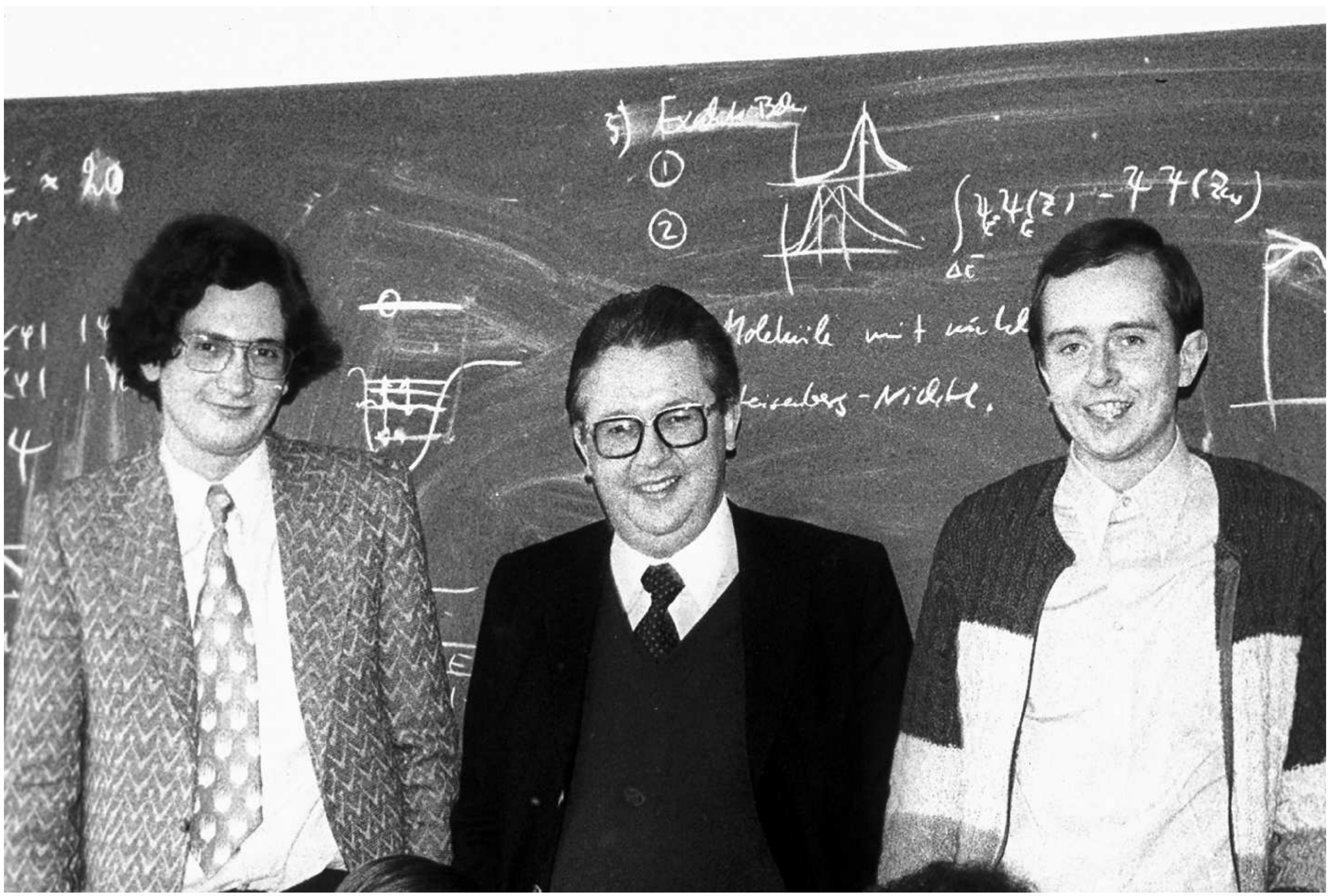
The Quark Universe

ISHIP 2006, FIAS

Three Quarks 1970

Structured Vacuum



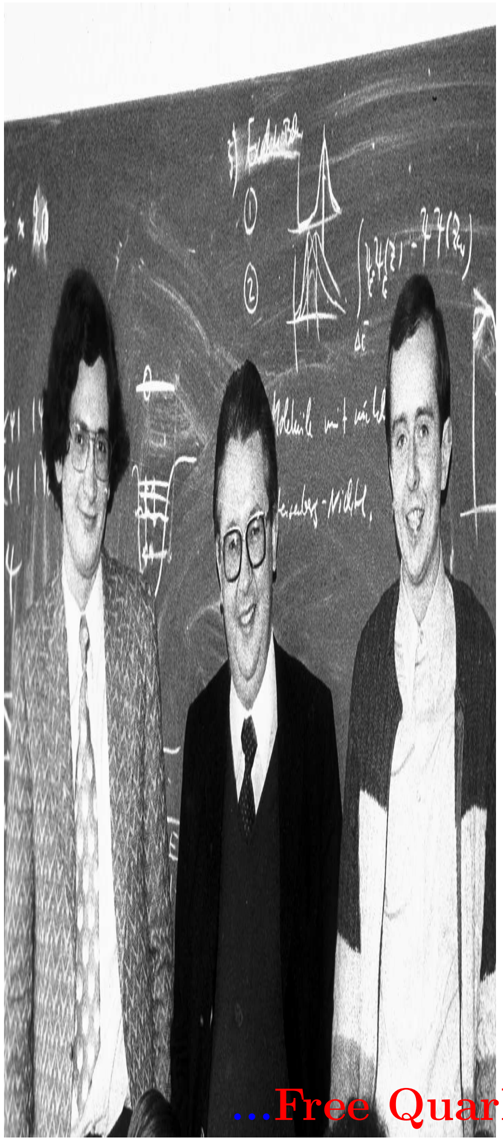
s **d** **u**

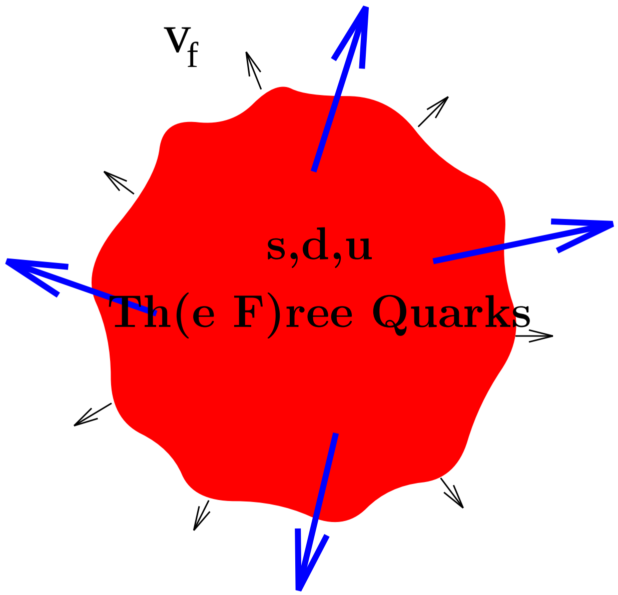
Structured Charged Vacuum

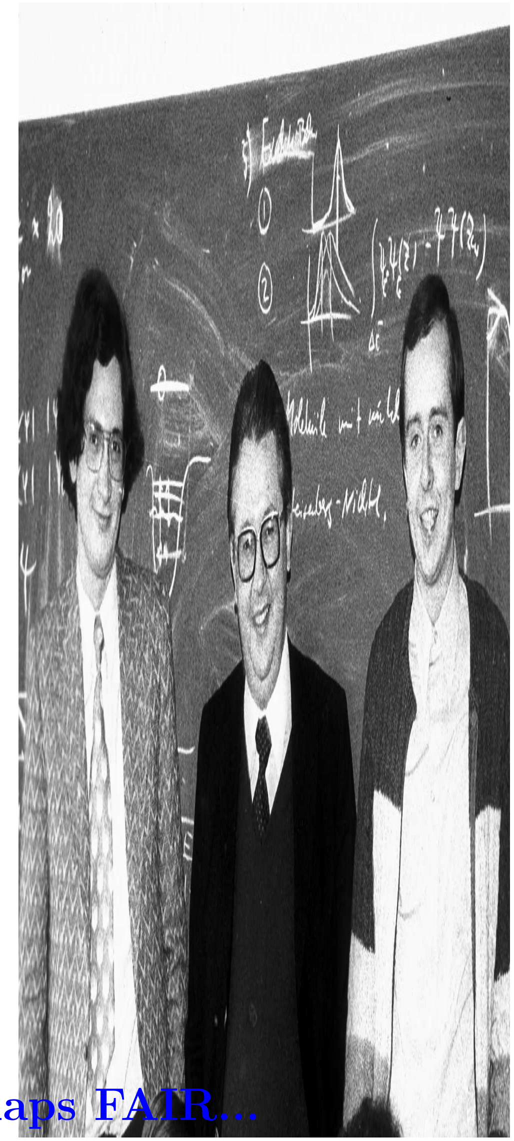
Introduced in Frankfurt by Walter Greiner and students

1. **"Superheavy Elements and an Upper Limit to the Electric Field Strength"**
   Phys. Rev. Lett. 27 (1971) 958.
2. **"Superheavy Electronic Molecules"**
   Lett. Nuovo Cimento 4 (1972) 469.
3. **"Solution of the Dirac Equation for Strong External Fields"**
   Phys. Rev. Lett. 28 (1972) 1235.
4. **"Electrons in Strong External Fields"**
   Z. Physik 257 (1972) 62.
5. **"Auto-ionization of Positrons in Heavy Ion Collisions"**
   Z. Physik 257 (1972) 188.
6. **"Electron Wave Functions in Overcritical Electrostatic Potentials"**
   Il Nuovo Cimento 18A (1973) 551.
7. **"Autoionization Spectra of Positrons in Heavy Ion Collisions"**
   Lett. Nuovo Cimento 8 (1973) 37.
8. **"Solution of the Dirac Equation with Two Coulomb Centers"**
   Phys. Lett. 47B (1973) 5.
9. **"Solution of the Dirac Equation for Scalar Potentials and its Implications in Atomic Physics"**
   Z. Naturforsch. 28a (1973) 1389.
10. **"The Charged Vacuum in Overcritical Fields"**
    Nucl. Phys. B68 (1974) 585.

Three Quarks ⟹ **Free Quarks** **⟸ Three Quarks**







...Free Quarks are found at RHIC, LHC, perhaps FAIR...

ROOTS OF RELATIVISTIC HEAVY ION COLLISION PROGRAM

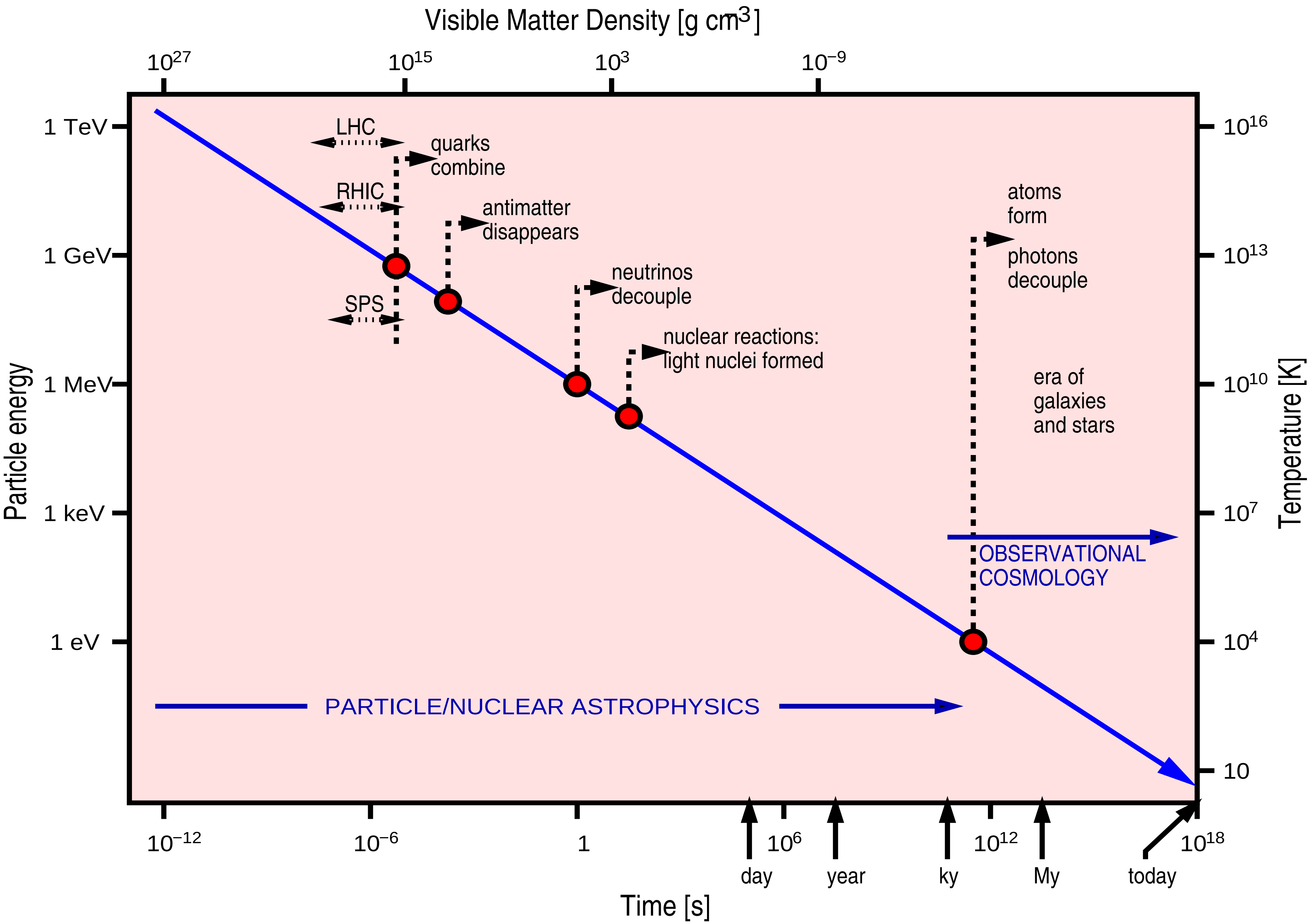
STRUCTURED VACUUM – ORIGIN OF MASS:
Melt the vacuum structure and demonstrate mobility of quarks – 'deconfinement' – vacuum state determines what fundamental laws prevail in nature. The confining vacuum state is the origin of 99.9% of the rest mass present in the Universe.

The celebrated Higgs mechanism covers the remaining 0.1% .

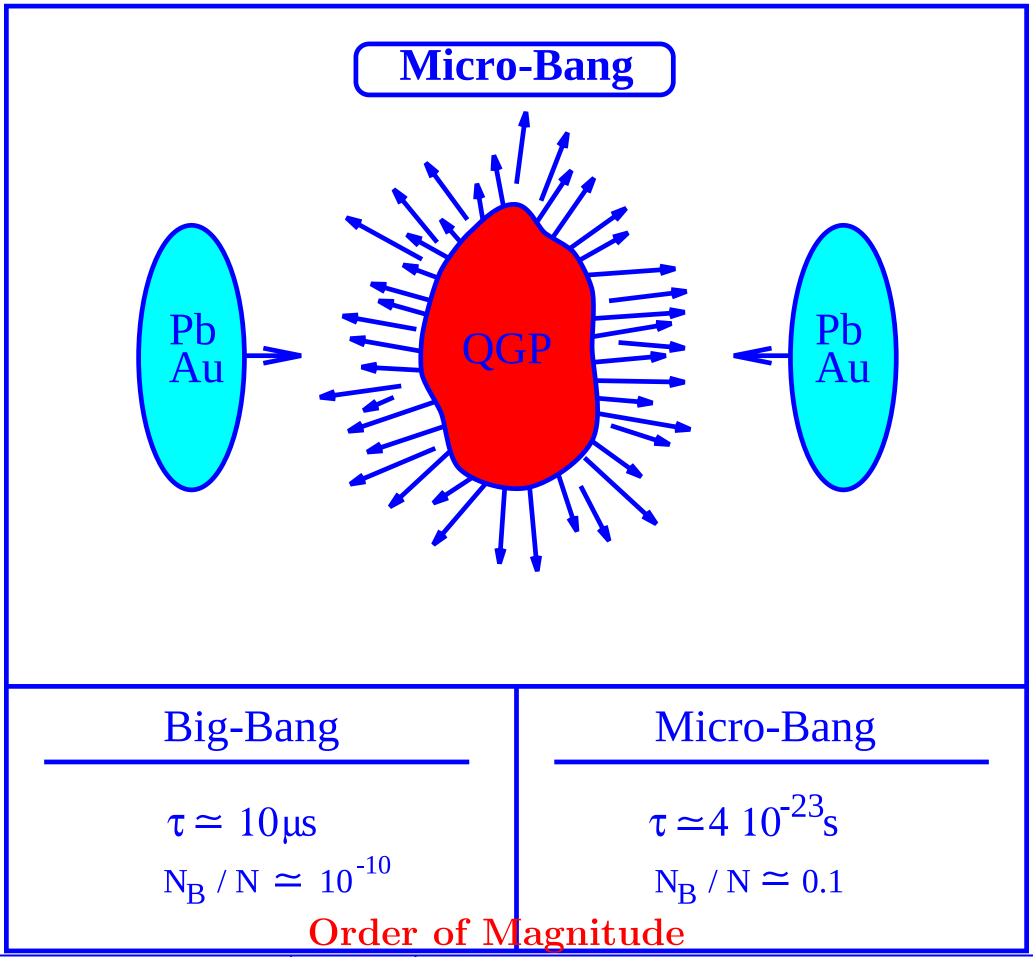
RECREATE THE EARLY UNIVERSE IN LABORATORY:
Recreate and understand the high energy density conditions prevailing in the Universe when matter formed from elementary degrees of freedom (quarks, gluons) at about 10-40 μs after big bang.

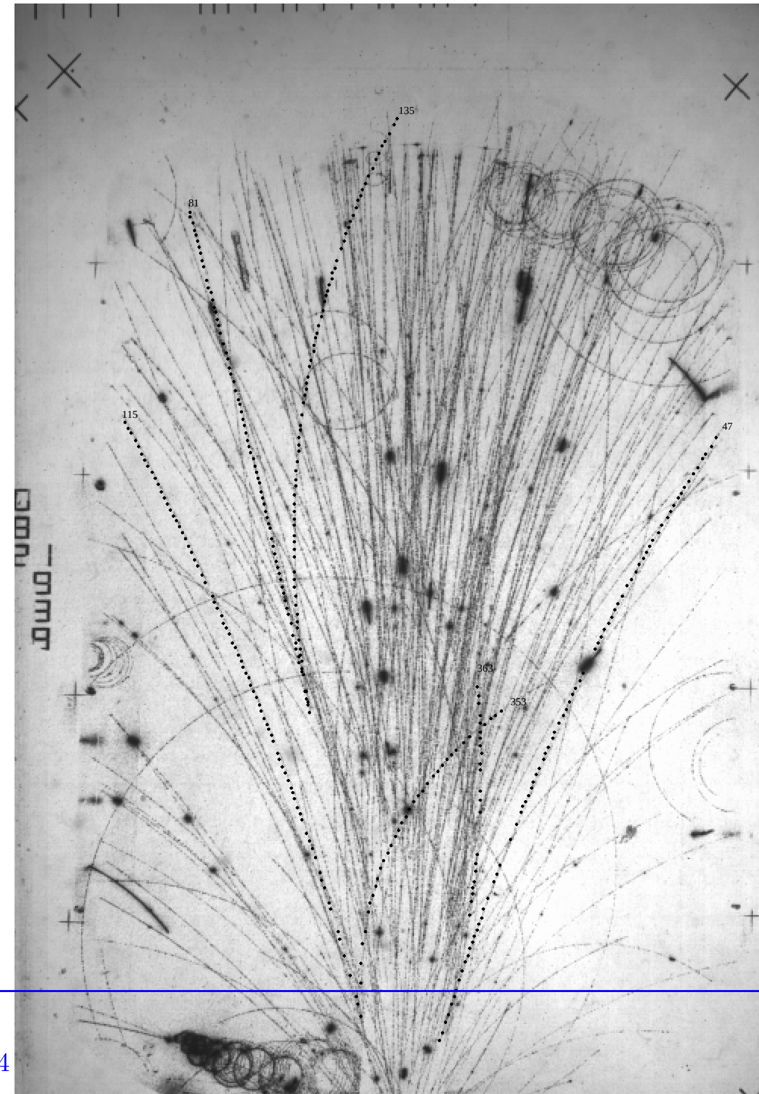
Hadronization of the Universe led to nearly matter-antimatter symmetric state, the sequel annihilation left the small 10^{-10} matter asymmetry, the world around us.

Stages in the evolution of the Universe



II RECREATING THE EARLY UNIVERSE IN LABORATORY



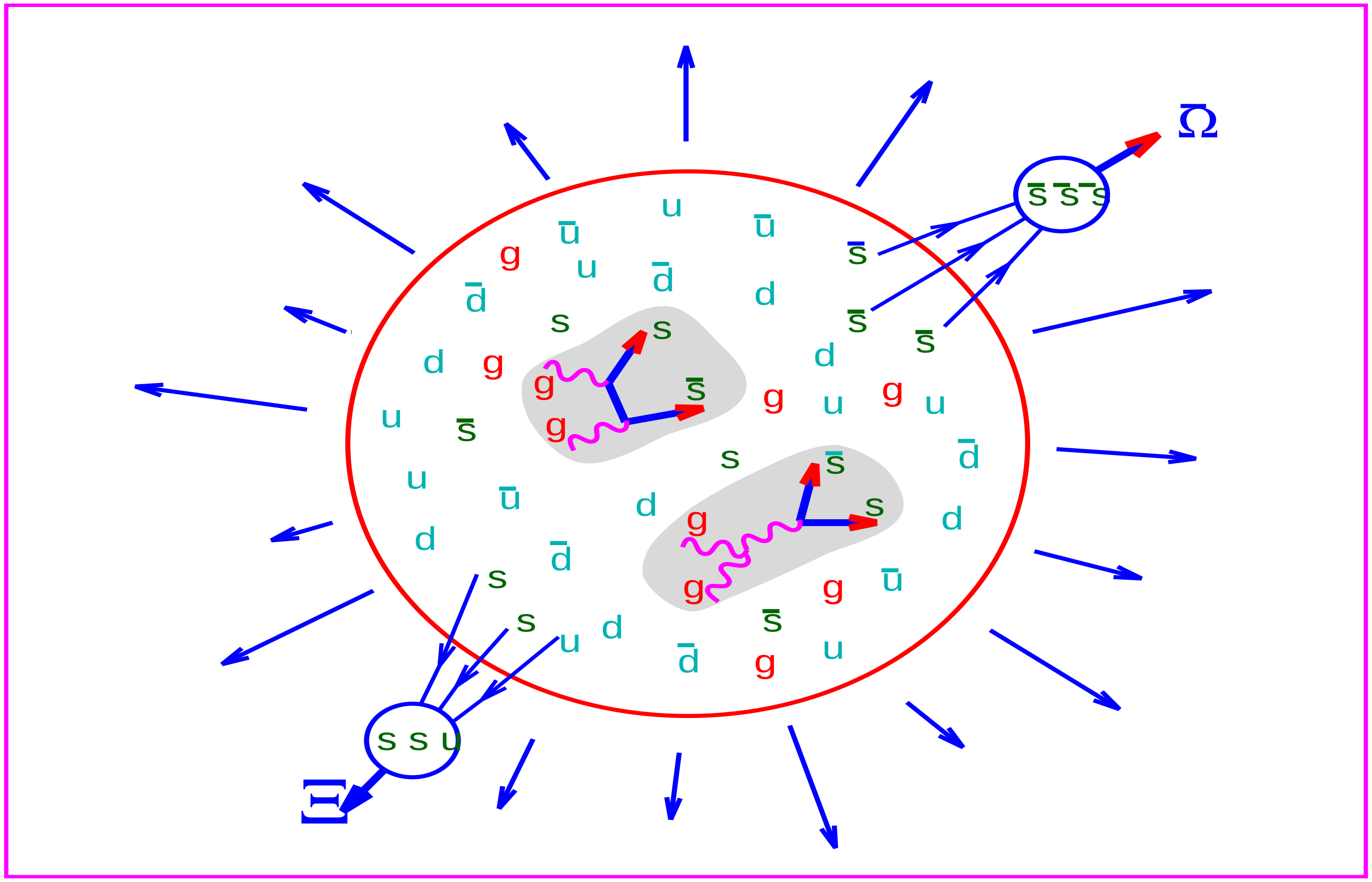


S–Ag Reaction at 200AGeV (by NA35)

Order of Magnitude

ENERGY density	ϵ	$\simeq 1$–$\mathbf{5GeV/fm^3} = 1.8$–$9\,10^{15}$**g/cc**
Latent vacuum heat	B	$\simeq 0.1$–$\mathbf{0.4GeV/fm^3} \simeq (166$–$234\mathbf{MeV})^4$
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**

(Al)chemy of particle production



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

Expect creation of complex rarely seen exotic flavor composition (multi, strange, charm, bottom anti-) particles enabled by available populations of (anti) quarks preformed in independent microscopic reactions.

SIGNATURE OF DECONFINEMENT

Strangeness is a popular QGP diagnostic tool

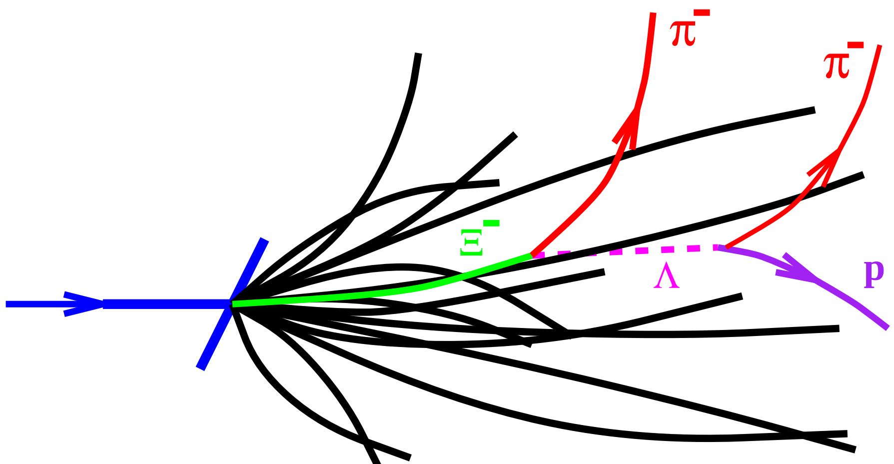
GENERAL REASONS

- **There are many strange particles** $(q = u, d)$**:**

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

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

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



- **Strong interaction high production rates.**

THEORETICAL CONSIDERATIONS

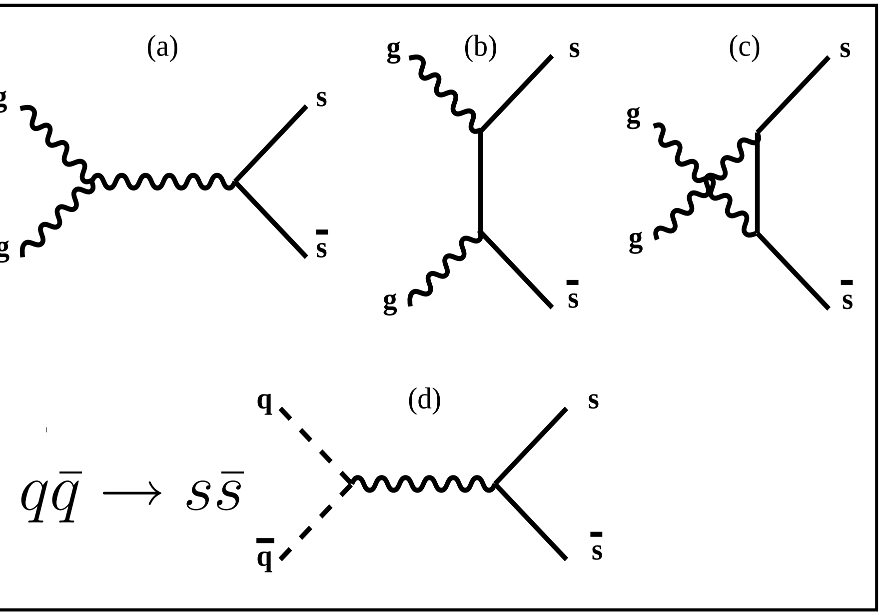
- **QGP production of strangeness in gluon fusion**

dominant processes:

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

abundant strangeness =evidence for gluons

10–15% of total rate: $q\bar{q} \to s\bar{s}$



- **coincidence of scales:**

$$\boxed{m_s \simeq T_c} \to \boxed{\tau_s \simeq \tau_{\mathrm{QGP}}} \to \textbf{QGP clock}$$

strangeness chemical equilibration in QGP possible

$$\gamma_s(t) \equiv \frac{\rho_s(t)}{\rho_s^{\mathrm{eq}}(t \to \infty)} \qquad 0.2 \leq \gamma_s^{\mathrm{Q}}(t) \to 1$$

OBSERVABLE: Strangeness / Entropy in QGP

s/S measures the number of active degrees of freedom, in chemical equilibrium:

$$\frac{s}{S}=\frac{\frac{g_s}{2\pi^2}T^3(m_s/T)^2K_2(m_s/T)}{(g2\pi^2/45)T^3+(g_sn_{\rm f}/6)\mu_q^2T}\simeq\frac{1}{35}=0.0286$$

with $\mathcal{O}(\alpha_s)$ interaction $s/S\to 1/31=0.0323$

CENTRALITY A, and ENERGY DEPENDENCE

Allow for chemical non-equilibrium of strangeness $\gamma_s^{\rm Q}$, and

$$\frac{s}{S}=\frac{0.03\gamma_s^{\rm Q}}{0.4\gamma_{\rm G}+0.1\gamma_s^{\rm Q}+0.5\gamma_q^{\rm Q}+0.05\gamma_q^{\rm Q}(\ln\lambda_q)^2}\to 0.03\gamma_s^{\rm Q}.$$

We expect the yield of gluons and light quarks to approach chemical equilibrium fast and first: $\gamma_{\rm G}\to 1$ and $\gamma_q^{\rm Q}\to 1$.

**To fix s/S we count strange hadrons and all hadrons:
we use Fermi model (statistical hadronization) to extrapolate to unmeasured particle yields and/or kinematic domains.**

STATISTICAL MODEL Example: Counting of Nucleons

$$dE + P\,dV - T\,dS = \sigma_N\,dN + \sigma_{\overline{N}}\,d\overline{N}$$
$$= \mu_b(dN - d\overline{N}) + T\ln\gamma_N(dN + d\overline{N}).$$

where $\sigma_N \equiv \mu_b + T\ln\gamma_N,\qquad \sigma_{\overline{N}} \equiv -\mu_b + T\ln\gamma_N;$

$$\Upsilon_N = \gamma_N e^{\frac{\mu_b}{T}},\qquad \Upsilon_{\overline{N}} = \gamma_N e^{\frac{-\mu_b}{T}}$$

The counting of hadrons done by counting valence quark content, assures continuity of chemical potentials, i.e. fugacity $\lambda_u, \lambda_d, \lambda_s$, and $\lambda_q^2 = \lambda_u\lambda_d, \lambda_{I3} = \lambda_u/\lambda_d$:

$$\Upsilon_i \equiv \Pi_i\gamma_i^{n_i}\lambda_i^{k_i} = e^{\sigma_i/T};\qquad \lambda_q \equiv e^{\frac{\mu_q}{T}} = e^{\frac{\mu_b}{3T}},\qquad \lambda_s \equiv e^{\frac{\mu_s}{T}} = e^{\frac{[\mu_b/3-\mu_S]}{T}}$$

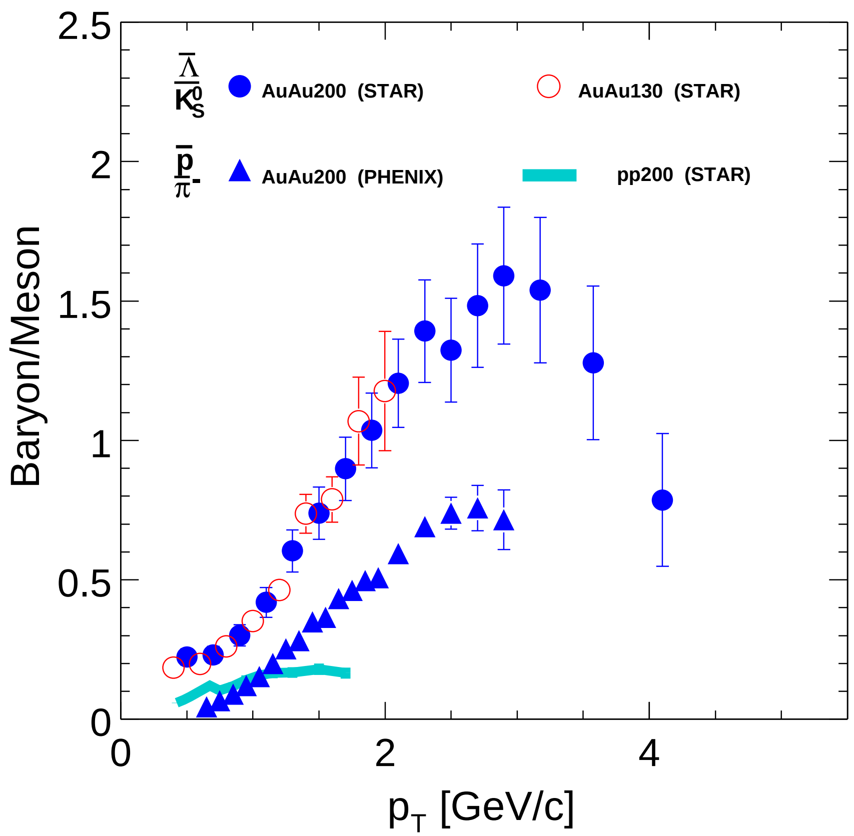
Physical Impact of Non-Equilibrium Parameters

- $\tilde\gamma_s \equiv \gamma_s/\gamma_q$ **shifts the yield of strange vs non-strange hadrons:**

$$\frac{\mathrm{K}^+(u\bar s)}{\pi^+(u\bar d)} \propto \frac{\gamma_s}{\gamma_q},\qquad \frac{\phi}{h} \propto \frac{\gamma_s^2}{\gamma_q^2},\qquad \frac{\Omega(sss)}{\Lambda(sud)} \propto \frac{\gamma_s^2}{\gamma_q^2},$$

- **For fixed** $\tilde\gamma_s \equiv \gamma_s/\gamma_q$ **and fixed other statistical parameters** $(T, \lambda_i, \ldots)$**:**

$$\frac{\text{baryons}}{\text{mesons}} \propto \frac{\gamma_q^3}{\gamma_q^2} = \gamma_q\,.$$



Baryon to Meson Ratio

Ratios of $\overline{\Lambda}$ to K_S from AuAu and pp collisions (STAR) and $\overline{p}$ to π from AuAu collisions (PHENIX) as a function of transverse momentum ($p_\perp$). The large ratio at the intermediate $p_\perp$ region: evidence that particle formation at RHIC distinctly different from fragmentation processes for the elementary e^+e^- and nucleon-nucleon collisions.

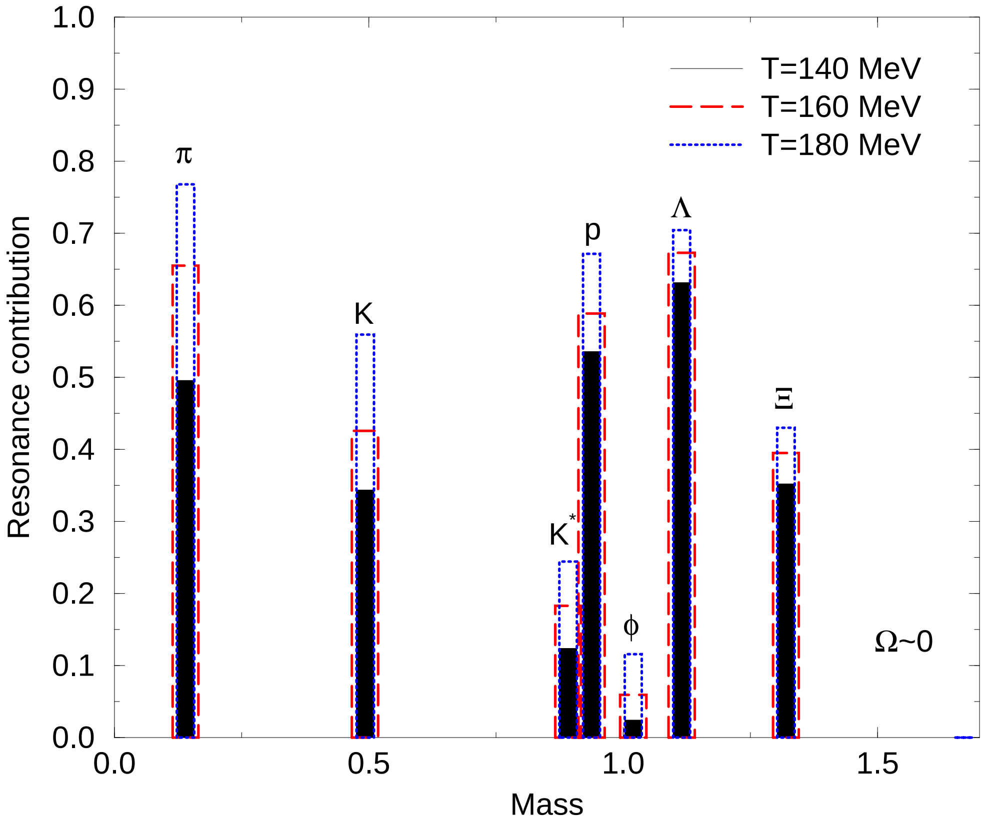
We expect that the value of γ_q depends on system considered with the most extreme cases being A–A at RHIC compared to p–p. Thus in study of particle yields it is of considerable importance to include this parameter which remains often ignored.

FERMI STATISTICAL HADRONIZATION

Hypothesis: particle production can be described by evaluating the accessible phase space.

Verification of statistical hadronization:

Particle yields with same valance quark content are in relative chemical equilibrium, e.g. the relative yield of $\Delta(1230)/N$ as of K^*/K, $\Sigma^*(1385)/\Lambda$, etc, is controlled by chemical freeze-out i.e. Hagedorn Temperature $T_{\rm H}$:



$$\frac{N^*}{N} = \frac{g^*(m^*T_{\rm H})^{3/2}e^{-m^*/T_{\rm H}}}{g(mT_{\rm H})^{3/2}e^{-m/T_{\rm H}}}$$

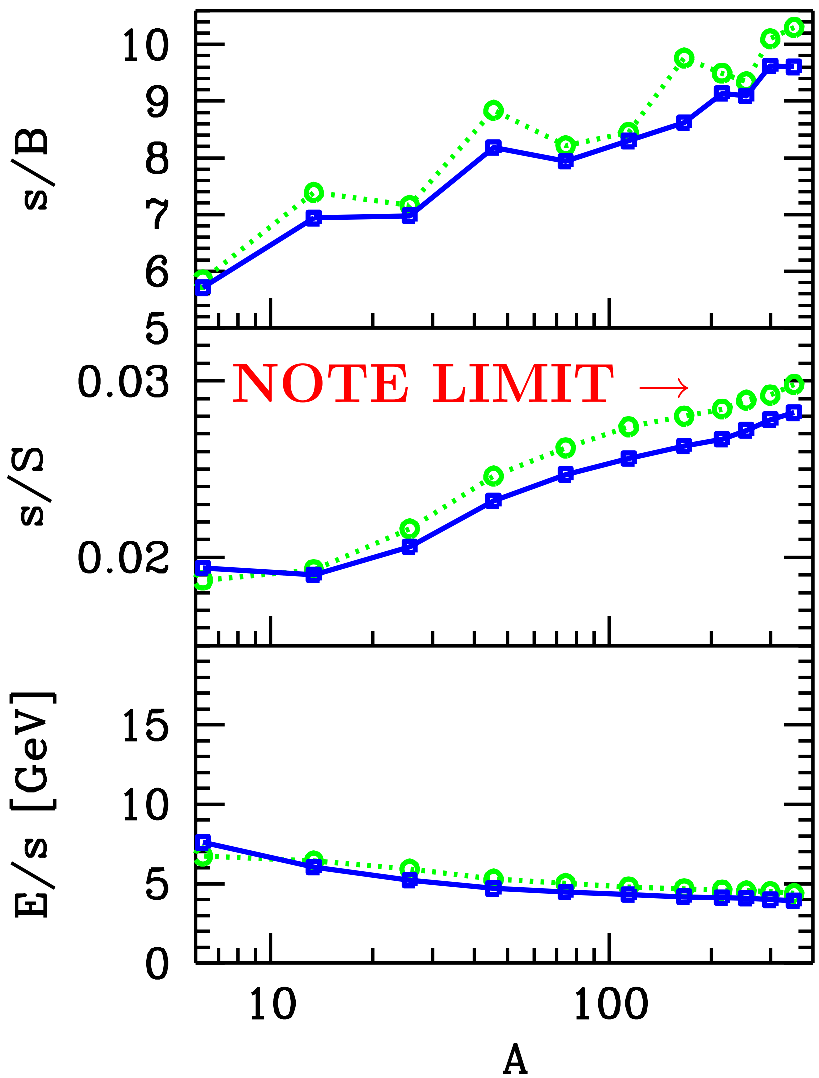
Resonances decay rapidly into 'stable' hadrons and dominate the yield of most stable hadronic particles.

Resonance yields test statistical hadronization principles.

Resonances reconstructed by invariant mass; important to consider potential for loss by rescattering.

HADRONIZATION GLOBAL FIT:→

RHIC-200 s/b and s/S rise with increasing centrality $A \propto V$; E/s falls



Showing results for both $\gamma_q, \gamma_s \neq 1$, for $\gamma_s \neq 1, \gamma_q = 1$. Note little difference in the result, even though the value of T will differ significantly.

1) $s/S \to 0.027$, as function of V;
2) most central value near QGP chemical equilibrium;
3) no saturation for largest volumes available;

Behavior is consistent with QGP prediction of steady increase of strangeness yield with increase of the volume, which implies longer lifespan and hence greater strangeness yield, both specific yield and larger γ_s^{QGP}.

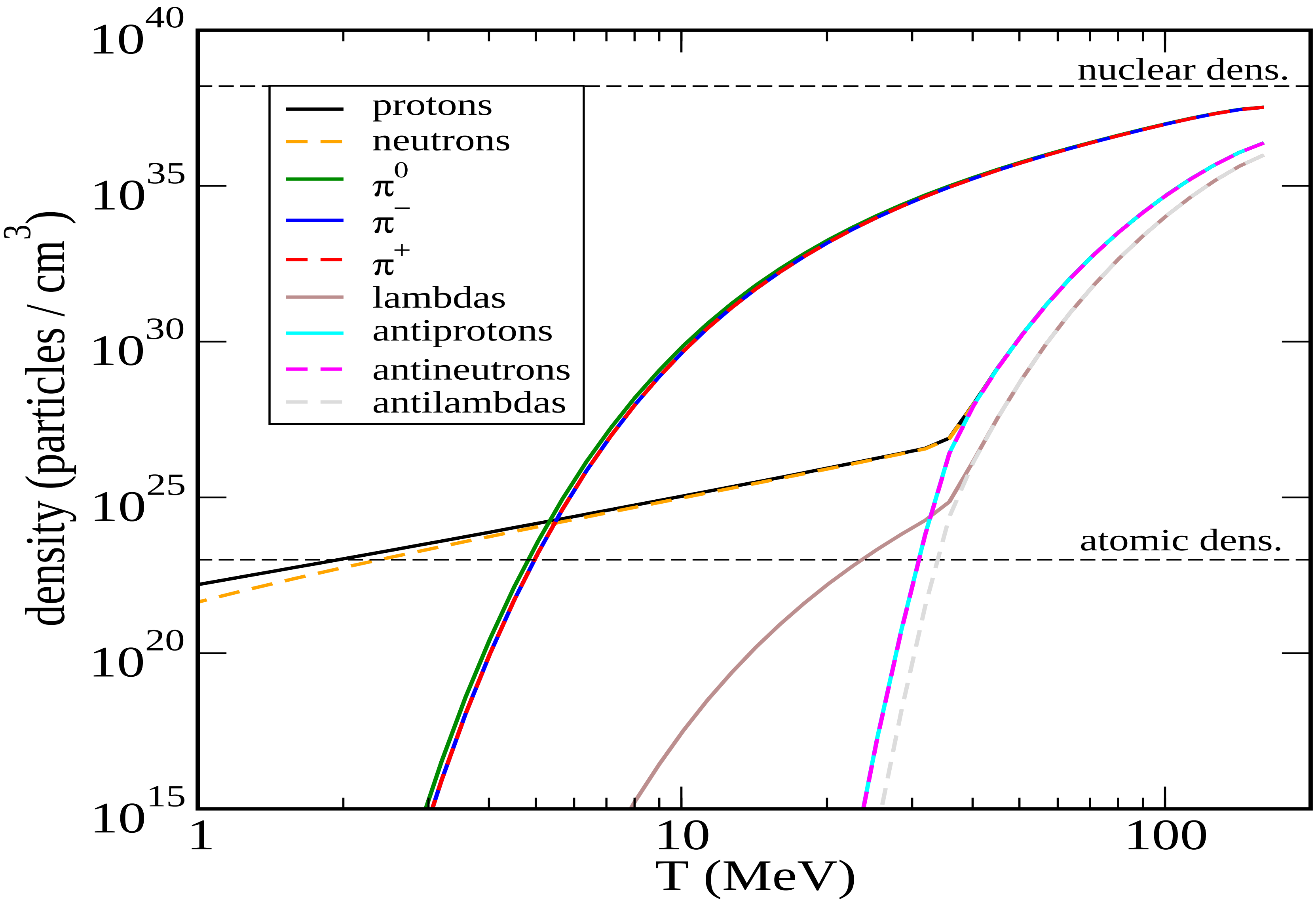
Strangeness chemically equilibrated in the QGP drop in most central RHIC-200 collisions. NOT probe of initial conditions, but of last 3-5fm of deconfined state evolution.

III Hadronization of the Quark Universe

Upon QGP hadronization there is initially nearly as much matter as antimatter (to within 10^{-9}–10^{-10}). In an initially nearly homogeneous Universe this symmetry remains during the ensuing annihilation period till annihilation consumed all but the tiny initial state asymmetry that remains.

- **When do antinucleons, strangeness, pions disappear in homogeneous Universe?**
- **What happens to the Universe during matter-antimatter annihilation?**
- **When is pion density equal to baryon density?**

Hadronic Particle Densities BEFORE CHEMICAL FREEZE-OUT



Note the baryon remnant beyond $T \simeq 37$ MeV and that pion density remains at baryon density down to $T \simeq 4.5$ MeV.

WHAT WE NEED TO TRACE PARTICLE YIELDS

- **Chemical conditions in the early Universe (chemical potentials, equilibriums);**
- **Resolve conflict of Gibbs hadronization conditions with super-selection rules such as local charge conservation/neutrality;**
- **When do antinucleons, strangeness, pions disappear in homogeneous Universe (chemical nonequilibrium in hadron phase)?**

Many questions open, the above is simply the uncomplicated conventional chemical equilibrium method first step.

What is the time scale of Universe hadronization? Information needed to know which interactions are active.

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:

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

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

IN THE EARLY UNIVERSE aside of strong also EM and WEAK reactions relax towards equilibrium. Many additional (compared to heavy ion reactions) active degrees of freedom.

Since T determined by Universe expansion, we need to understand the chemical conditions fixing chemical potentials and control the emergence of matter as we know it today in the hadronization of quark-gluon plasma.

WHAT FIXES CHEMICAL POTENTIALS?

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

2) Trace out chemical potentials as function of T, (which we can study separately as function of time);

3) Evaluate the 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 distillation of conserved quantum numbers: baryon, electrical charge (not in this talk, time constraint).

CHEMICAL POTENTIALS IN THE UNIVERSE

The slow hadronization of the Universe implies hadronic chemical equilibrium and full participation of electromagnetically interacting photon and lepton degrees of freedom.

- **Photons in chemical equilibrium, Planck distribution, zero photon chemical potential; i.e.:** $\mu_\gamma = 0$
- **reactions such as** $f + \bar{f} \rightleftharpoons 2\gamma$ **are in equilibrium, (here** f **and** $\bar{f}$ **are a fermion – antifermion pair), hence:** $\mu_f = -\mu_{\bar{f}}$
- **Minimization of the Gibbs free energy implies that chemical equilibrium arises for the condition:** $\nu_i \mu_i = 0$
  for any reaction $\nu_i A_i = 0$, **where** ν_i **are the reaction equation coefficients of the chemical species** A_i;
- **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:** $\mu_{\nu_e} = \mu_{\nu_\mu} = \mu_{\nu_\tau} \equiv \mu_\nu$
  neutrino mixing may be 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:

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

Physical observables and chemical conditions

The three chemical potentials not constrained by chemical reactions are obtained from three 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* **($L = B$):**

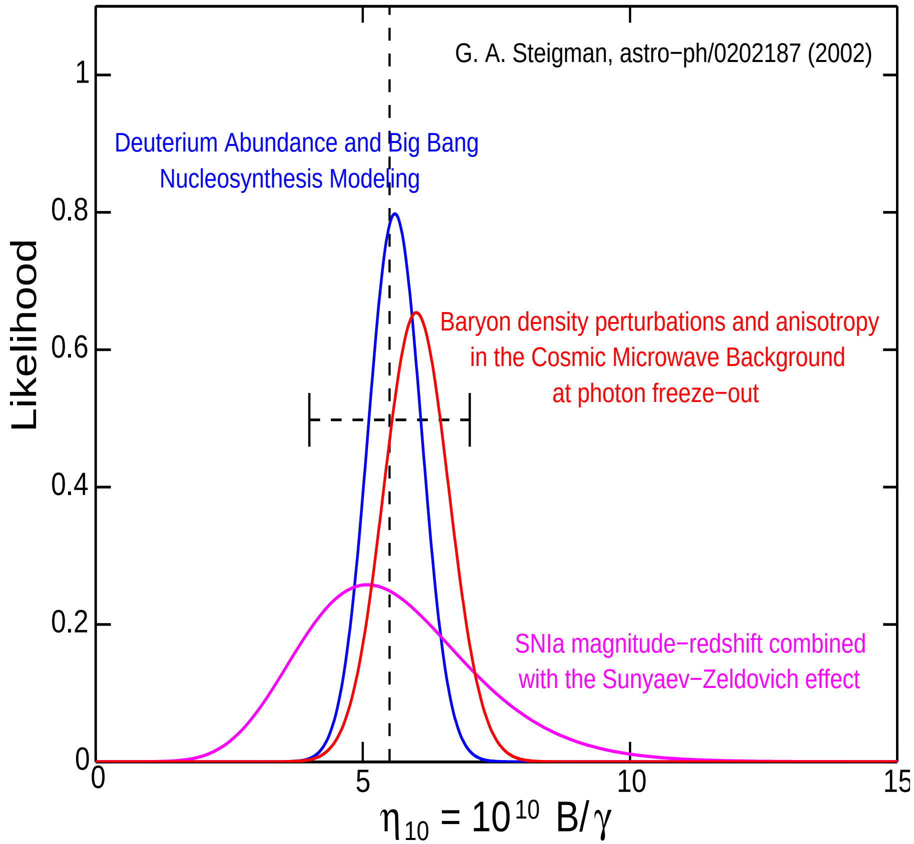
$$n_L - n_B \equiv \sum_i (L_i - B_i)\, n_i(\mu_i, T) = 0,$$

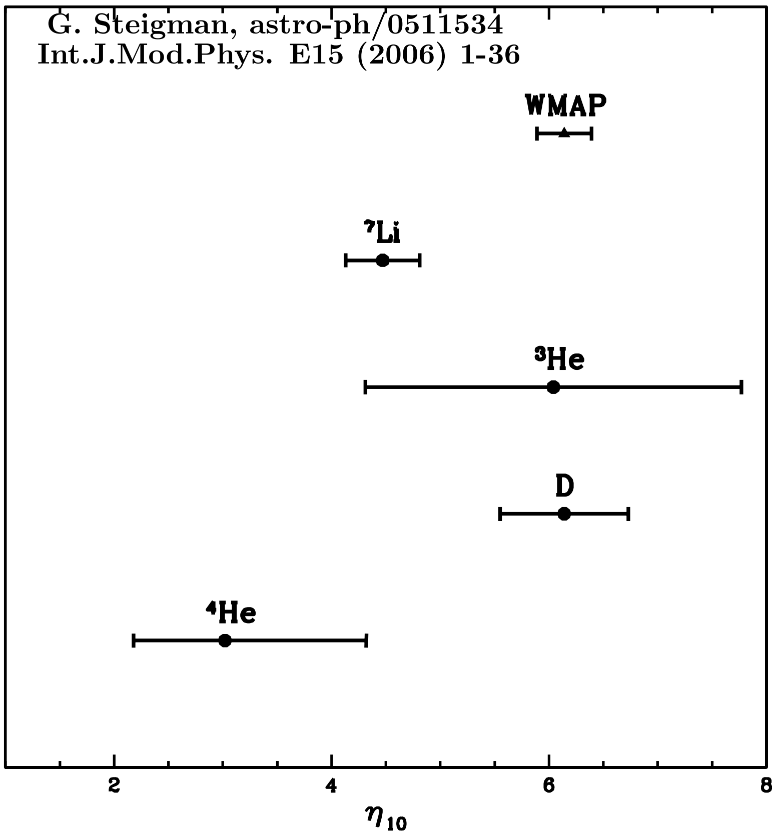
(standard condition in baryo-genesis models, generalization to finite $B - L$ easily possible)

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



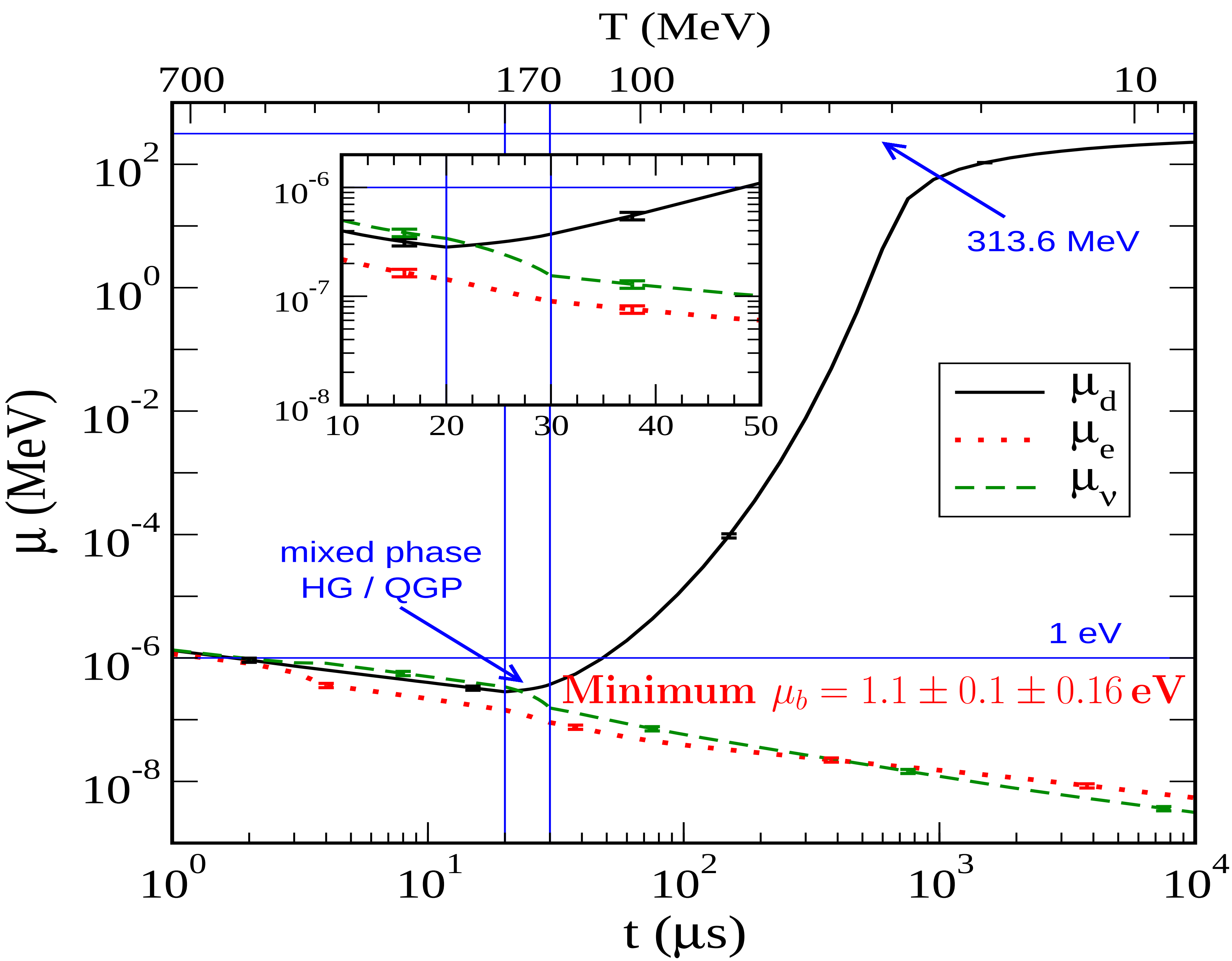


Deuteron abundance, W-MAP: $\eta_{10} = 6.1 \pm 0.15 \times 10^{-10}$**;**

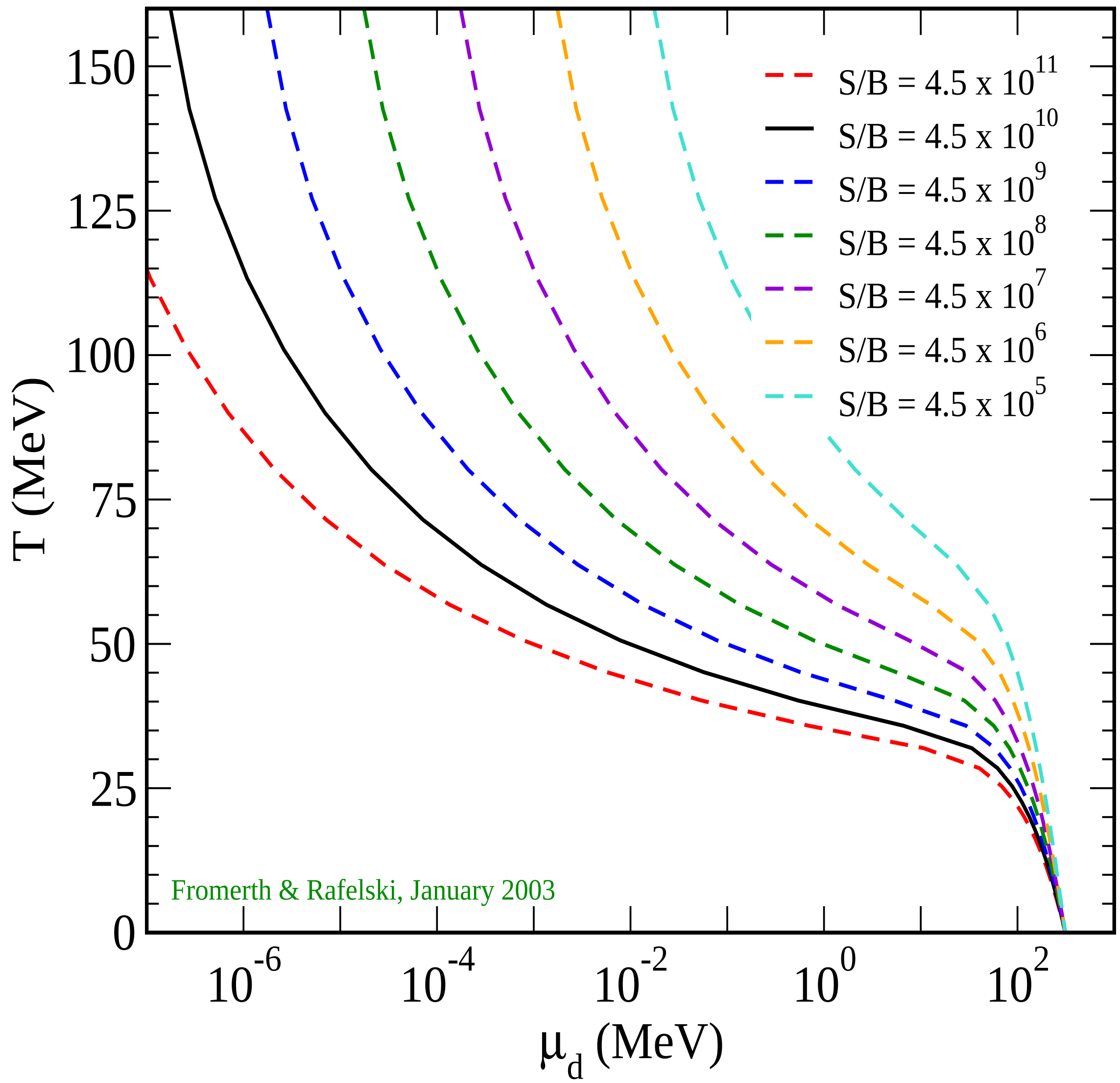
This yields entropy per baryon: $\frac{S}{n_B} = \frac{S}{n_\gamma}\frac{n_\gamma}{n_B} = \frac{8.0}{\eta} = 1.3 \pm 0.1\, 10^{10}$

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

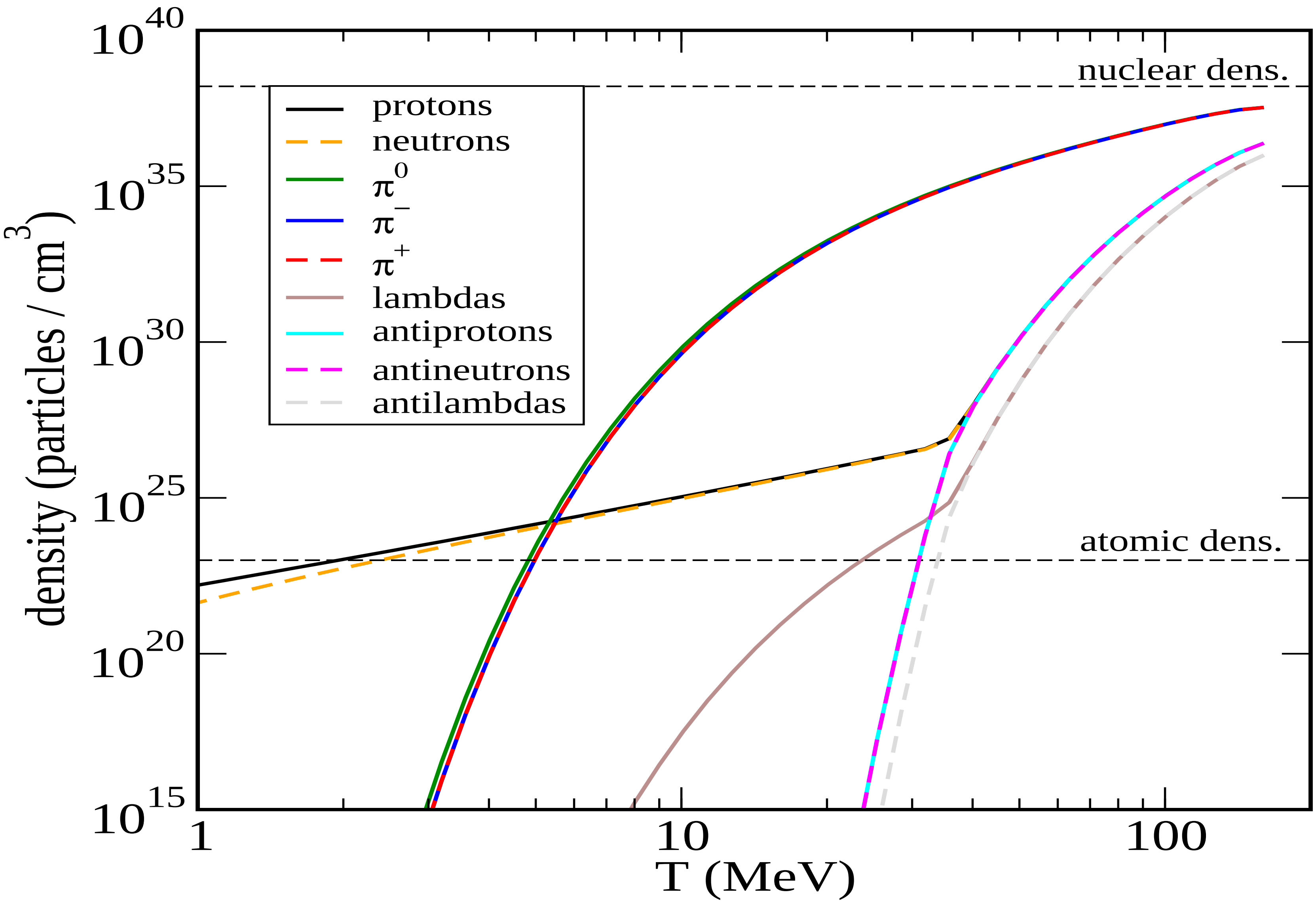
TRACING μ_d IN THE UNIVERSE



TRACING μ_d IN A UNIVERSE a la GUTBROD

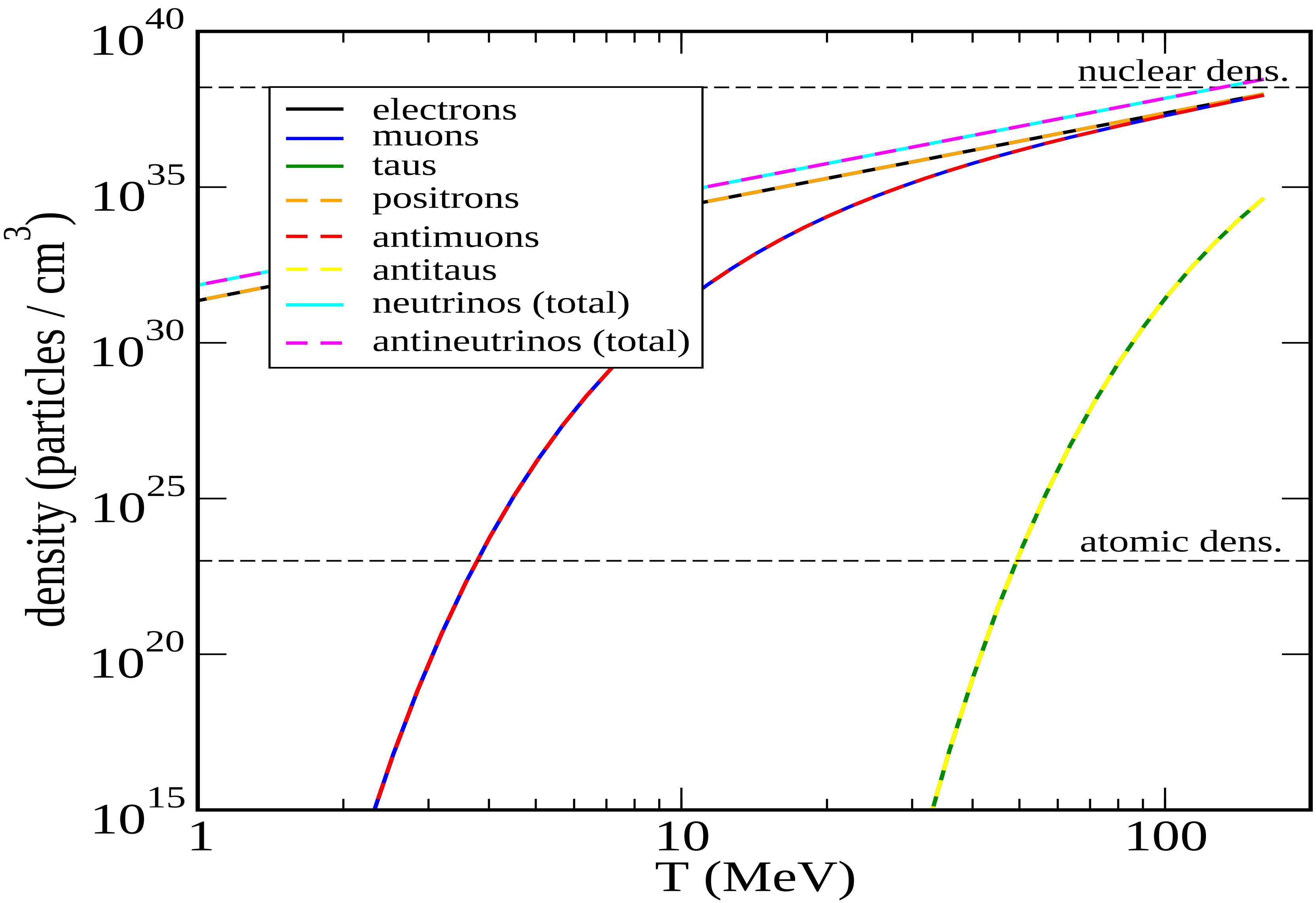


Hadronic Particle Densities



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



Distillation Process–Separation of Phases

Strangeness distillation mechanism proposed for QGP hadronization. In HI collisions no time to distill, applicable in early Universe to electrical charge, baryon number etc. distillation. 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.

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

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

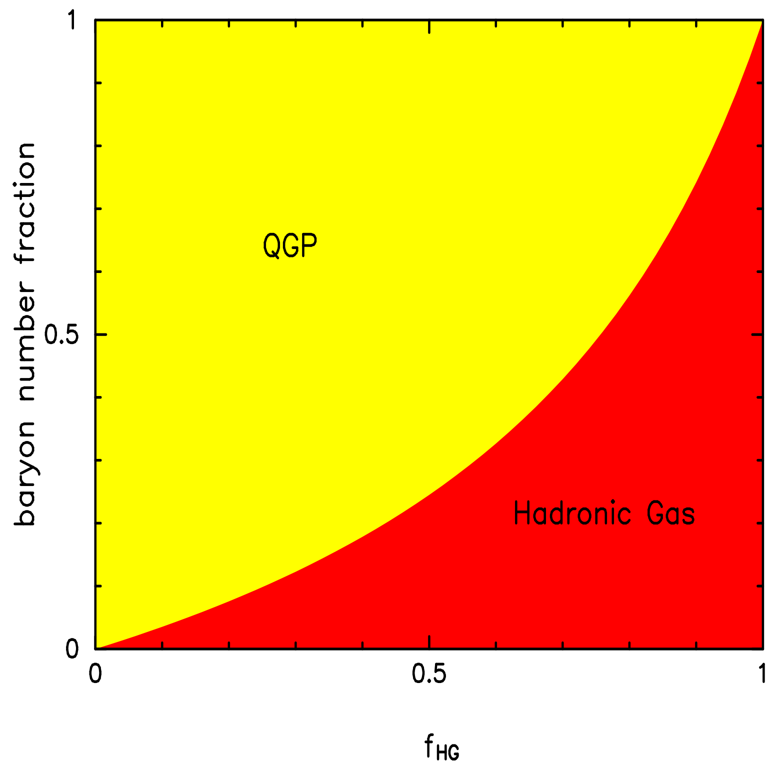
$f_{\rm HG} \equiv V_{\rm HG}/V_{\rm tot}$ **is the fraction of space belonging to HG phase.**

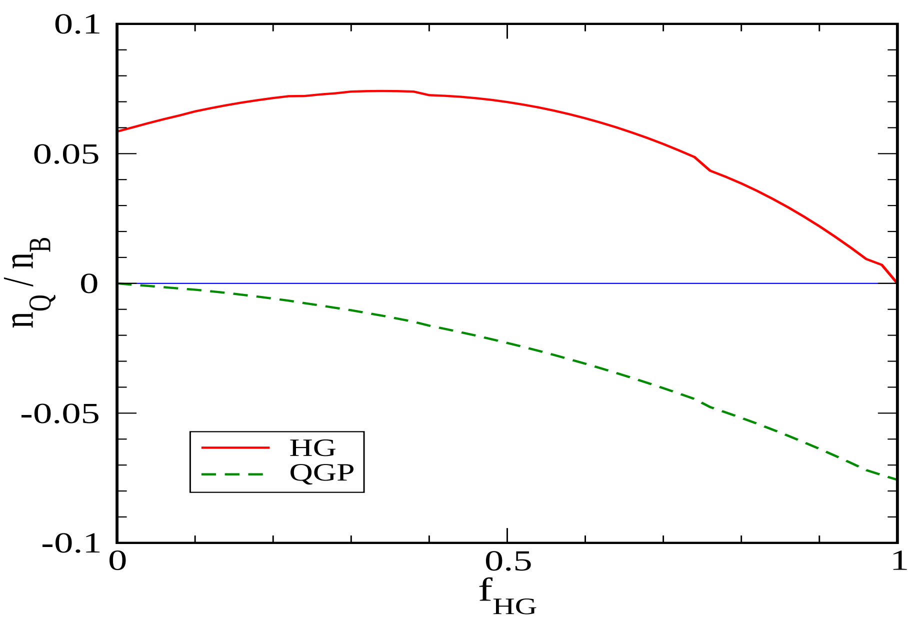
Note: Mixed phase lasts $\simeq 10\,\mu s$ (25% of prior lifespan), we had assumed that $f_{\rm HG}$ changes linearly in time. Actual values will require dynamic nucleation and transport theory description of the phase transformation.

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.

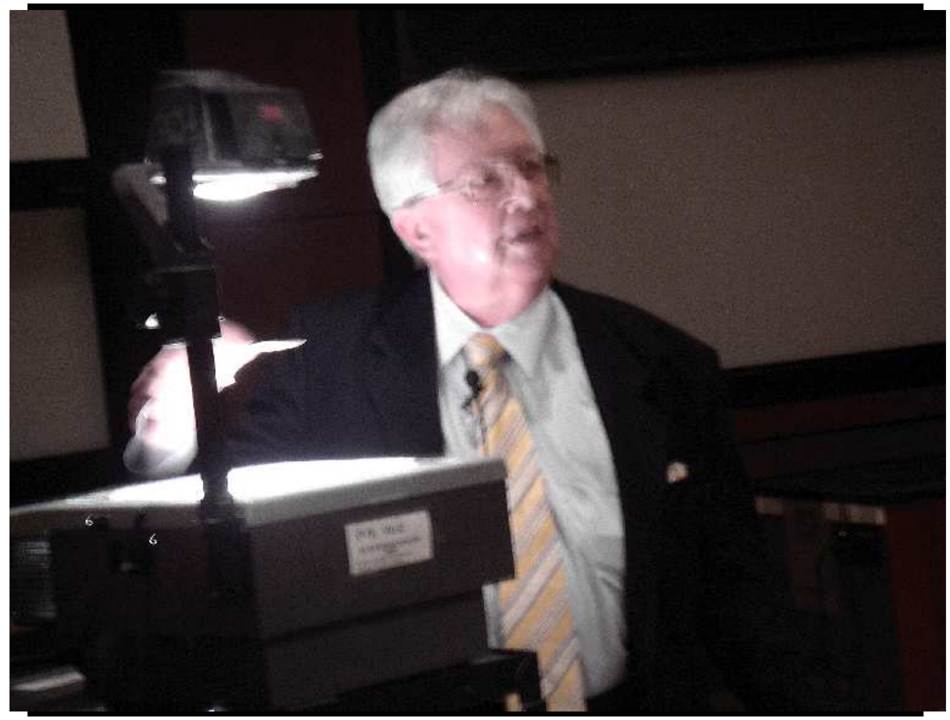




Even a small charge separation between phases introduces a finite non-zero local Coulomb potential and this amplifies any existent baryon asymmetry (protons vs antiprotons).

Dedicated to Walter Greiner, my teacher,

1968



2006

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SUMMARY

[I] Introductory remarks

[II] Recreating the early Universe in the laboratory

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

Strangeness a diagnostic tool of QGP properties

[III] Hadronization of the Quark Universe

Scale of Universe hadronization time

Chemical potentials in the early Universe

Particle populations in the early Universe

Mixed phase, distillation process