delta N)\frac{3}{4}$$

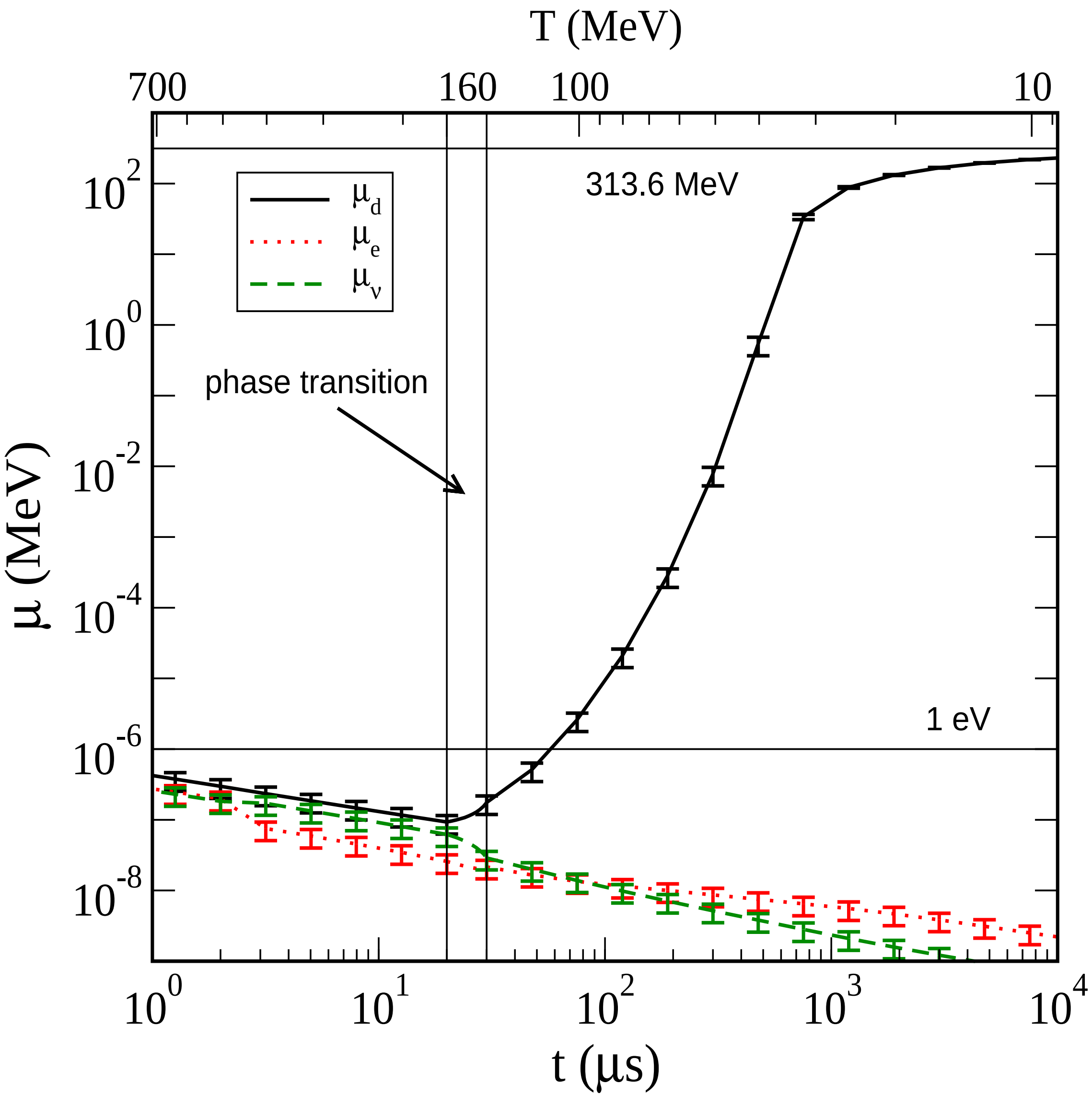
Here 3/4 is the universal statistical particle ratio fermion to boson at equal T

$$\frac{S_{\rm Universe}}{N_\gamma} = 3.601 + 4.202(5+\delta N_\nu)0.75 = 19.36 + 3.15\delta N_\nu$$

$$\boxed{\frac{S_{\rm Universe}}{N_B} = \frac{19.36+3.15\delta N_\nu}{N_B/N_\gamma} = \frac{19.36+3.15\delta N_\nu}{\eta_{10}}10^{10}}$$

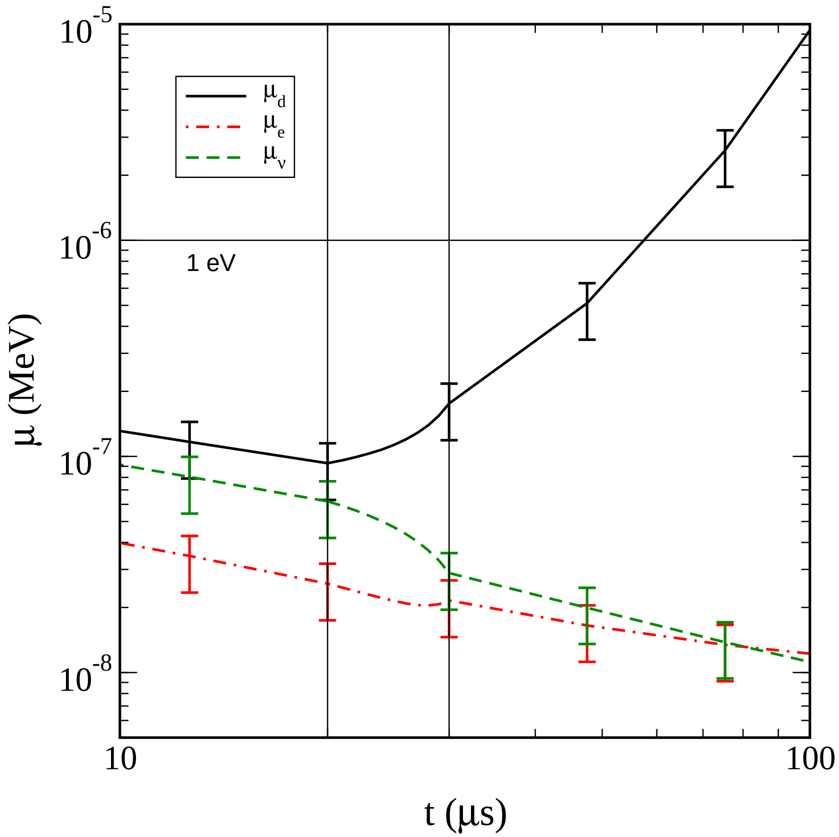
Note, current value S/B=3.5 but results shown for older value 4.5

TRACING μ_d IN THE UNIVERSE

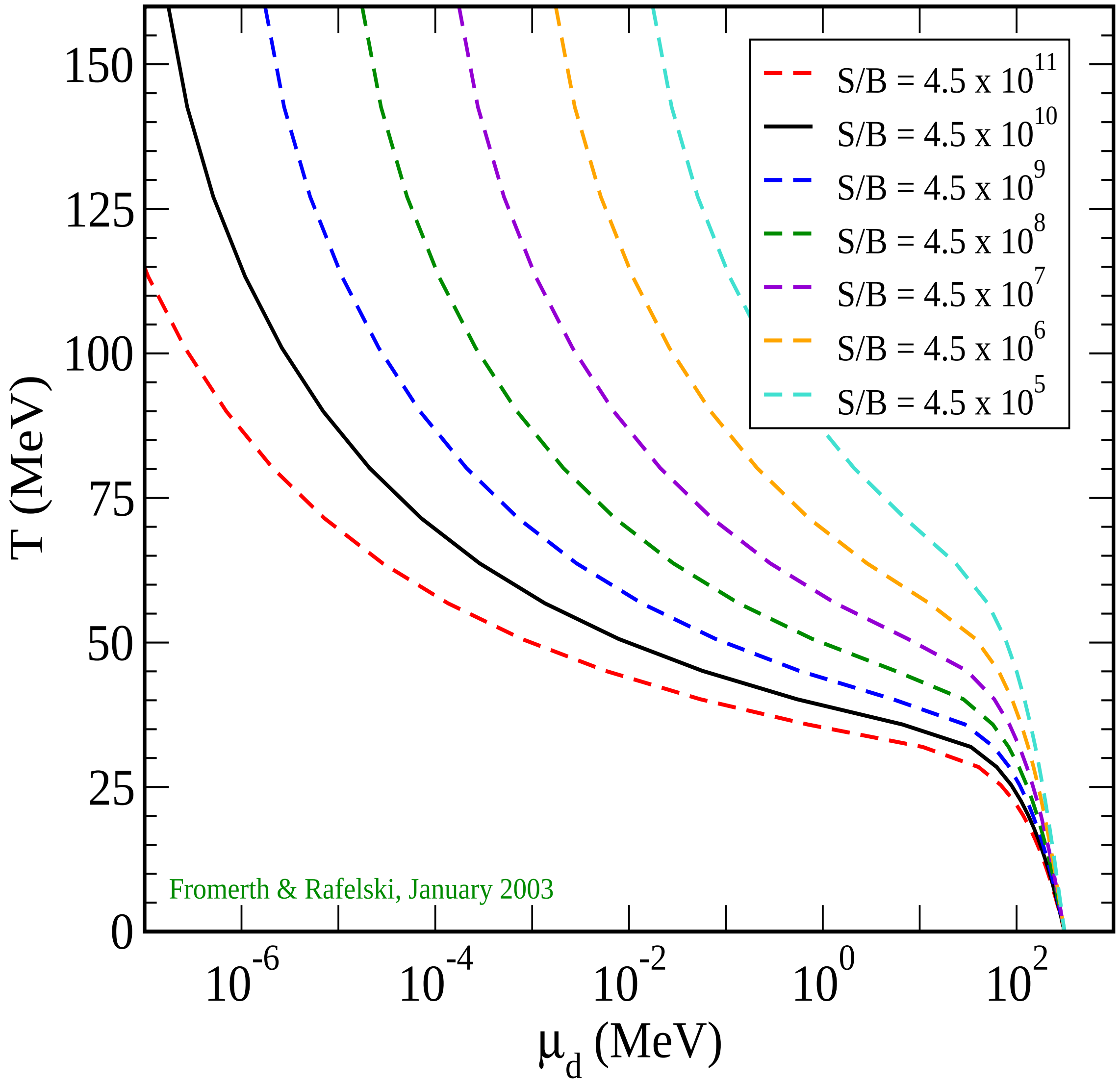


Minimum $\mu_b = 0.33^{+0.11}_{-0.08}$ eV.

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 $Q = 0$:

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

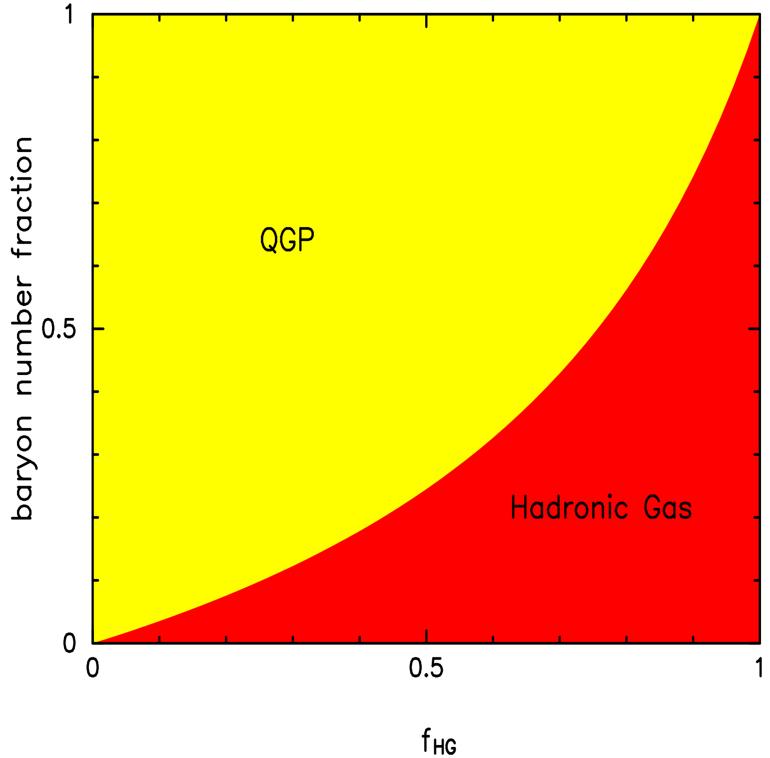
where the total volume $V_{\rm tot}$ is irrelevant to the solution. Analogous expressions are used for $L - B$ and S/B constraints. Note that $f_{\rm HG}(t)$ is result of dynamics of nucleation, assumed not generated here

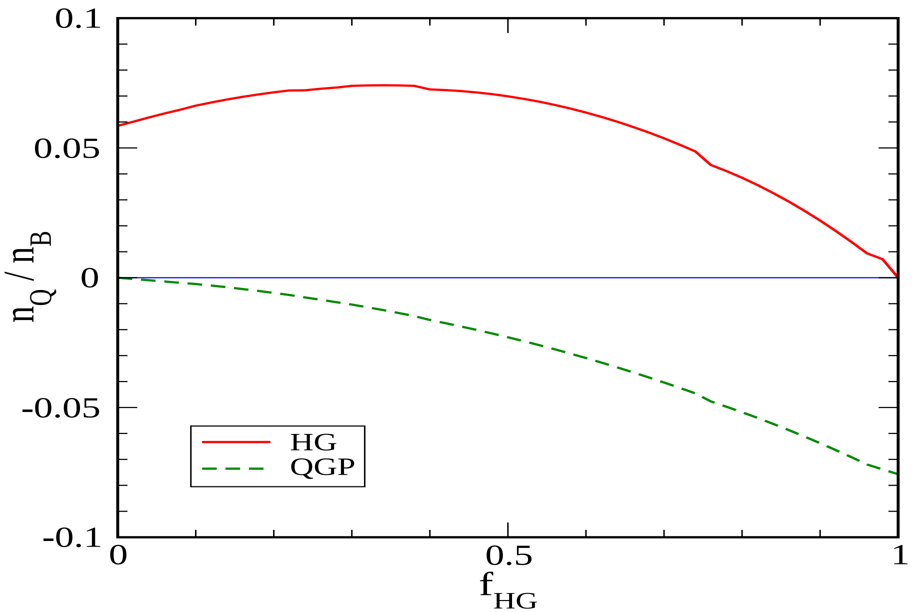
We assume that mixed phase exists $10\,\mu s$ and that $f_{\rm HG}$ changes linearly in time. Actual values will require dynamic nucleation transport theory description.

Charge and baryon number distillation

Initially at $f_{\rm HG} = 0$ 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

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

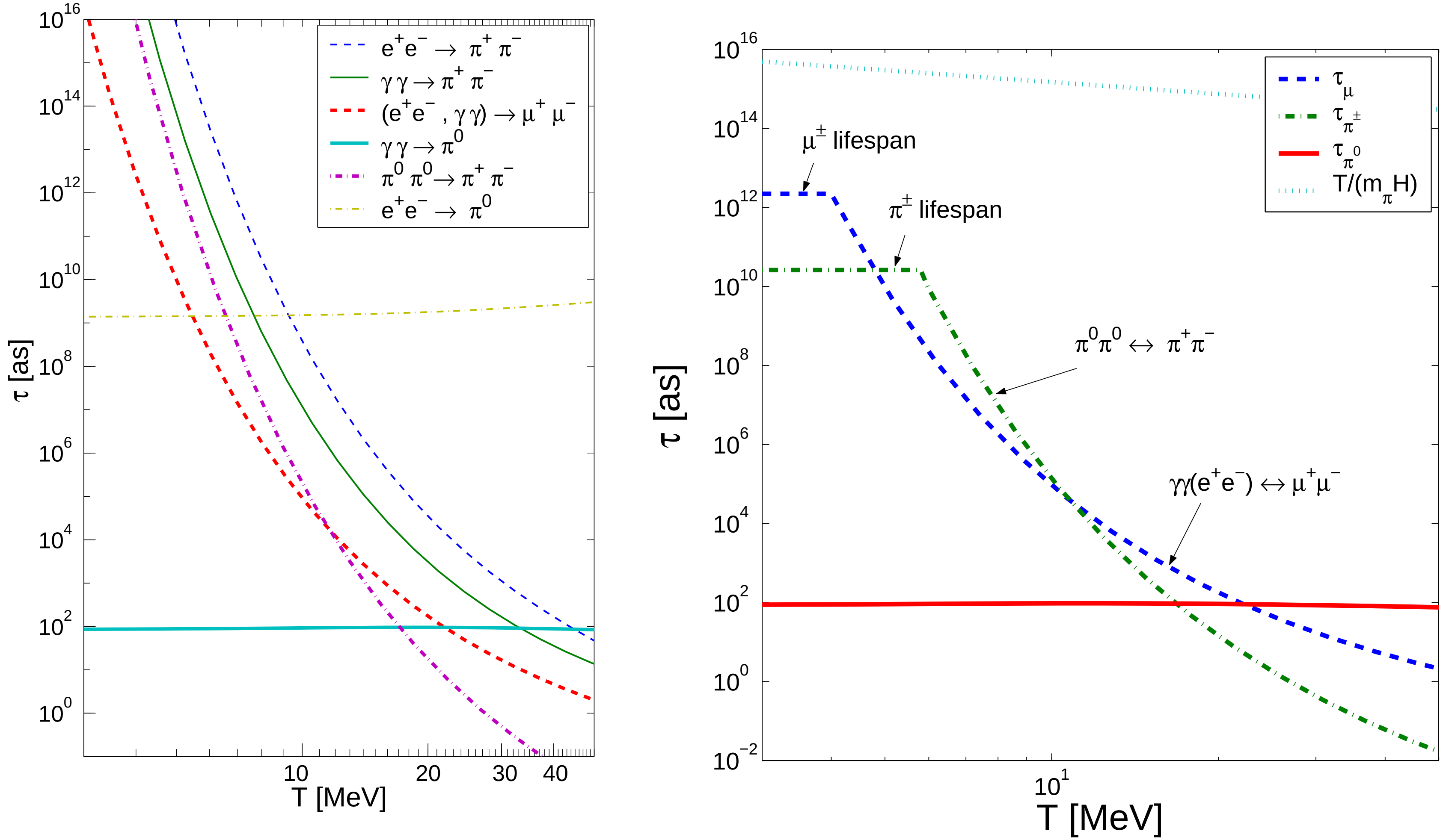
'freeze' out, that is the π^0 decay overwhelms the production rate and the yield falls out from chemical equilibrium yield. Since π^0 lifespan ($8.4\,10^{-17}$ s) is rather short, one is tempted to presume that the decay process dominates. However, there must be at sufficiently high density a detailed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

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

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

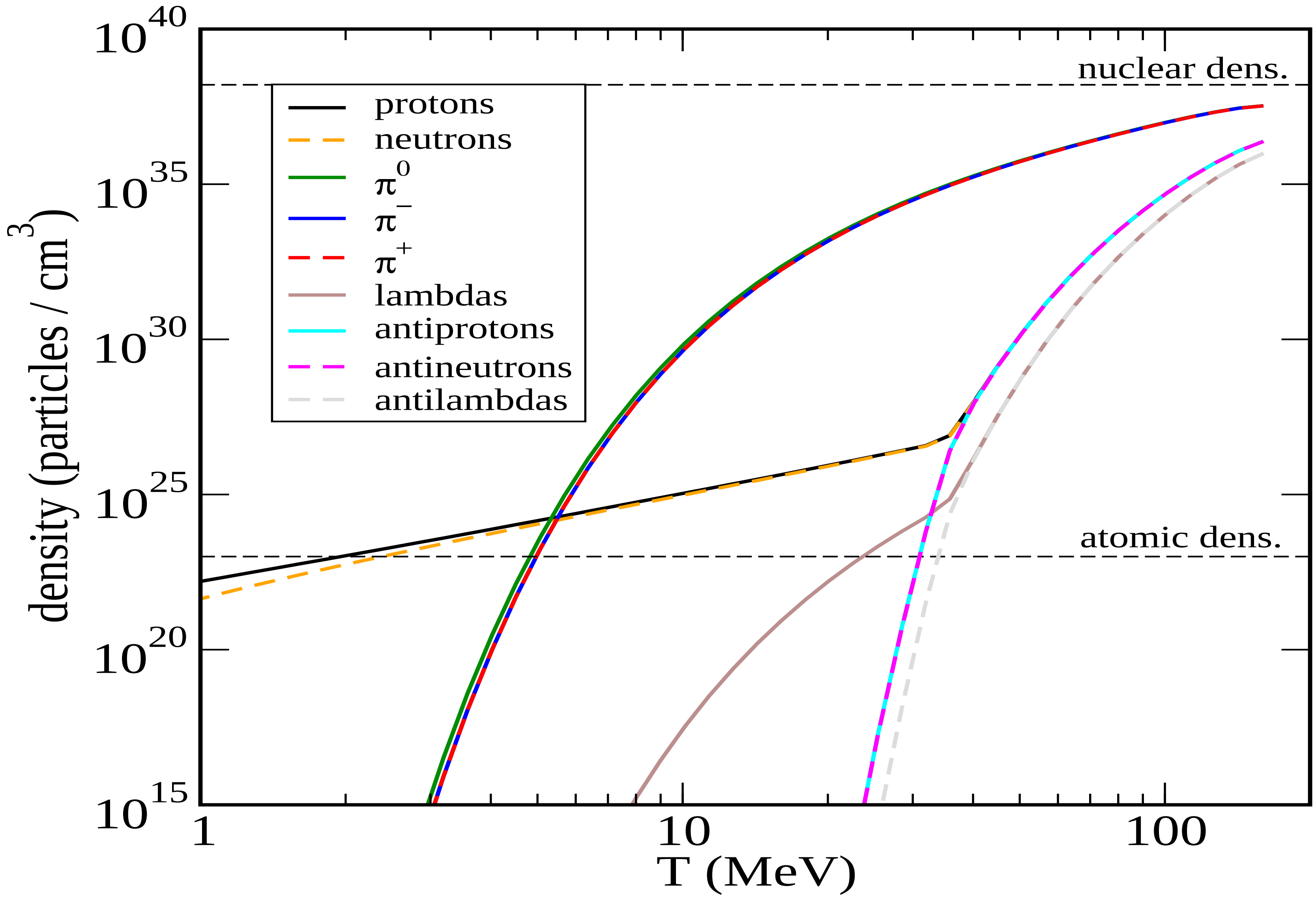
All hadrons will be present: the π^0 creates the doorway.

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.

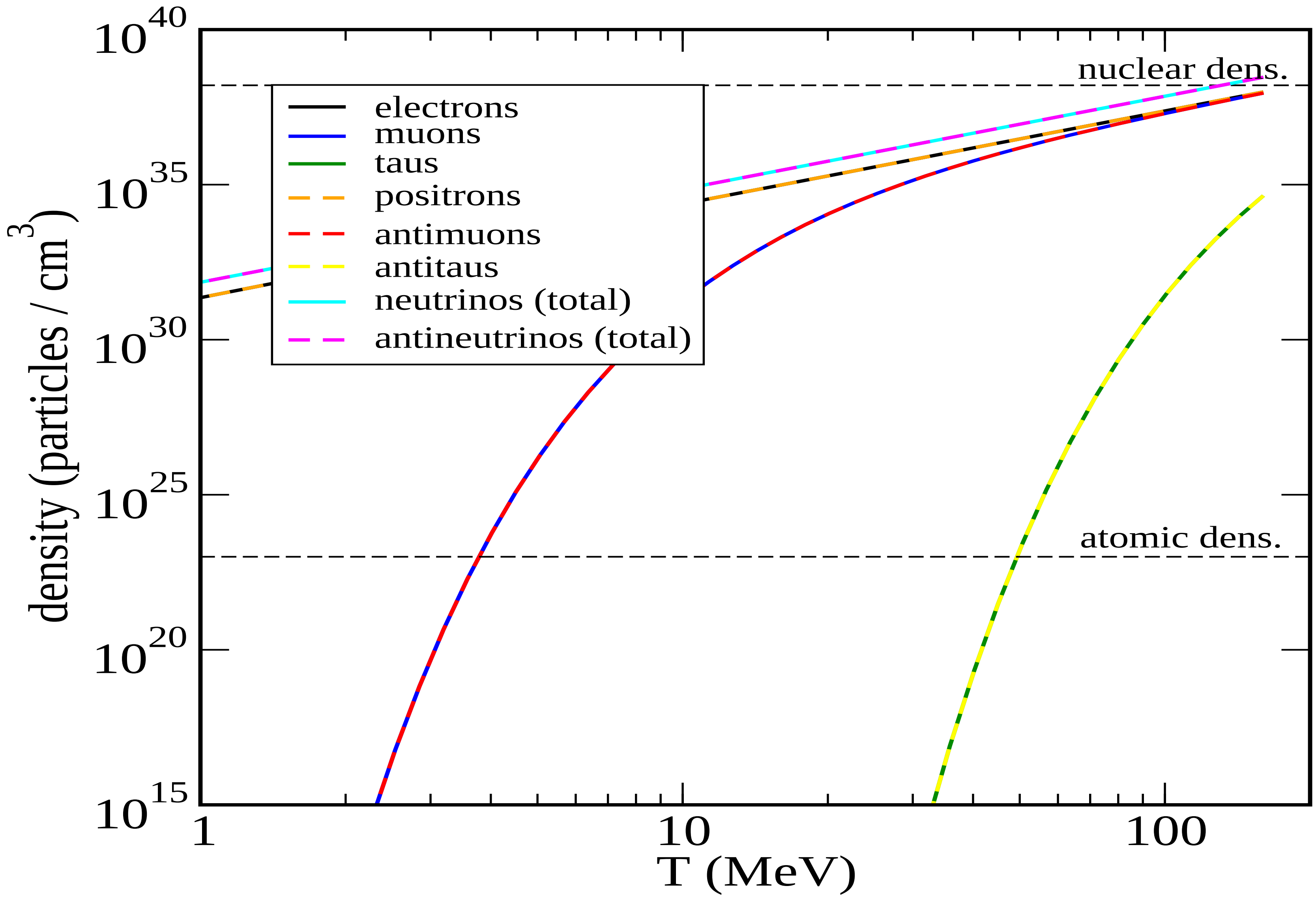


Relaxation times for dominant reactions for pion (and muon) equilibration. At small temperatures $T < 10$ MeV relaxation times for $\mu^{\pm}$ and $\pi^{\pm}$ equilibration becomes constant and much below Universe expansion rate and τ_T (dotted turquoise line on right).

Hadronic Universe Hadron Densities



Universe Lepton Densities



Did we learn anything useful?

- **We have a pretty good view how the Universe looks when it was less then 0.1 s old.**
- **Is there global homogeneity? Probably not, but domains – may also relate to kinks from the ElectroWeak transformation. Much more work is needed, we laid first foundation stone for this.**
- **Strangeness in a significant abundance down to $T = 10$ MeV, potential for production of strange nuclearites**
- **Pretty big mess between neutrino decoupling and e^+e^- annihilation, with small abundance of hadrons falling out of equilibrium, another opportunity for new physics such as ΔN_ν formation.**
- **More speculative: Hadronic Universe with huge hadron collision rate persistent on one second scale, potential for CP violation to take hold.....**