Hadronization of the Quark Universe

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[I] Probing the Universe with Heavy Ions

[II] Recreating the early Universe in the laboratory

Energy to matter: the (al)chemy of particle production:

Use as a diagnostic tool of QGP formation

[III] Hadronization of the Quark Universe

(i) Scale of Universe hadronization time

(ii) Formation of (visible) matter

(iii) Chemical potentials in the early Universe

(iv) Baryon to photon ratio, mixed phase

(v) Particle populations in the early Universe

[IV] Inhomogeneous Matter-Antimatter Universe?

(i) Distillation process

(ii) Mass (a)symmetry?

[V] Final Remarks

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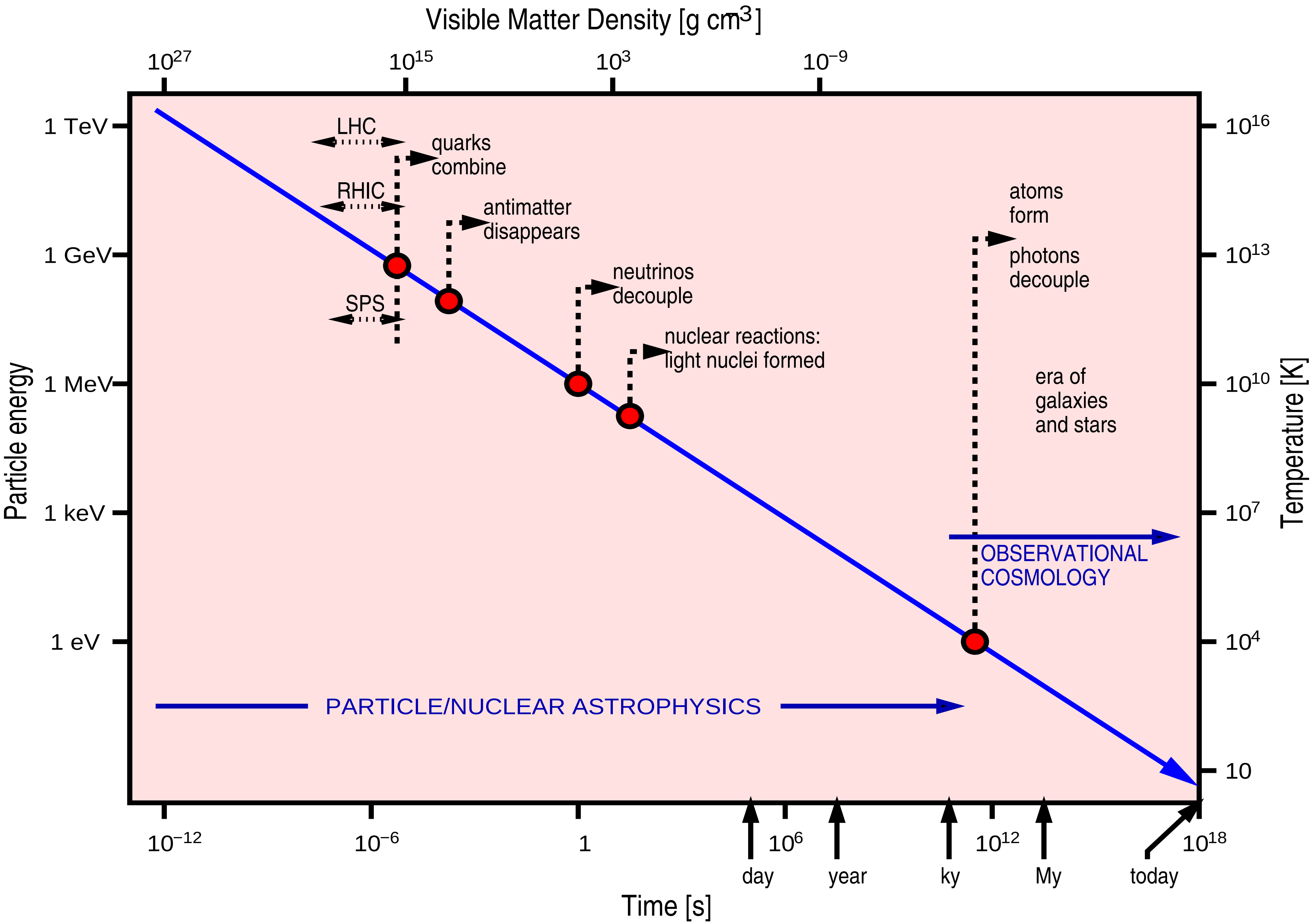
Stages in the evolution of the Universe



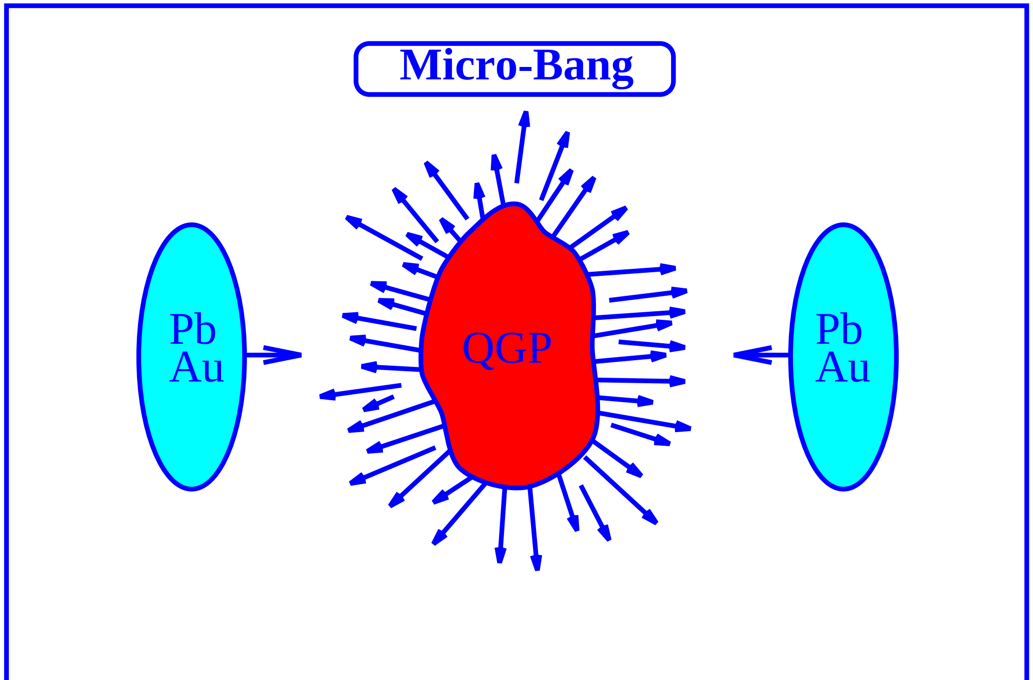
The study of hadronic particle production in relativistic heavy ion collision experiments at SPS, RHIC, LHC provides the knowledge required to develop the understanding of the physics of the Universe at the time period

THE VISIBLE MATTER AS WE KNOW IT HAS BEEN FORMED

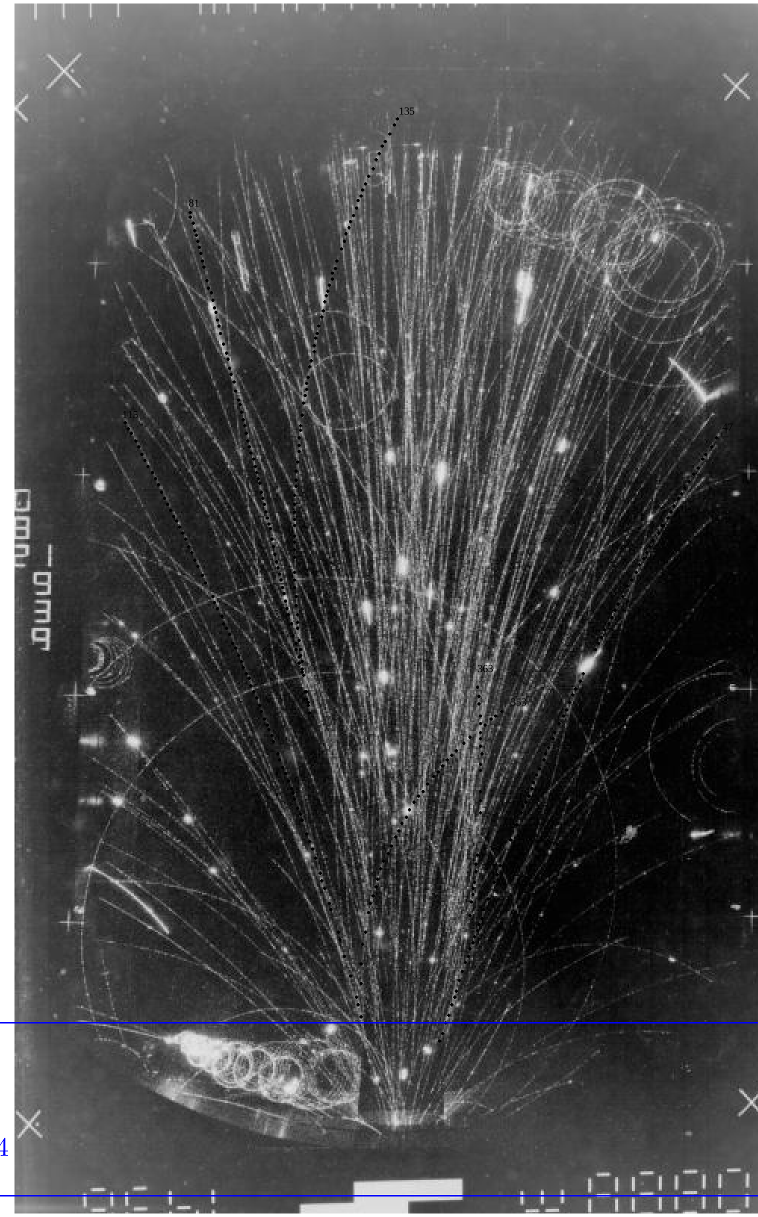
In the process

- **we discover a new state of matter, the QUARK-GLUON PLASMA.**
- **We learn about mechanisms how energy turns into particles WHEN MATTER, ANTIMATTER AND MESON are formed**
- **we learn about the period of STRANGENESS AND ANTIMATTER DISAPPEARANCE. Little is known today about this relatively long lasting phase of the Universe evolution in which the Universe cools down by two orders of magnitude.**

II RECREATING THE EARLY UNIVERSE IN LABORATORY



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

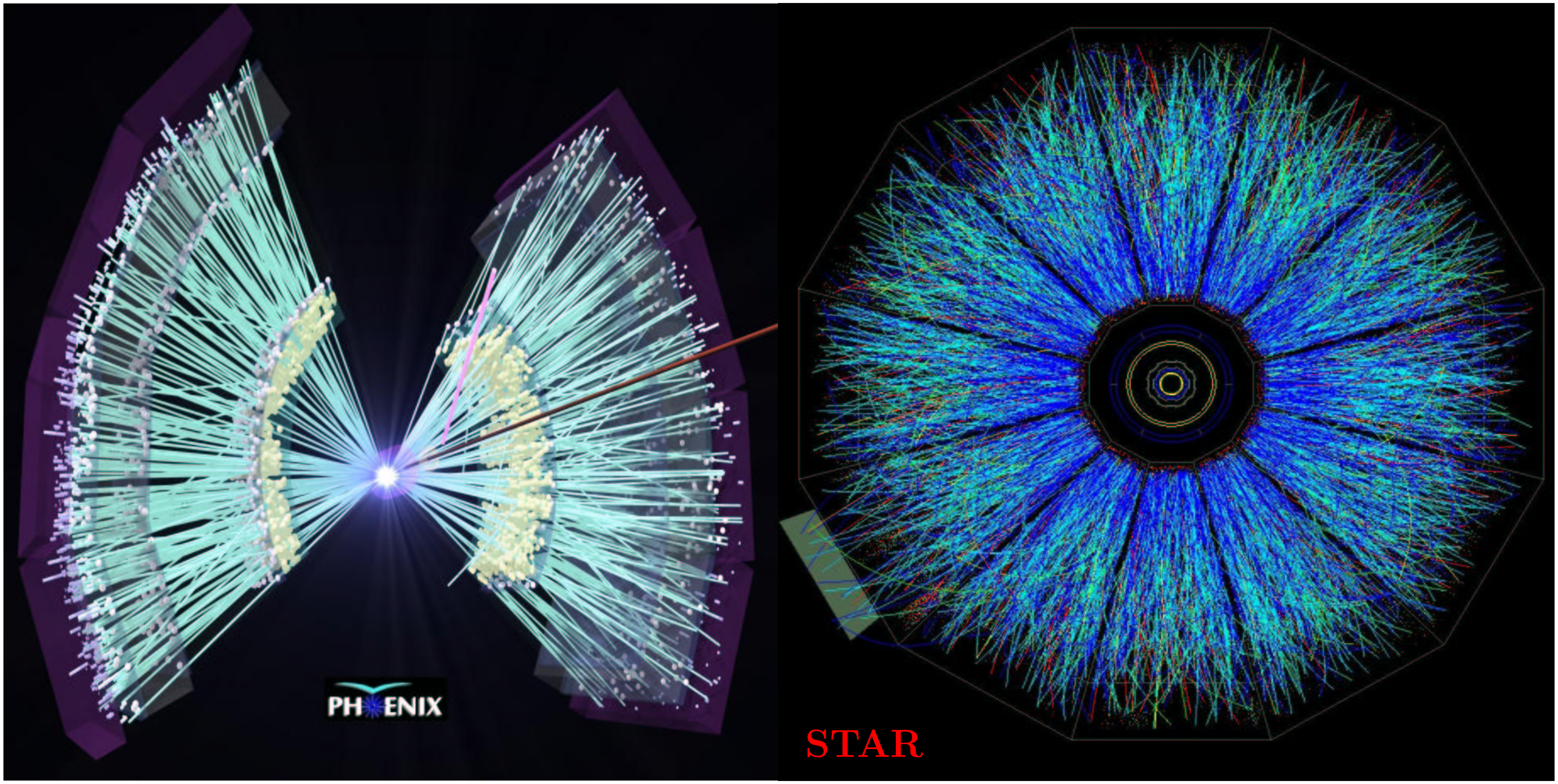


S–Ag Reaction at 200AGeV (by NA35)

Order of Magnitude

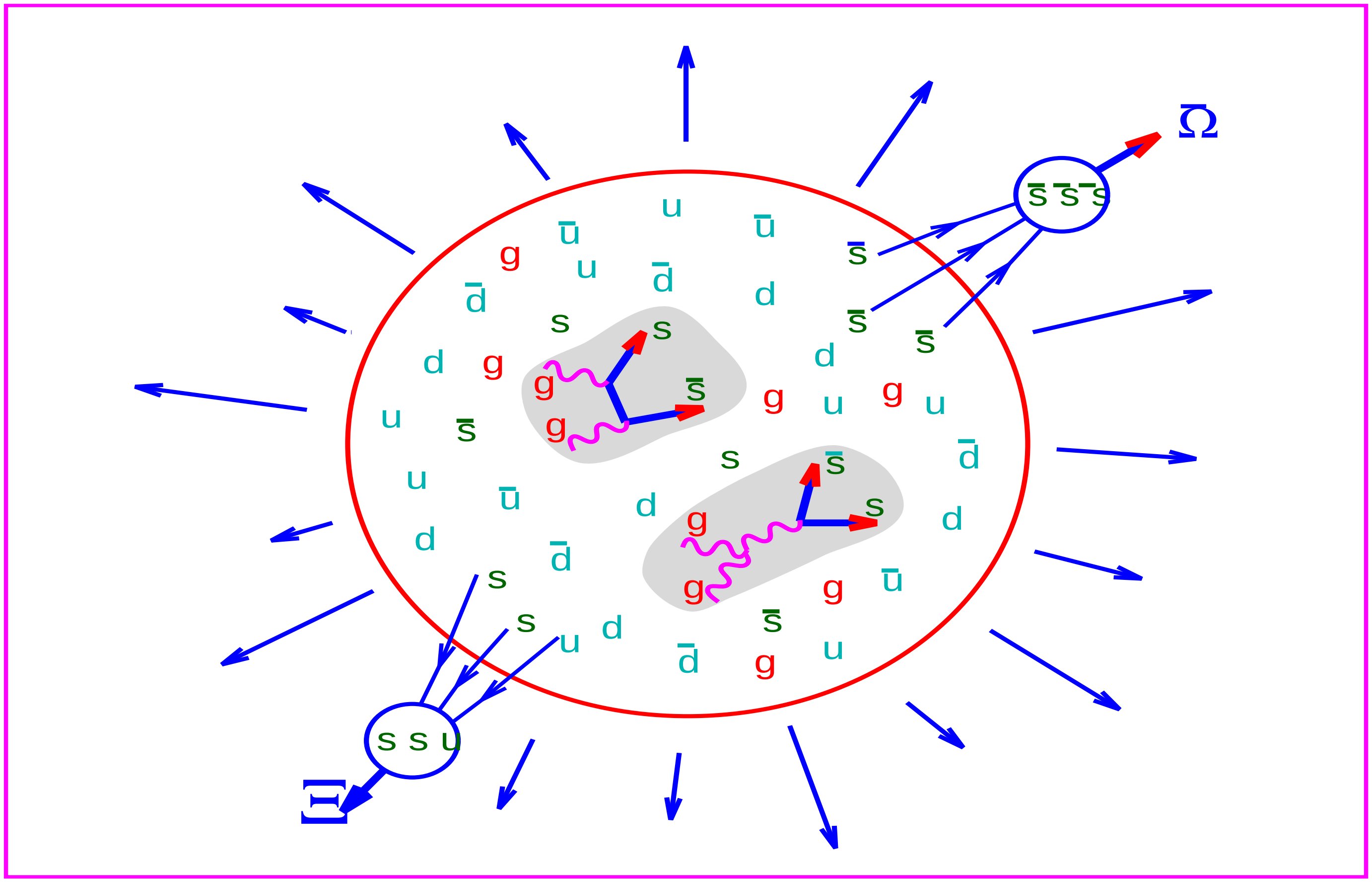
ENERGY density	ϵ	$\simeq 1$–**5GeV/fm**^{3} $= 1.8$–$9\ 10^{15}$**g/cc**
Latent vacuum heat	B	$\simeq 0.1$–**0.4GeV/fm**^{3} $\simeq (166$–$234\text{MeV})^4$
PRESSURE	P	$= \frac{1}{3}\epsilon = 0.52\ 10^{30}$ **barn**
TEMPERATURE	T_0, T_f	**300–250, 175–145 MeV;** **300MeV$\simeq$3.5** 10^{12}**K**

THE EARLY UNIVERSE AT RHIC



. . . and BRAHMS, PHOBOS: How is this maze of tracks of newly produced particles telling us what we want to know about the early Universe and its properties?
Study of patterns in particle production: correlations, new flavors (strangeness, charm), resonances, etc..

(Al)chemy of particle production



Hadron formation from a drop of deconfined matter which filled the early Universe

Expect creation of complex rarely seen (multi, strange, anti-) particles enabled by available populations of particles (strange quarks etc) made in independent microscopic reactions.

Strangeness: a popular laboratory QGP diagnostic tool

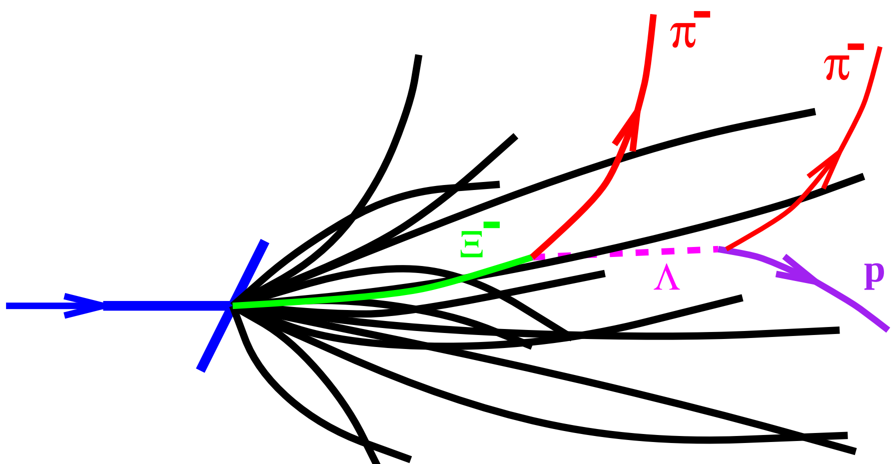
EXPERIMENTAL REASONS

- **There are many strange particles allowing to study different physics questions $(q = u, d)$:**

$$\phi(s\bar{s}), \quad K(q\bar{s}), \quad \overline{K}(\bar{q}s), \quad \Lambda(qqs), \quad \overline{\Lambda}(\bar{q}\bar{q}\bar{s}),$$

$$\Xi(qss), \quad \overline{\Xi}(\bar{q}\bar{s}\bar{s}), \quad \Omega(sss), \quad \overline{\Omega}(\bar{s}\bar{s}\bar{s}) \quad \ldots\textbf{resonances}\ldots$$

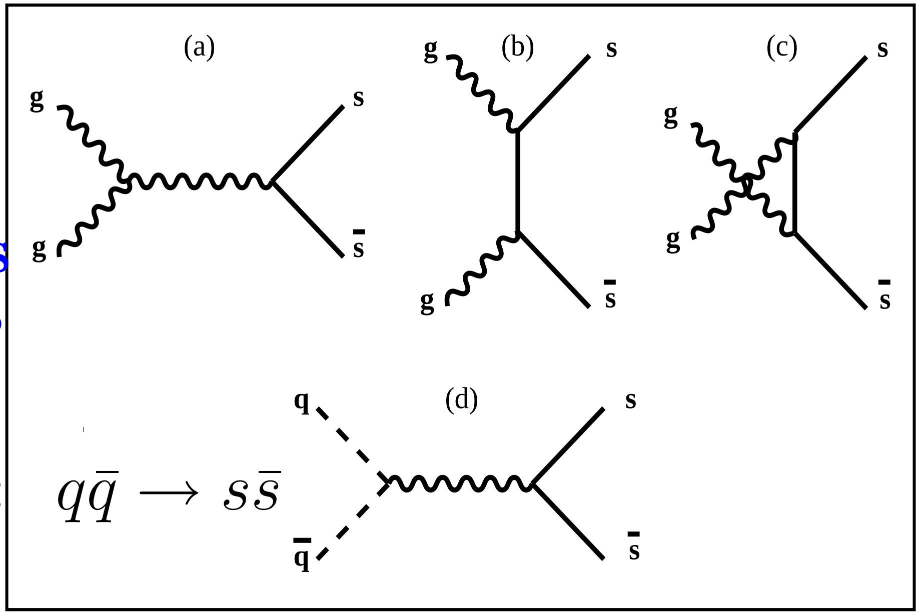
- **Strange hadrons are subject to a self analyzing decay within a few cm from the point of production;**



- **Production rates hence statistical significance is high;**

THEORETICAL CONSIDERATIONS

- **production of strangeness in gluon fusion** $\boxed{GG \to s\bar{s}}$
  strangeness linked to gluons from QGP;



dominant processes:

$$GG \to s\bar{s}$$

abundant strangeness
=evidence for gluons

10–15% of total rate:

- **coincidence of scales:**

$$\boxed{m_s \simeq T_c} \to \boxed{\tau_s \simeq \tau_{\rm QGP}} \to$$

strangeness a clock for QGP phase

- $\boxed{\bar{s} \simeq \bar{q}} \to$ **strange antibaryon enhancement**
  at RHIC (anti)hyperon dominance of (anti)baryons.

III Hadronization of the Quark Universe

What we know:

Upon QGP hadronization in the early Universe there is as much matter as antimatter (to within 10^{-9}). This symmetry diminishes progressively during the annihilation period.

Questions and Issues

- **Chemical conditions in the early Universe (chemical potentials, equilibria)**
- **Mechanisms and conditions at hadronization (conflict of Gibbs conditions with superselection rules such as charge conservation/neutrality)**
- **When do antinucleons, strangeness, pions disappear (chemical nonequilibrium in hadron phase)?**
- **How much antimatter remains in the homogeneous/non-homogeneous Universe?**
- **What happens to the Universe during matter-antimatter annihilation? Very Large Scale Structure formation?**
- **Influence on nucleosynthesis epoch?**

Time scale in Universe hadronization

The expanding Universe cools, the hot quark-gluon plasma freezes into individual hadrons. In laboratory we do this suddenly, in the early Universe slowly as seen on time scale of strong interactions.

STRONG INTERACTIONS TIME CONSTANT:
Nucleon size / light velocity$\simeq 10^{-23}$**s**

UNIVERSE HADRONIZATION TIME CONSTANT:

$$\tau_{\rm U} = \sqrt{\frac{3c^2}{32\pi G\mathcal{B}}} = 36\,\mu\mathbf{s}\,\sqrt{\frac{\mathcal{B}_0}{\mathcal{B}}}, \qquad \mathcal{B}_0 = 0.19\,\frac{\mathbf{GeV}}{\mathbf{fm}^3}$$

Naively, $4\mathcal{B}$ **is energy density inside particles like protons, and is the amount of energy required per unit of volume to deconfine quarks.**

10–50 μs Hadronization Timescale in the Universe

Universe has two components: luminous matter ϵ_l and at this early time scale probably still a small 'cold' dark matter ϵ_d energy density component. The pressure is all due the luminous component: $P = P_l$.

Einstein Equations: $\mathcal{R}_{\mu\nu} - \frac{1}{2}g_{\mu\nu}\mathcal{R} = 8\pi G T_{\mu\nu}$ comprise two dynamical equations for the size scale $R(t)$ of the Robertson-Walker metric:

$$ds^2 = g^{\mu\nu}dx_\mu dx_\nu = dt^2 - R^2\left[\frac{dr}{1-kr^2} + r^2 d\theta^2 + r^2\sin^2\theta d\phi^2\right]:$$

1. **Consider $T^{\mu\nu}{}_{;\nu} = 0$, describing entropy conserving expansion:**

$$dE + P\,dV = T\,dS = 0, \quad dE = d(\epsilon V), \qquad \frac{dV}{V} = \frac{3\,dR}{R}, \qquad \frac{3dR}{R} = -\frac{d\epsilon}{\epsilon+P}.$$

NOTE: for $\epsilon = \epsilon_l + \epsilon_d$ and $\epsilon_d \simeq \epsilon_d^0/R^3$ (cold dark matter) this reduces to exactly

$$\frac{3dR}{R} = -\frac{d\epsilon_l}{\epsilon_l+P} \quad \textbf{keep in mind} \quad P_d \ll P_l.$$

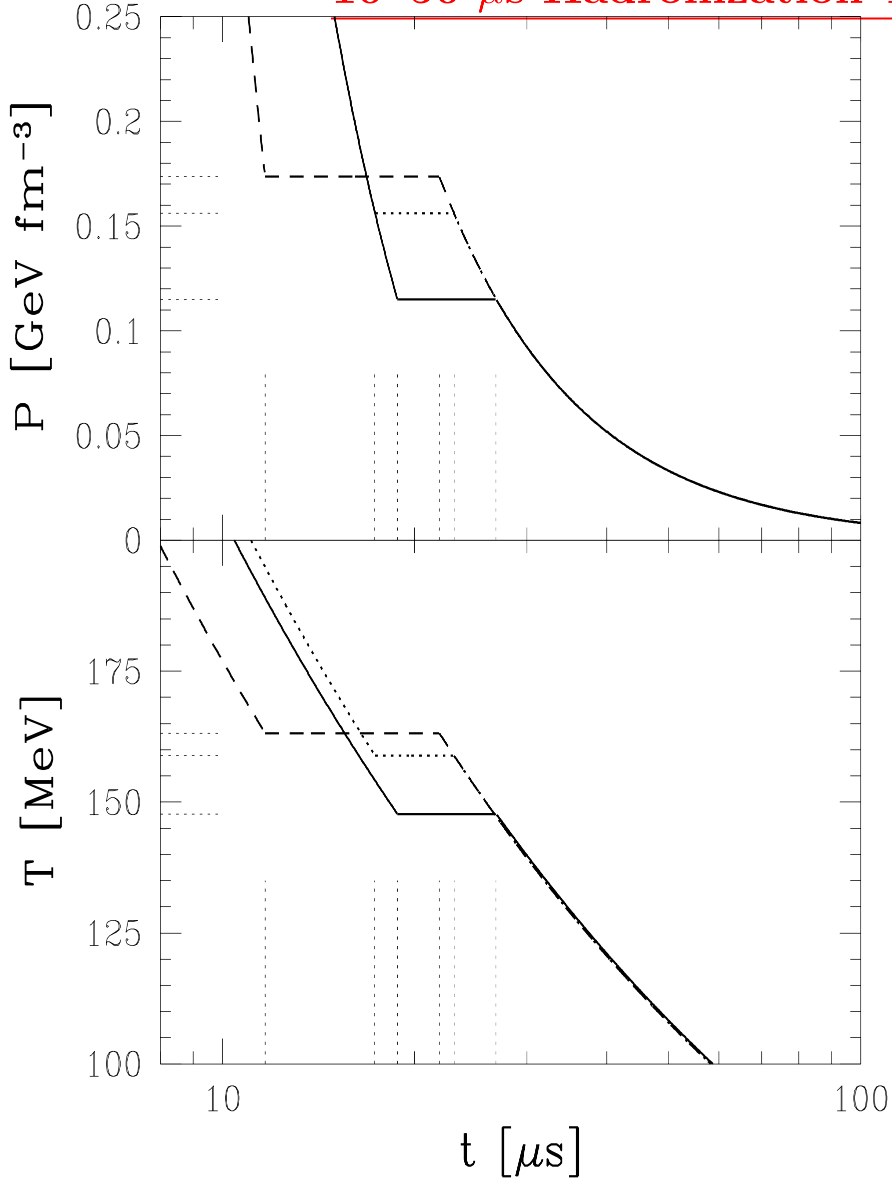
2. **We use the 0-0 component of Einstein equations**

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

In a flat $(k = 0)$ Robertson-Walker Universe we find exactly:

$$\dot{\epsilon_l}^2 = 24\pi G\,(\epsilon_l + \epsilon_d)\,(\epsilon_l + P)^2, \qquad P = (\epsilon_l - 4\mathcal{B})/3 + P_d$$

10–50 μs Hadronization Timescale in the Universe



When dark component is insignificant:

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

and by matching at a given pressure we find the magnitude of the time the Universe inflates through the mixed hadron phase.

Pressure (upper) and temperature (lower part) in the Universe, as function of time, in the vicinity of the phase transition from the deconfined phase to the confined phase. Solid lines, $\mathcal{B}^{1/4} = 195$ MeV; dotted lines, $\mathcal{B}^{1/4} = 170$ MeV (lower part) and $\mathcal{B}^{1/4} = 220$ MeV (upper part) all for $\alpha_s = 0.6$ (reduces the active quark-gluon degrees of freedom).

Production of Matter of our Era

Our objective is to understand the chemical conditions at the emergence of matter as we know it today in the early Universe period at hadronization of quark-gluon plasma. This establishes the initial particle densities which can be followed to the end of the hadron gas era.

Quantitative Tasks

1) Identify the chemical conservation laws constraining potentials $\mu(T)$ and the pertinent conservation laws;

2) Trace out chemical potentials as function of temperature, which itself we can study separately as function of time (see above) – this separation is convenient given the lack of knowledge about dark matter;

3) Evaluate the chemical (particle) flavor composition of the Universe during evolution toward the condition of neutrino decoupling at

$$T \simeq 1\,\mathbf{MeV} \qquad t \simeq 10\,s$$

4) Explore the quark-hadron phase transformation dynamics, and establish potential for conserved quantum (baryon, electrical charge) number distillation;

CHEMICAL POTENTIALS IN THE UNIVERSE

The slow hadronization of the Universe implies chemical equilibrium is reached for all hadronic reactions (phase space occupancy saturated), and there is full participation of electromagnetically interacting photon and lepton degrees of freedom.

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

- **Whenever chemical and thermal equilibrium is attained, reactions such as $f + \bar{f} \rightleftharpoons 2\gamma$ are allowed, (here f and $\bar{f}$ are a fermion – antifermion pair), hence:** $\mu_f = -\mu_{\bar{f}}$

- **Minimization of the Gibbs free energy implies that for any reaction $\nu_i A_i = 0$, where ν_i are the reaction equation coefficients of the chemical species A_i, chemical equilibrium arises for the condition:** $\nu_i \mu_i = 0$

- **Example: weak interaction reactions lead to:** $\mu_s = \mu_d = \mu_u + \Delta\mu_l$

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

- **For the "large mixing angle" solution the neutrino oscillations $\nu_e \rightleftharpoons \nu_\mu \rightleftharpoons \nu_\tau$ imply that:** $\mu_{\nu_e} = \mu_{\nu_\mu} = \mu_{\nu_\tau} \equiv \mu_\nu$
  note that the mixing is accelerated in 'dense' matter.

PROCEDURE:

There are three chemical potentials which are 'free' and we choose to follow: μ_d**,** μ_e**, and** μ_ν**.**
(we need physical observables to fix these values)

Quark chemical potentials are convenient to characterize the particle abundances 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:

$$\mu_b \equiv \frac{\mu_P + \mu_N}{2} = 3\,\frac{\mu_d + \mu_u}{2} = 3\mu_d - \frac{3}{2}\Delta\mu_l = 3\mu_d - \frac{3}{2}(\mu_e - \mu_\nu).$$

Chemical Conditions

The three chemical potentials not constrained by chemical reactions are obtained from the physical constraints:

i. *Local electrical charge neutrality* **($Q = 0$):**

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

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

ii. *Net lepton number equals net baryon number* **($L = B$):**

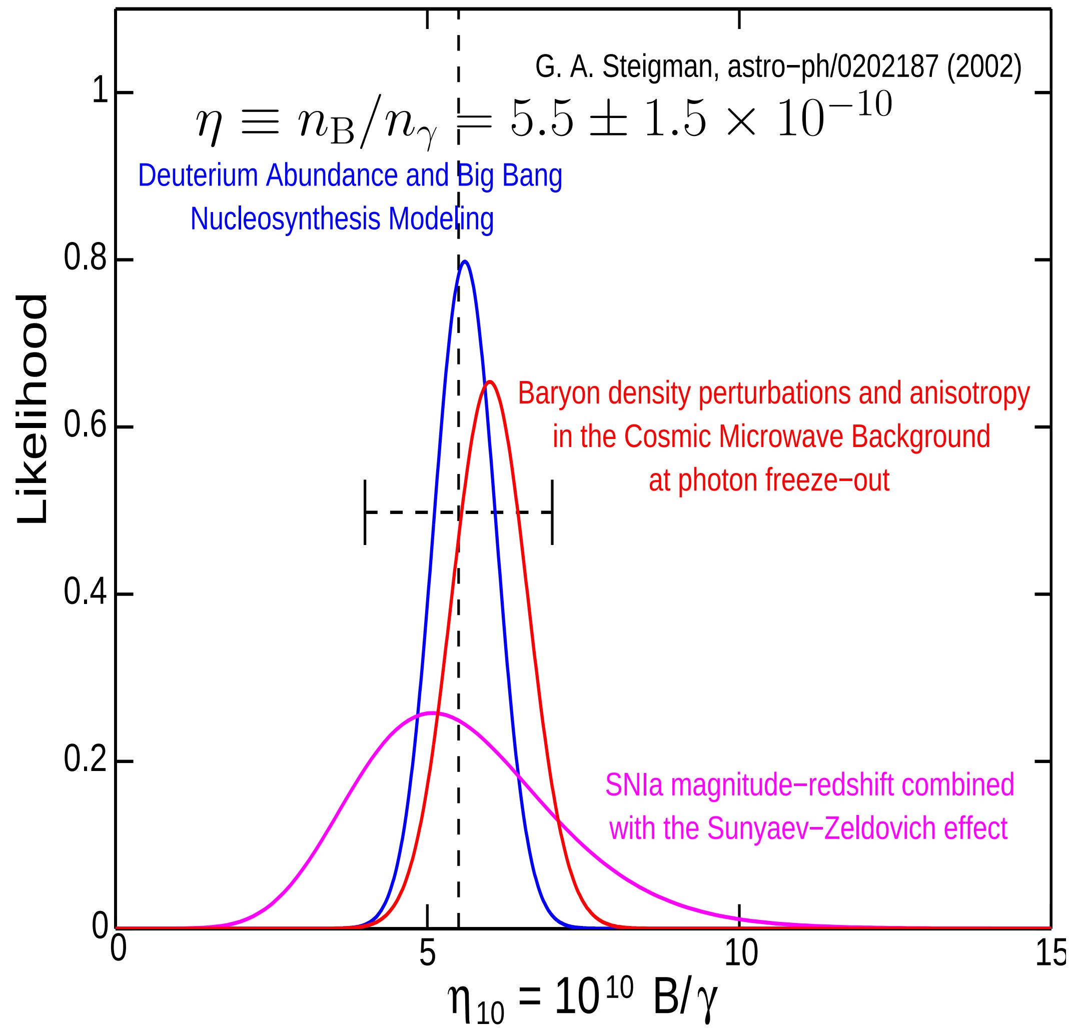
$$n_L - n_B \equiv \sum_i (L_i - B_i)\, n_i(\mu_i, T) = 0,$$

(standard condition in baryo-genesis models, generalization to finite $B - L$ easily possible)

iii. Universe evolves adiabatically i.e. at *constant in time entropy-per-baryon S/B*

$$\frac{\sigma}{n_B} \equiv \frac{\sum_i \sigma_i(\mu_i, T)}{\sum_i B_i\, n_i(\mu_i, T)} = 1.3 \pm 0.1 \times 10^{10} \;\Longleftarrow\; \textit{how do we know this?}$$

Baryon to photon ratio in the Universe



Revised by W-MAP: $\eta = 6.1^{+0.3}_{-0.2} \times 10^{-10}$**;**

This yields entropy per baryon: $\frac{S}{n_{\rm B}} = \frac{S}{n_\gamma}\frac{n_\gamma}{n_{\rm B}} = \frac{8.0}{\eta} = 1.3 \pm 0.1\; 10^{10}$

$(S_\gamma + S_\nu + S_i)/n_\gamma$ **is evaluated using stat.mech. and remembering** e^+e^- **reheating of photons.**

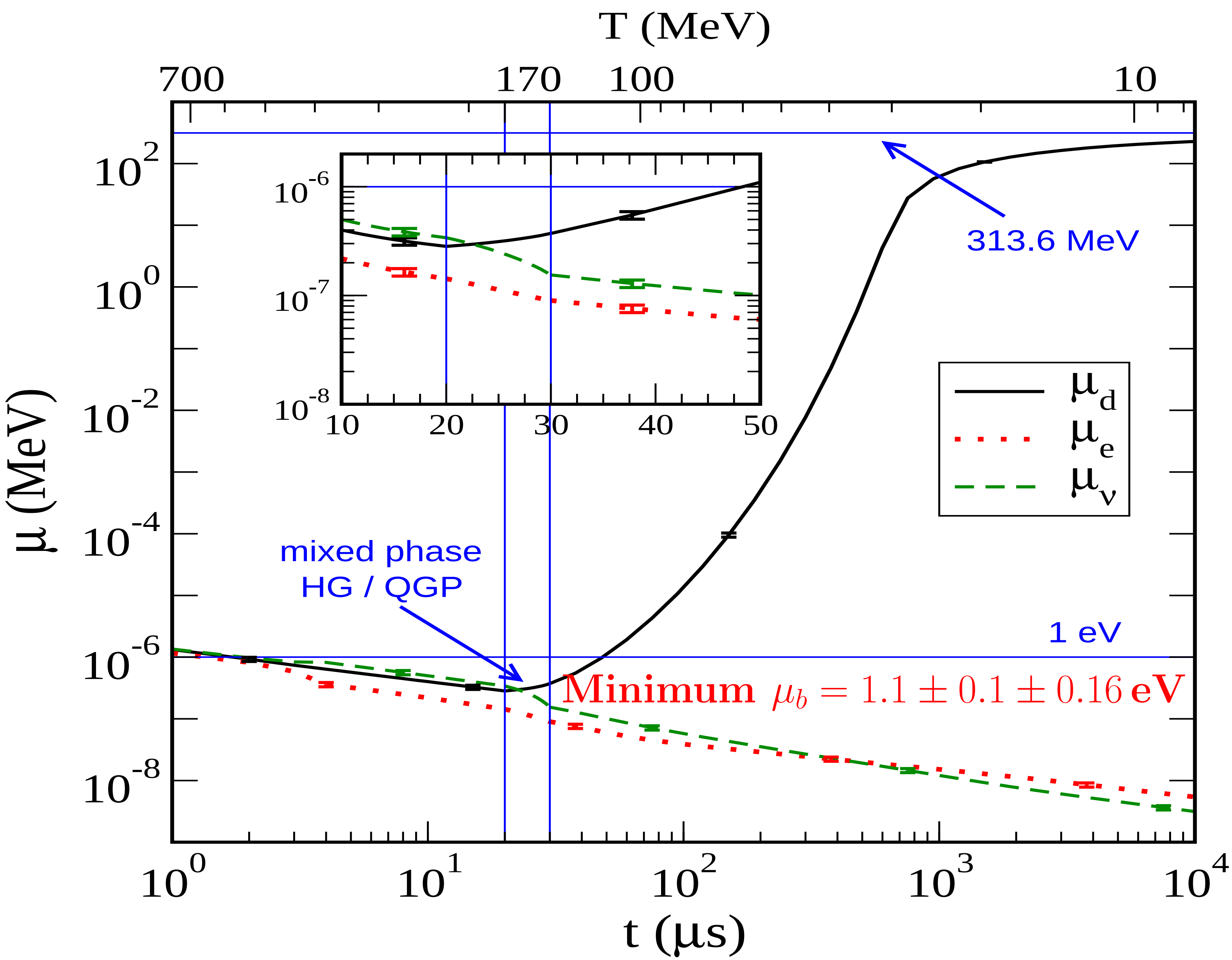
Mixed Phase at Phase Transformation

Mixed phase partition function for the SLOW phase transformation period:

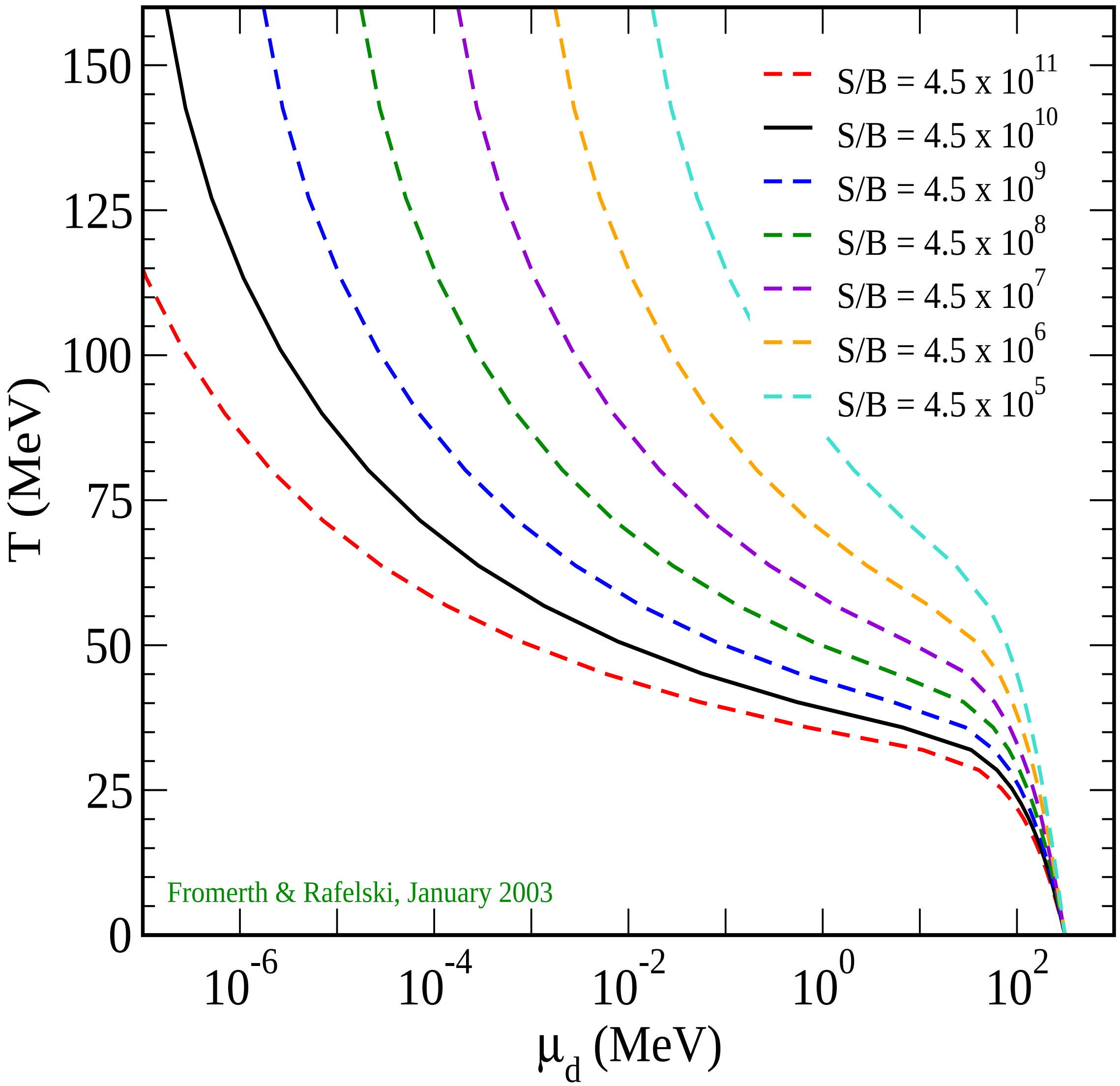
$$\ln Z_{\rm tot} = \frac{V_{\rm HG}}{V_{\rm tot}} \ln Z_{\rm HG} + \frac{V_{\rm QGP}}{V_{\rm tot}} \ln Z_{\rm QGP} \qquad V_{\rm tot} = V_{\rm HG} + V_{\rm QGP}$$

At QGP hadronization there is in general unequal conserved quantum number density in QGP and in hadron gas (HG) phases.

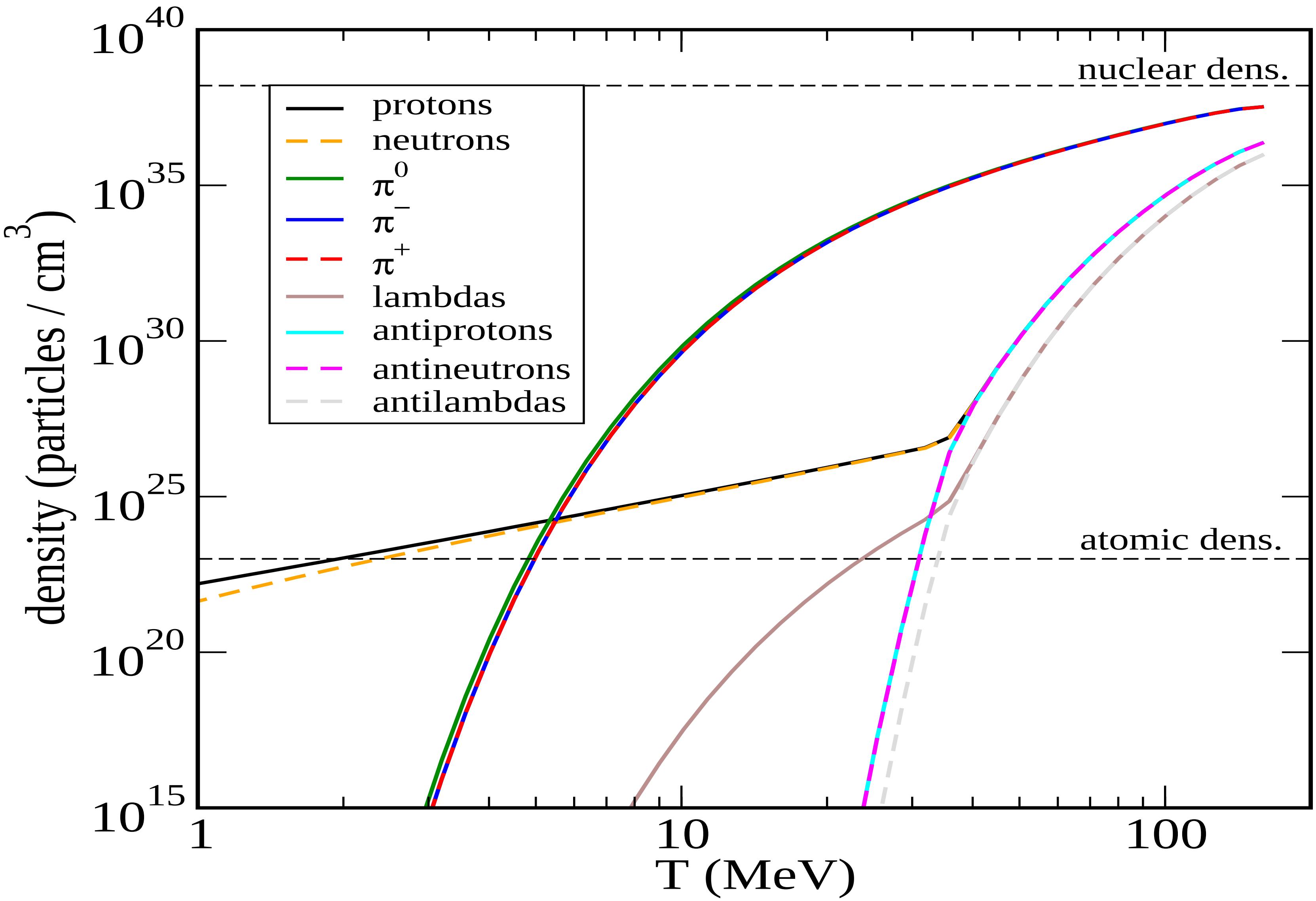
TRACING μ_d IN THE UNIVERSE



TRACING μ_d IN A UNIVERSE

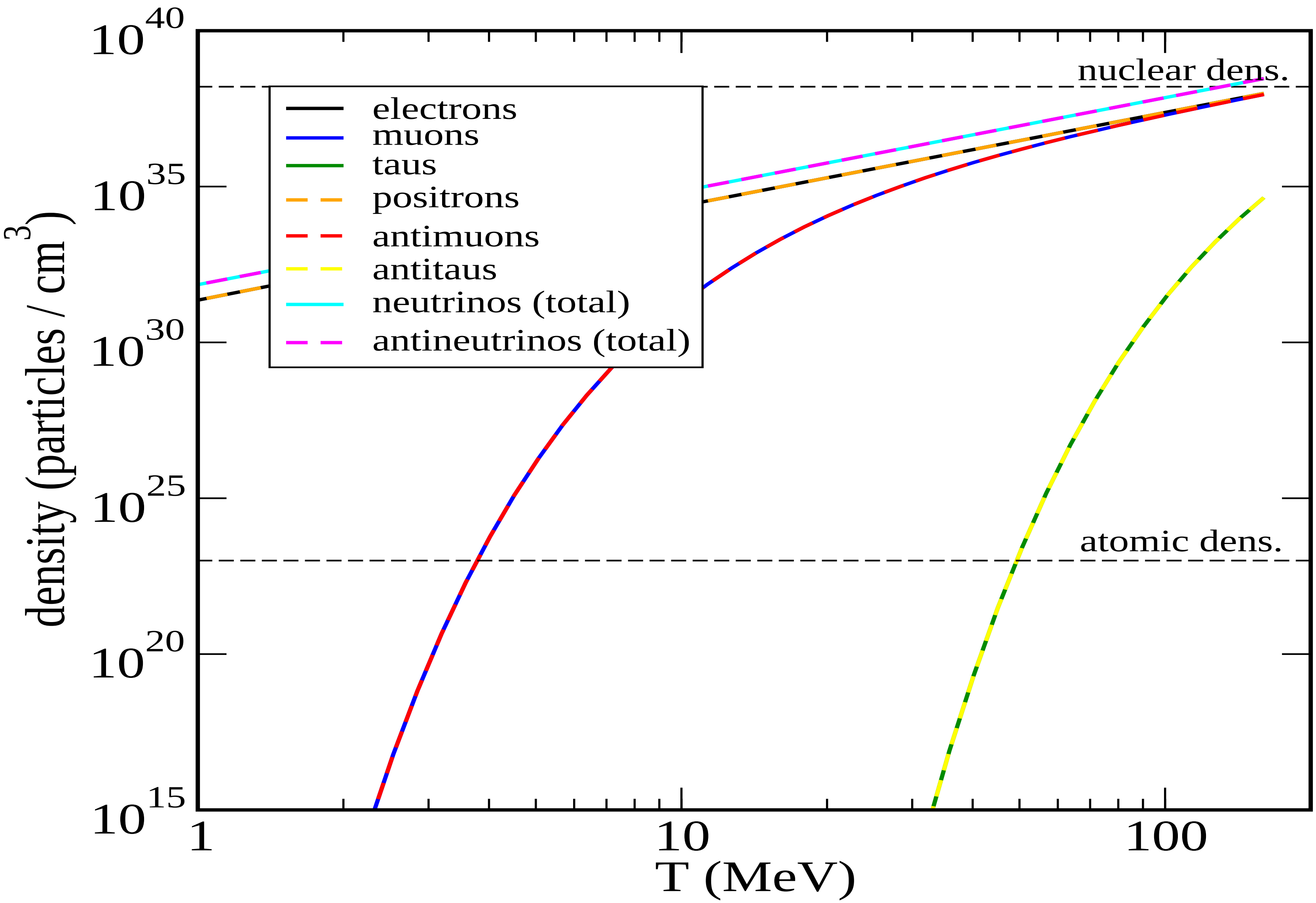


Hadronic Particle Densities

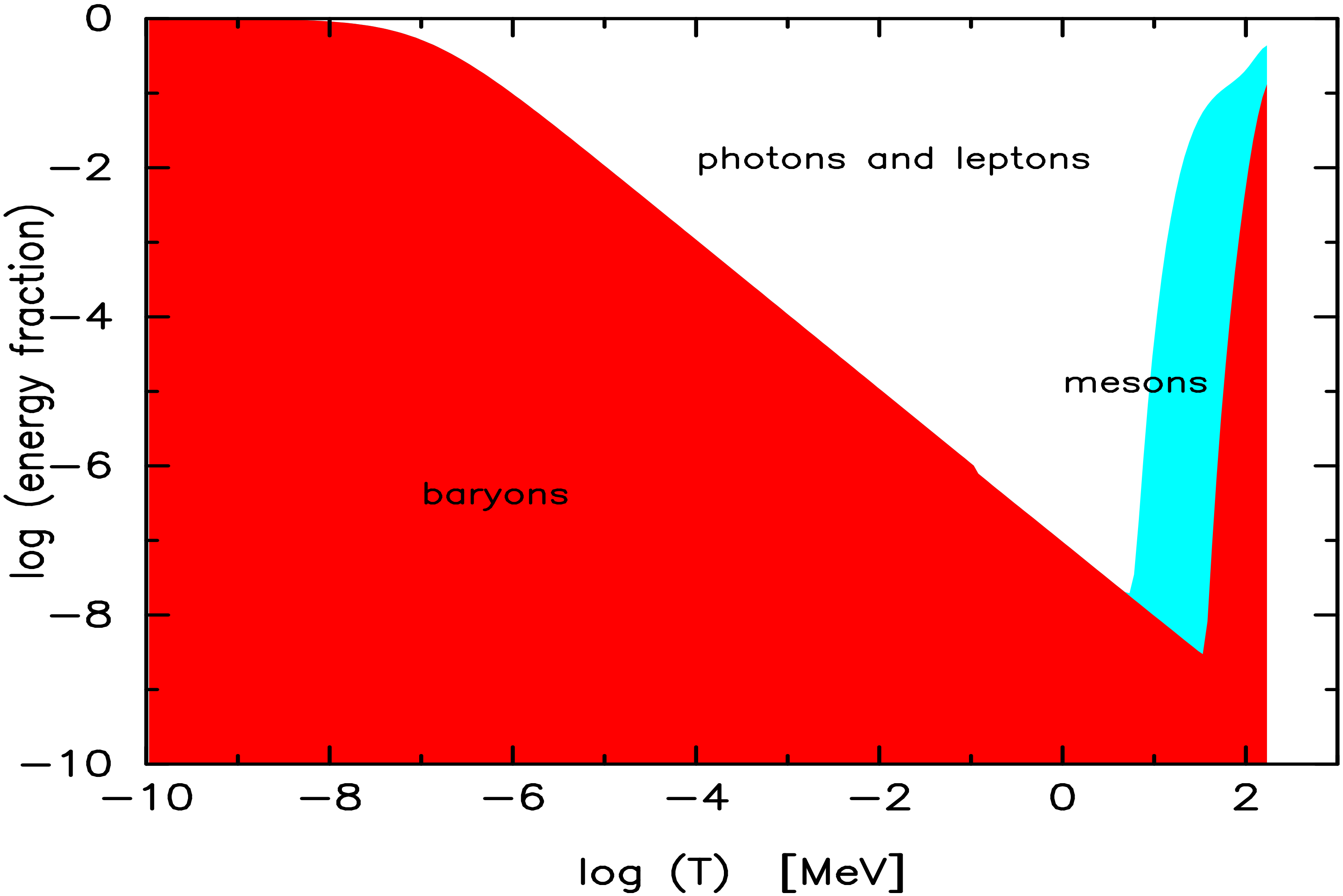


Note the baryon freeze-out at $T \simeq 37$ MeV and that pion density remains at baryon density down to $T \simeq 4.5$ MeV

Lepton Densities



Energy in luminous hadronic Universe



Dark Matter dilutes by factor 6 the role of luminous matter:

The Universe is matter dominated at hadron phase transition, and since decoupling of radiation from matter.

Thoughts about inhomogeneous Universe

The hadron Universe emerging from quark-gluon plasma hadronization is initially nearly matter-antimatter symmetric. The baryon asymmetry is at most $\simeq 10^{-9}$ and perhaps zero if the Universe were today inhomogeneous, divided into huge domains filled with matter and antimatter, respectively. Such separation of phases requires distillation processes which must operate on a time scale comparable to the age of the EARLY Universe. These would compete with the annihilation of matter with antimatter, which otherwise proceeds while the temperature drops from the phase transition value of $\simeq 160$–170 MeV toward a few MeV.

A mechanism which could drive separation of phases in mixed phase: at a given chemical condition both the baryon and charge density are different in the quark-gluon plasma and hadron gas phases. This was noticed by Witten in his 1984 paper, and exploited by A. Olinto for generation of current and thus magnetic field in the Universe. As matter of principle any baryon-antibaryon separation requires a CP-violating force, distillation will only enhance a preexisting asymmetry.

Distillation Process–Separation of Phases

Mixed phase partition function for the SLOW phase transformation period:

$$\ln Z_{\mathrm{tot}} = \frac{V_{\mathrm{HG}}}{V_{\mathrm{tot}}} \ln Z_{\mathrm{HG}} + \frac{V_{\mathrm{QGP}}}{V_{\mathrm{tot}}} \ln Z_{\mathrm{QGP}} \qquad V_{\mathrm{tot}} = V_{\mathrm{HG}} + V_{\mathrm{QGP}}$$

At QGP hadronization there is in general unequal conserved quantum number (e.g. charge) density in QGP and in hadron gas (HG) phases.

The constraints are accordingly, e.g. for charge:

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

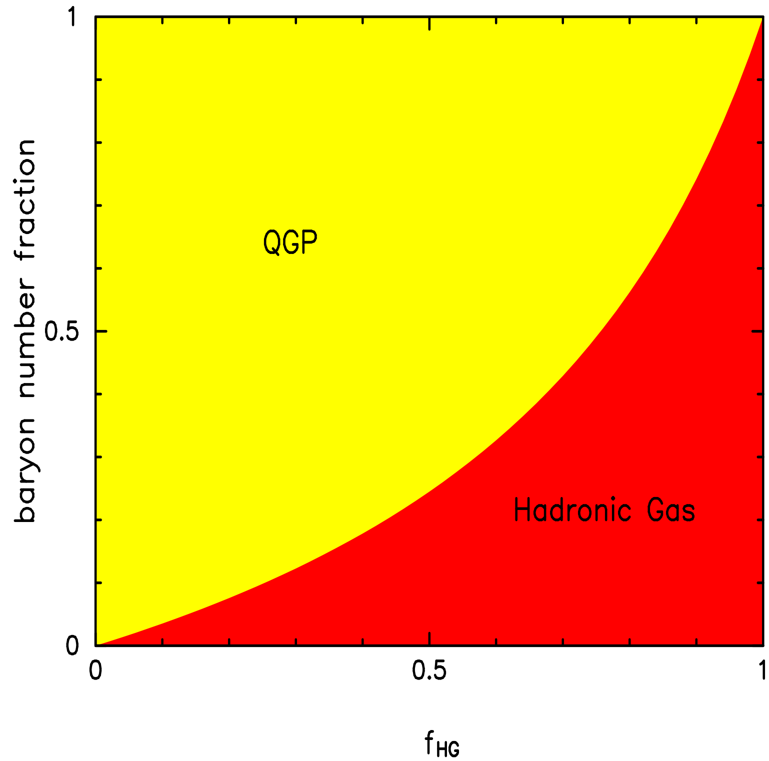
$f_{\mathrm{HG}} \equiv V_{\mathrm{HG}}/V_{\mathrm{tot}}$ **is the fraction of space belonging to HG phase. Analogous expressions considered for** $L - B$ **and** S/B**.**

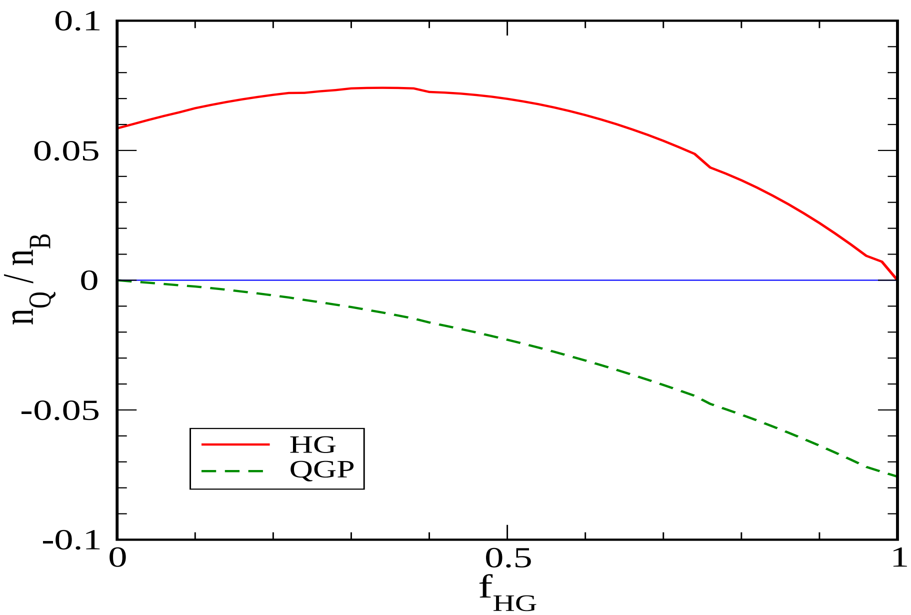
Note: Mixed phase lasts $\simeq 10\,\mu s$ **(25% of prior lifespan), assume that** f_{HG} **changes linearly in time. Actual values will require dynamic nucleation and transport theory description of the phase transformation.**

Charge (and baryon number) asymmetry 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 the SUM of charges in both fractions. Charge in each fraction can be and is non-zero.





Even a small charge separation between phases introduces a finite non-zero local Coulomb potential and this amplifies any existent baryon asymmetry (protons vs antiprotons).

Strangeness distillation mechanism proposed for RHIC has the same physical origin, but there is no time to build mixed phase. In the early Universe where there is time for weak interaction decay, electrical current can arise, and can lead to spontaneous generation of magnetic fields.

FINAL REMARKS

Theoretical study of the early Universe beginning at $t = 10\,\mu s$ is possible

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We have control of: chemical potentials, particle abundances,

but not of phase transition dynamics

Strangeness in early Universe under study

Distillation of baryon number in domains of the Universe a possibility

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We begin to transfer the 'know-how' from the study of nuclear collisions to the study of the early Universe

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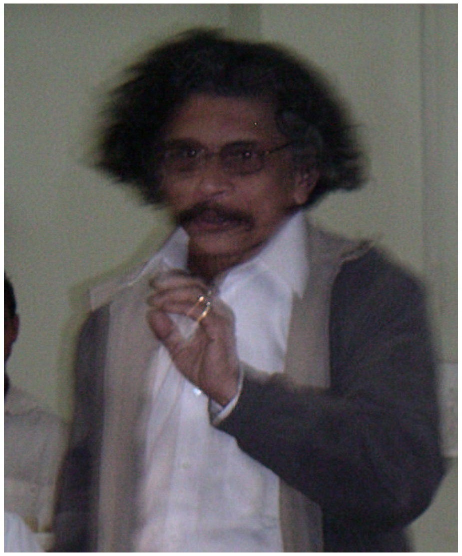

I thank the dynamic CINPP meeting chairman, Prof. Dipak Ghosh for introducing me to the celebrated Jadavpur University, for fantastic organization of the conference, and very generous hospitality in Calcutta.