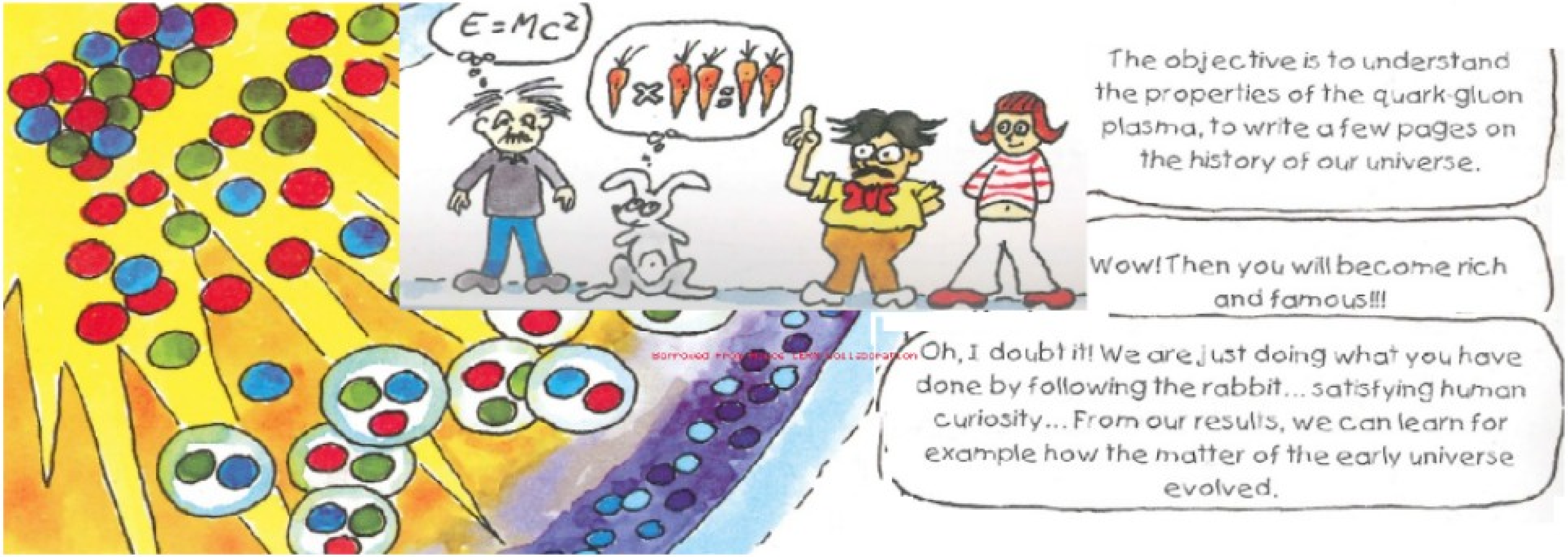
Connecting the Big Bang to present day
Jan Rafelski - group talk

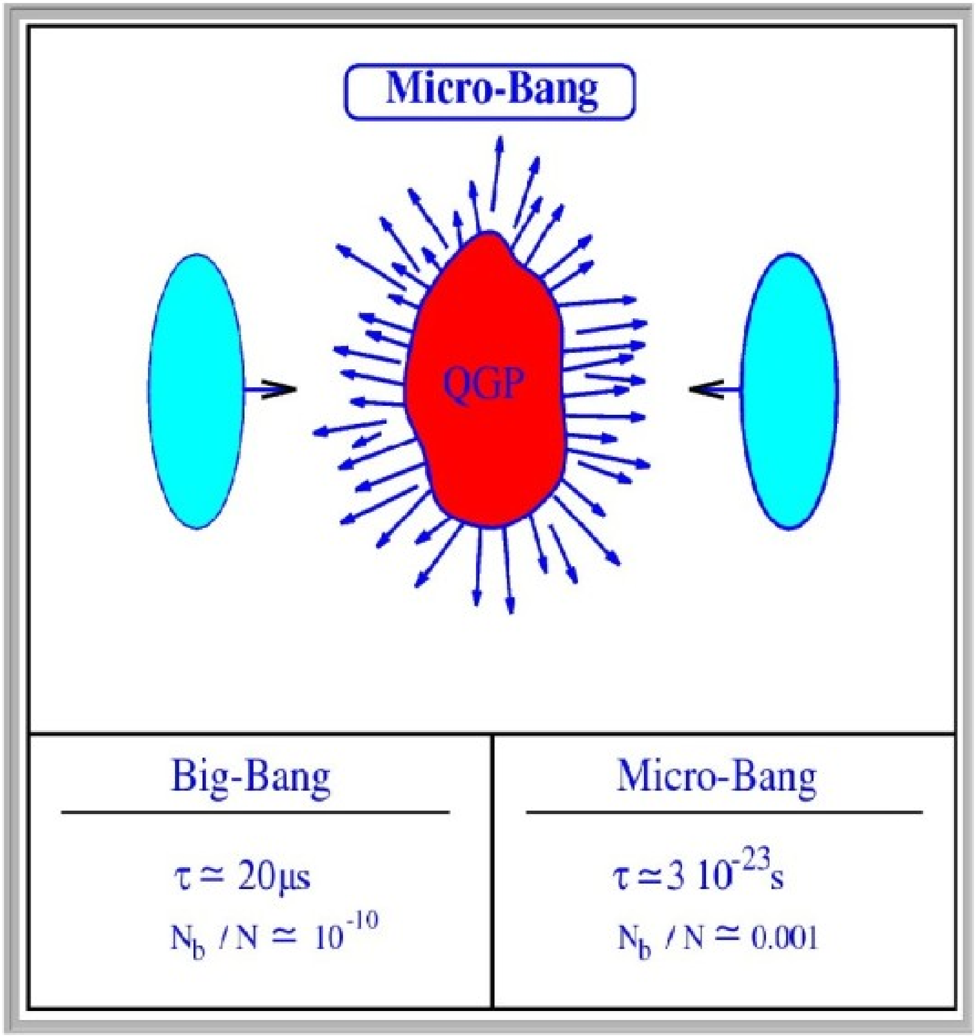
This talk is an extract from my related presentations in past 10 years – I omit neutrino decoupling (PhD of J. Birrell) and topics Cheng Tao works on: connecting hadron era to BBN (however I use many general JB results). This is a quick & easy (I hope) view on what you should know to appreciate Cheng Tao efforts.

Evolution of Matter in the Universe:
from quark-gluon plasma era to the present



Today we connect the present day visible Universe with prior eras, beginning with the primordial period above Hagedorn temperature before the emergence of matter as we know it. This was the quark-gluon plasma (QGP), a new phase of matter discovered in recent experimental laboratory work. QGP was omni-present up to when the Universe was 13 microseconds old. As the universe expands and cools QGP hadronizes, forming abundant matter and antimatter. Only a nano-fraction surplus of matter survives the ensuing annihilation process. A dense electron positron photon neutrino plasma remains. Electrons and positrons annihilate while neutrinos decouple. All this takes less than a second, and within this time also the few remaining neutrons are fixed in their final abundance; <u>the first second</u> creates the context for the big-bang nucleo-synthesis and ultimately leads to the visible Universe around us; we show how different components in the Universe evolves from QGP to the present era.

Is lab/RHI collision a good simulation of Big-Bang?

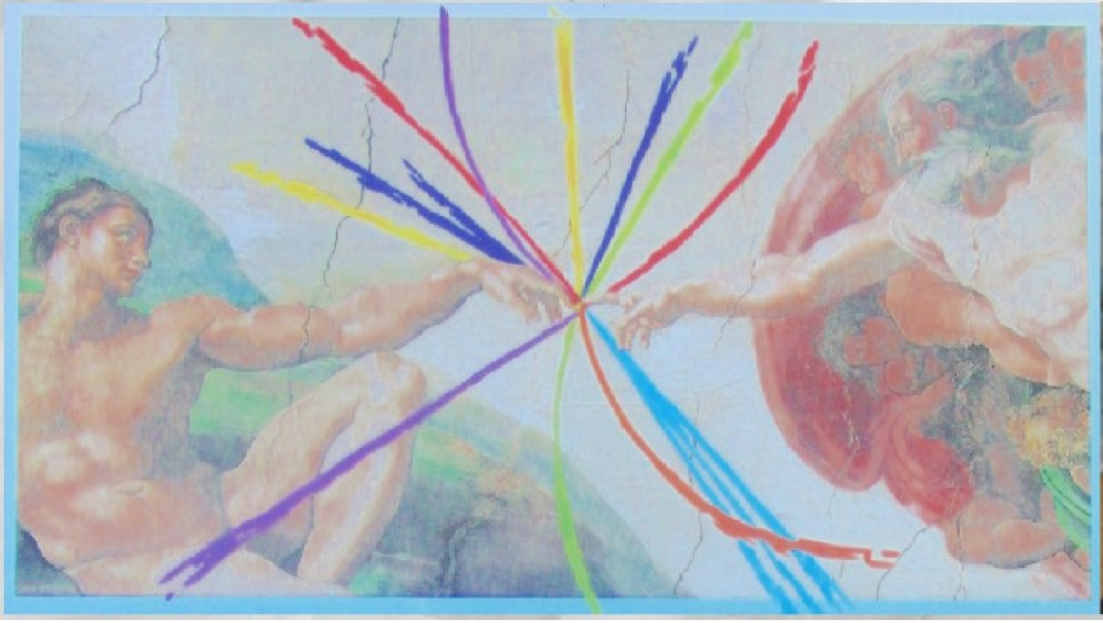


Big-Bang	Micro-Bang
$\tau \simeq 20\mu s$	$\tau \simeq 3\ 10^{-23}s$
$N_b\ /N \simeq 10^{-10}$	$N_b\ /N \simeq 0.001$

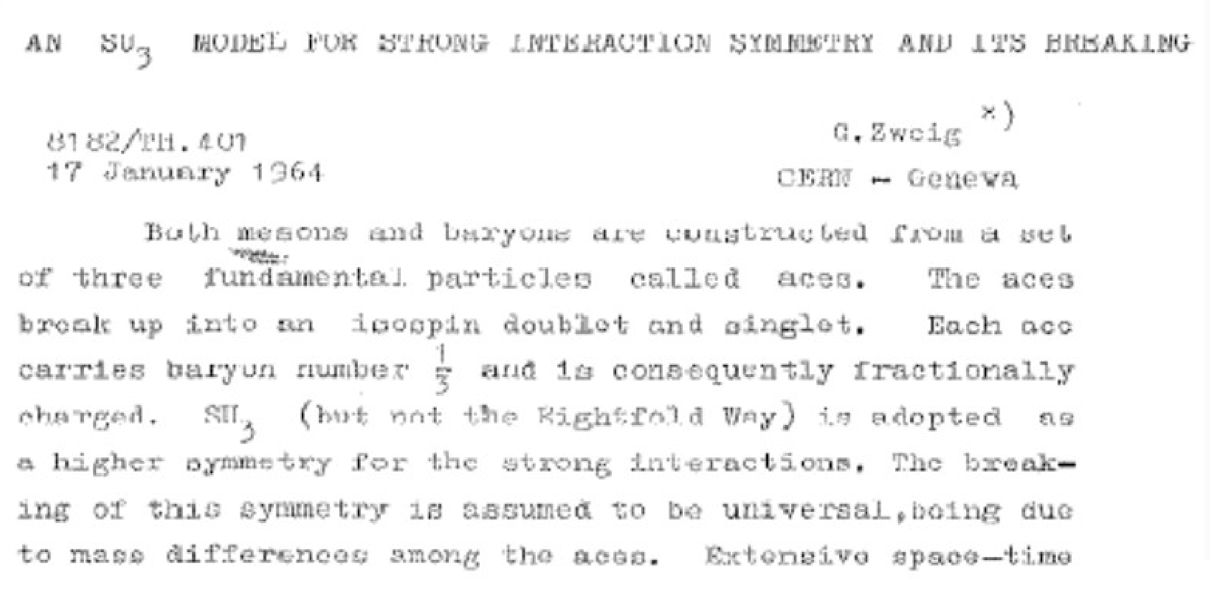
- Universe time scale 18 orders of magnitude longer, hence equilibrium of leptons & photons
- Baryon asymmetry six orders of magnitude larger in Laboratory, hence chemistry different
- Universe: dilution by scale expansion, Laboratory explosive expansion of a fireball

$\Longrightarrow$ Theory connects RHI collision experiments to Universe

1. Convergence of 1964-68 ideas
    - Quarks + Higgs → Standard Model of particle physics
    - CMB discovered → Big Bang
    - Hagedorn Temperature T_H, Statistical Bootstrap=initial singularity
2. QGP in the Universe, in laboratory
3. Antimatter disappears, neutrinos free-stream, (BBN) . . .
4. Evolution of matter components in the Universe



1964: Quarks + Higgs → Standard Model

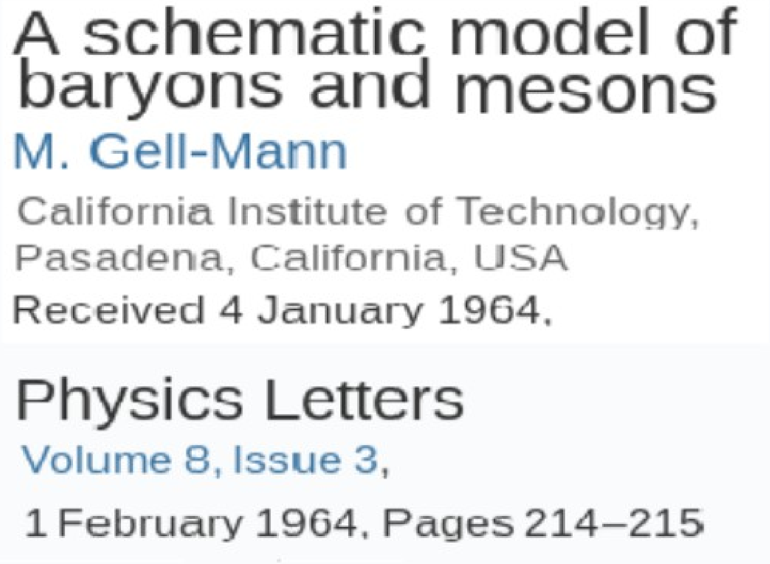


AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

8182/TH.401
17 January 1964

G. Zweig *)
CERN – Geneva

Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces break up into an isospin doublet and singlet. Each ace carries baryon number $\frac{1}{3}$ and is consequently fractionally charged. SU_3 (but not the Eightfold Way) is adopted as a higher symmetry for the strong interactions. The breaking of this symmetry is assumed to be universal, being due to mass differences among the aces. Extensive space-time



A schematic model of baryons and mesons

M. Gell-Mann

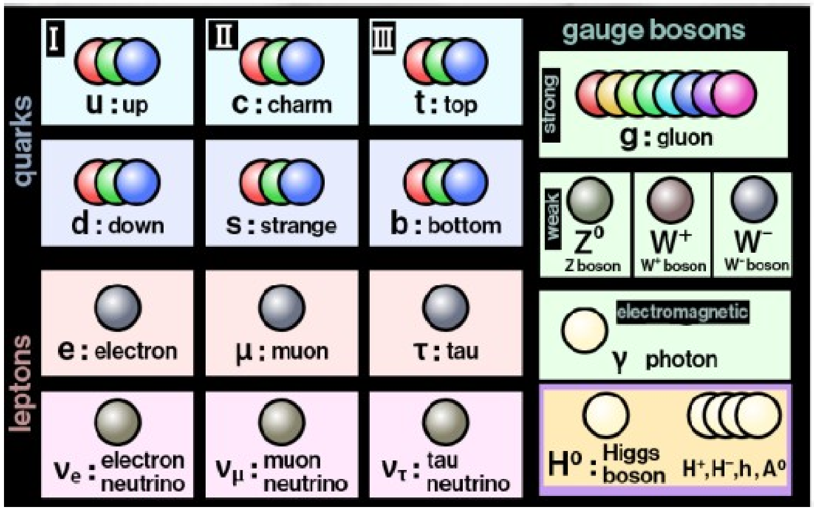
California Institute of Technology, Pasadena, California, USA

Received 4 January 1964.

Physics Letters

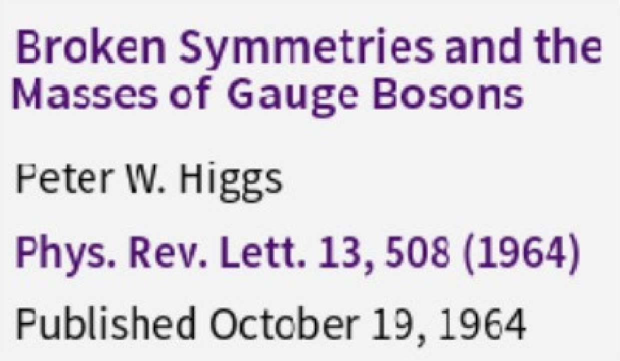
Volume 8, Issue 3,

1 February 1964, Pages 214–215



Nearly 50 years after its prediction, particle physicists have finally captured the Higgs boson.

Mass

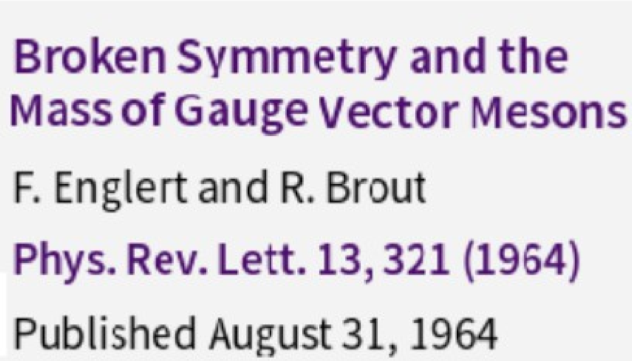


Broken Symmetries and the Masses of Gauge Bosons

Peter W. Higgs

Phys. Rev. Lett. 13, 508 (1964)

Published October 19, 1964

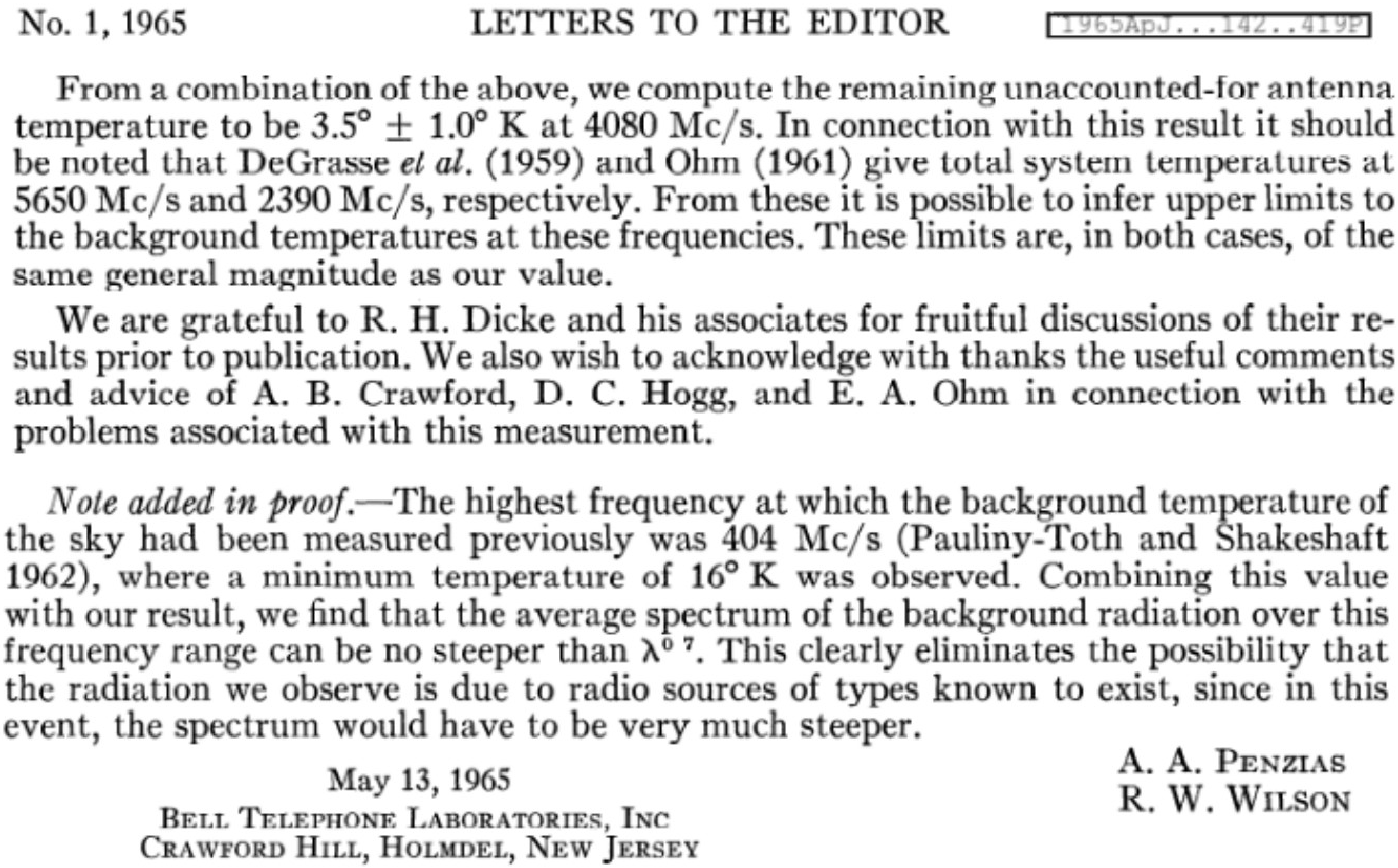


Broken Symmetry and the Mass of Gauge Vector Mesons

F. Englert and R. Brout

Phys. Rev. Lett. 13, 321 (1964)

Published August 31, 1964



From a combination of the above, we compute the remaining unaccounted-for antenna temperature to be 3.5° ± 1.0° K at 4080 Mc/s. In connection with this result it should be noted that DeGrasse *et al*. (1959) and Ohm (1961) give total system temperatures at 5650 Mc/s and 2390 Mc/s, respectively. From these it is possible to infer upper limits to the background temperatures at these frequencies. These limits are, in both cases, of the same general magnitude as our value.

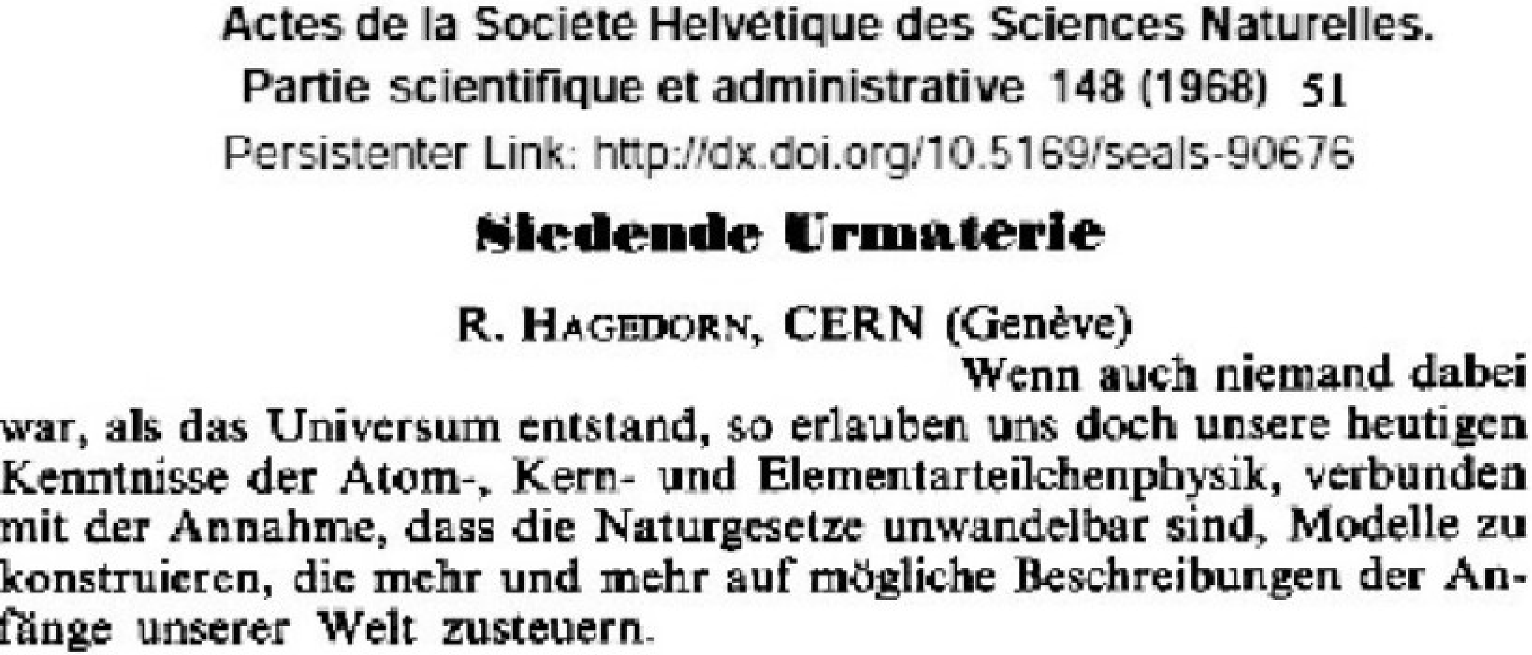
We are grateful to R. H. Dicke and his associates for fruitful discussions of their results prior to publication. We also wish to acknowledge with thanks the useful comments and advice of A. B. Crawford, D. C. Hogg, and E. A. Ohm in connection with the problems associated with this measurement.

Note added in proof.—The highest frequency at which the background temperature of the sky had been measured previously was 404 Mc/s (Pauliny-Toth and Shakeshaft 1962), where a minimum temperature of 16° K was observed. Combining this value with our result, we find that the average spectrum of the background radiation over this frequency range can be no steeper than $\lambda^{0.7}$. This clearly eliminates the possibility that the radiation we observe is due to radio sources of types known to exist, since in this event, the spectrum would have to be very much steeper.

A. A. Penzias
R. W. Wilson

May 13, 1965
Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey

1965-7 – Hagedorn’s singular Statistical Bootstrap Model accepted as ‘the’ initial singular hot Big-Bang theory



Actes de la Société Helvétique des Sciences Naturelles.

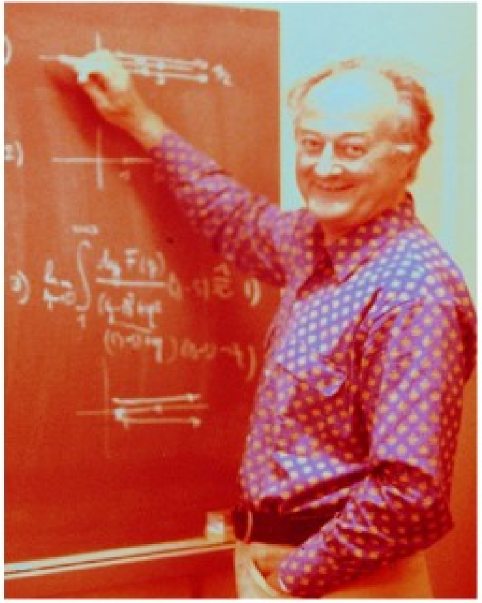
Partie scientifique et administrative 148 (1968) 51

Persistenter Link: http://dx.doi.org/10.5169/seals-90676

Siedende Urmaterie

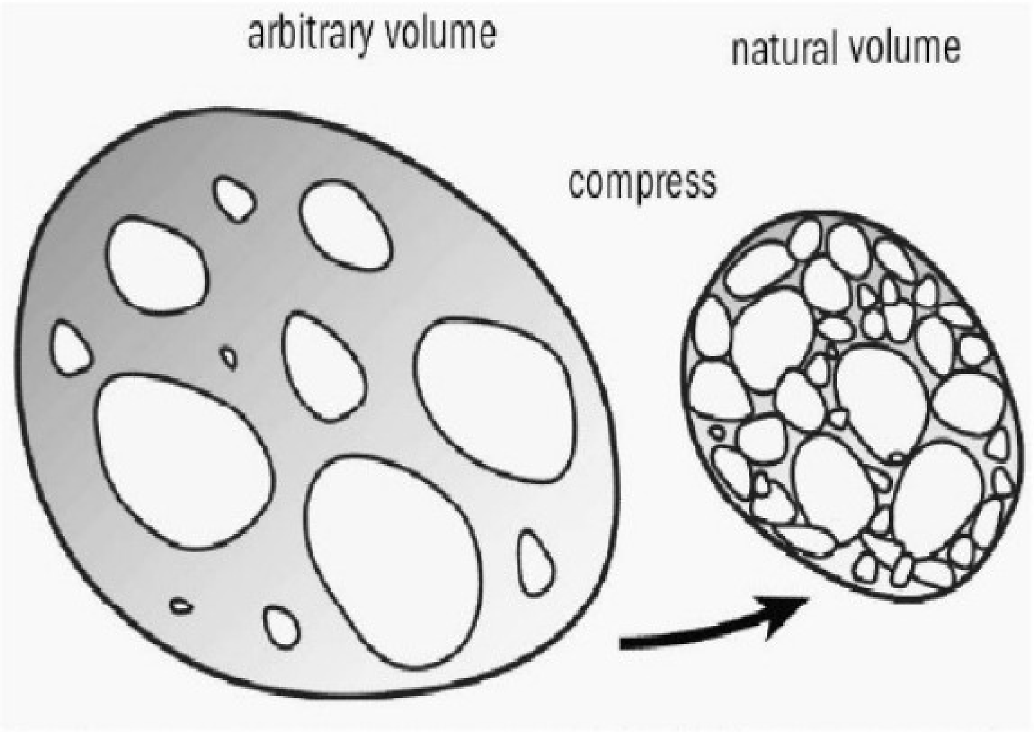
R. Hagedorn, CERN (Genève)

Wenn auch niemand dabei war, als das Universum entstand, so erlauben uns doch unsere heutigen Kenntnisse der Atom-, Kern- und Elementarteilchenphysik, verbunden mit der Annahme, dass die Naturgesetze unwandelbar sind, Modelle zu konstruieren, die mehr und mehr auf mögliche Beschreibungen der Anfänge unserer Welt zusteuern.



Boiling Primordial Matter *Even though no one was present when the Universe was born, our current understanding of atomic, nuclear and elementary particle physics, constrained by the assumption that the Laws of Nature are unchanging, allows us to construct models with ever better and more accurate descriptions of the beginning.*

What is the Statistical Bootstrap Model (SBM)?



A volume comprising a gas of fireballs compressed tonatural volume is itself again a fireball.

$$\tau(m^2)\mathrm{d}m^2 \equiv \rho(m)\mathrm{d}m \quad \rho(m) \propto m^{-a}\exp(m/T_\mathrm{H}).$$

nature

article

Nature **228**, 258 - 260 (17 October 1970); doi:10.1038/228258a0

Comments on the Big-bang

E. R. HARRISON*

Institute of Theoretical Astronomy, University of Cambridge
*On leave from the Department of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01002.

Is the big-bang hot, warm or cold? And are galactic masses determined by the interplay of gravitational and strong interactions in the very early universe?

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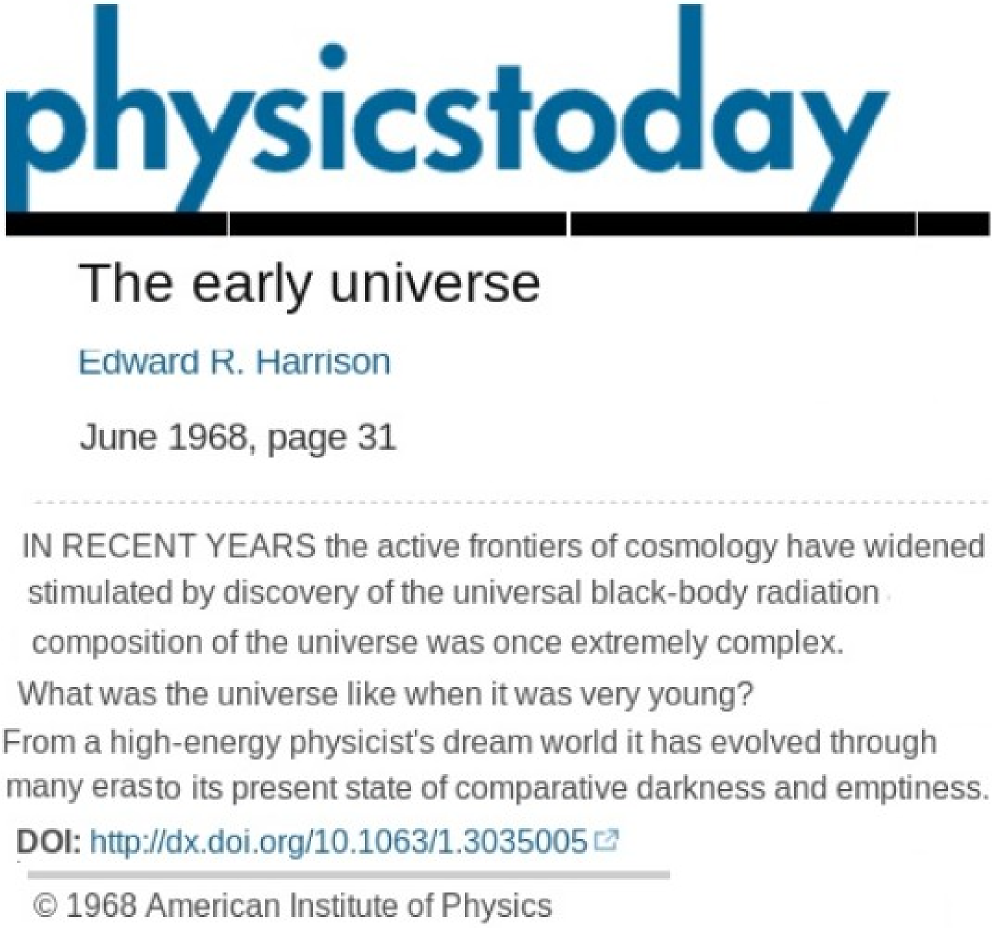
14. Hagedorn, R., *Suppl. Nuovo Cim.*, **3**, 147 (1965); *Ibid.*, **6**, 311 (1968); *Nuovo Cim.*, **52**A, 1336 (1967); *ibid.*, **56**A, 1027 (1968); *Astron. Astrophys.*, **5**, 184 (1970).
15. Hagedorn, R., and Ranft, J., *Suppl. Nuovo Cimento*, **6**, 169 (1968).

1965: Penzias and Wilson discover CMB

1966-1968: Hot Big-Bang becoming conventional wisdom



physicstoday

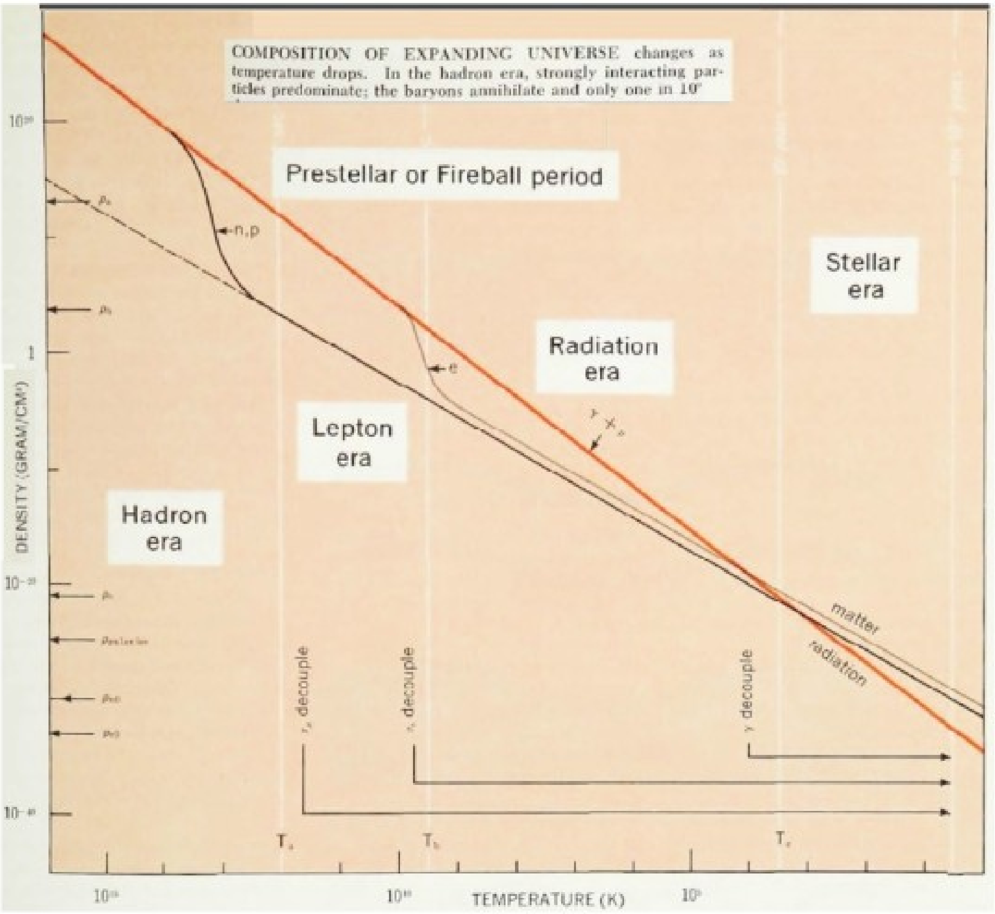
The early universe

Edward R. Harrison

June 1968, page 31

IN RECENT YEARS the active frontiers of cosmology have widened stimulated by discovery of the universal black-body radiation composition of the universe was once extremely complex.
What was the universe like when it was very young?
From a high-energy physicist's dream world it has evolved through many erasto its present state of comparative darkness and emptiness.

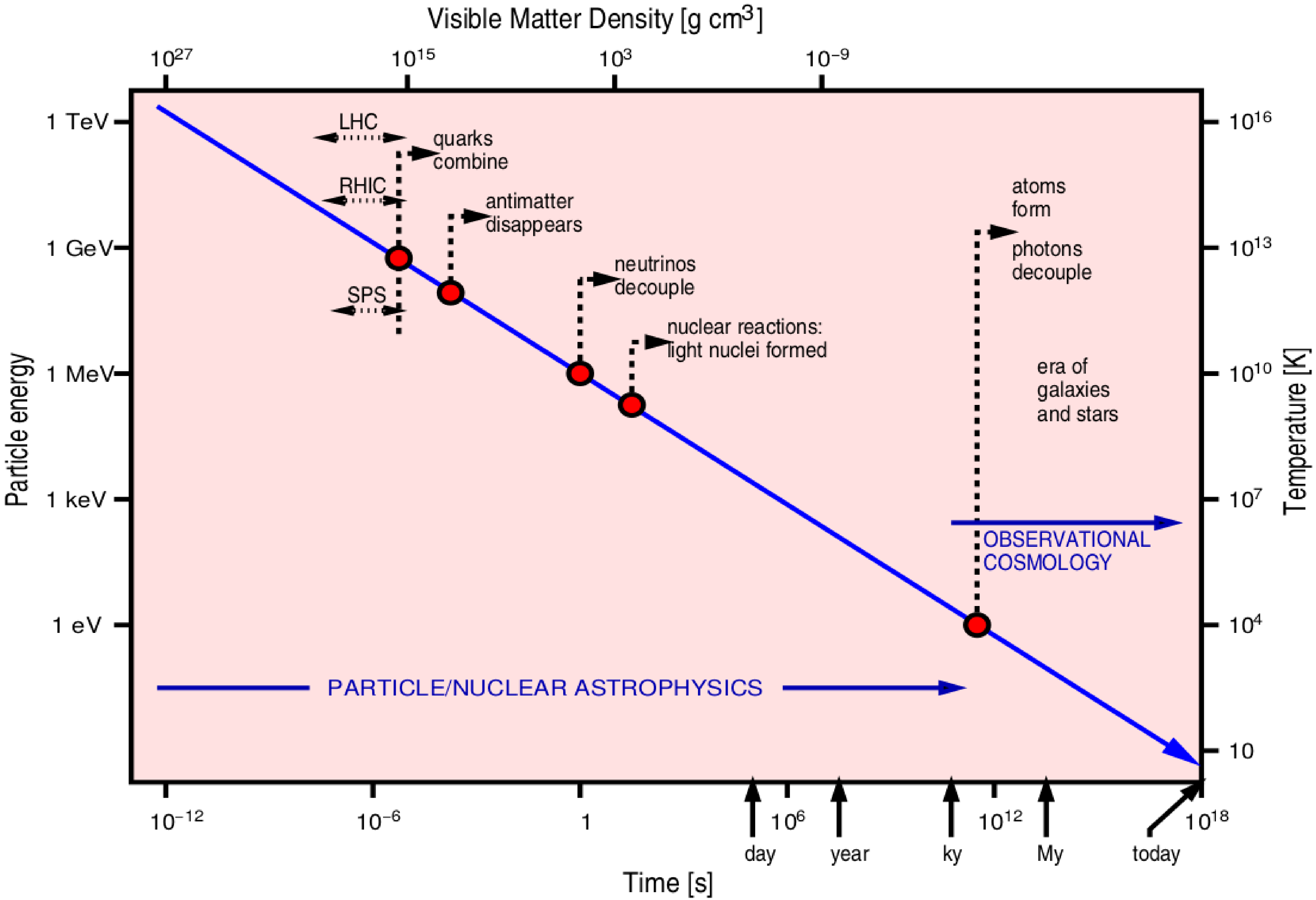
DOI: http://dx.doi.org/10.1063/1.3035005



COMPOSITION OF EXPANDING UNIVERSE changes as temperature drops. In the hadron era, strongly interacting particles predominate; the baryons annihilate and only one in 10

We did NOT know what was there at the 'Beginning' how matter was created.

Overview of the evolution of the Universe



Distinct Composition Eras in the Universe

Composition of the Universe changes as function of T:

- From Higgs freezing to freezing of QGP
- QGP hadronization
- Hadronic antimatter annihilation
- Onset of neutrino free-streaming just before and when
- e^+e^- annihilate; overlapping with begin of
- Big-Bang nucleosynthesis within a remnant e^+e^- plasma
- Radiation ‘Desert’(ν, γ)
- emergence of free streaming dark matter
- Photon Free-streaming (CMB) – Composition Cross-Point
- emergence of Dark energy = vacuum energy

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** $\Lambda = 8\pi G\mathcal{B}$**:**

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

Definitions: Hubble parameter H and deceleration parameter q:

$$H(t) \equiv \frac{\dot{a}}{a}; \quad q \equiv -\frac{a\ddot{a}}{\dot{a}^2} = -\frac{1}{H^2}\frac{\ddot{a}}{a}, \Rightarrow \dot{H} = -H^2(1+q).$$

Two dynamically independent Einstein equations arise

$$\frac{8\pi G_N}{3}\rho = \frac{\dot{a}^2+k}{a^2} = H^2\left(1+\frac{k}{\dot{a}^2}\right), \quad \frac{4\pi G_N}{3}(\rho+3P) = -\frac{\ddot{a}}{a} = qH^2.$$

solving both these equations for $8\pi G_N/3 \to$ we find for the deceleration parameter:

$$q = \frac{1}{2}\left(1+3\frac{P}{\rho}\right)\left(1+\frac{k}{\dot{a}^2}\right); \quad k=0$$

In flat $k=0$ Universe: ρ fixes H; with P also q fixed, and thus also $\dot{H}$ fixed so also $\dot{\rho}$ fixed, and therefore also for $\rho = \rho(T(t))$ and also $\dot{T}$ fixed. Knowing the Universe composition in present era we can integrate back IF we know what is the contents.

Evolution Eras and Deceleration Parameter q

Using Einsteins equations solving for $G_N = G_N$

$$q \equiv -\frac{\ddot{a}a}{\dot{a}^2} = \frac{1}{2}\left(1 + 3\frac{P}{\rho}\right)\left(1 + \frac{k}{\dot{a}^2}\right) \quad k = 0 \text{ favored}$$

- Radiation dominated universe: $P = \rho/3 \implies q = 1.$
- Matter dominated universe: $P \ll \rho \implies q = 1/2.$
- Dark energy (Λ) dominated universe: $P = -\rho \implies q = -1.$
  Accelerating Universe

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**

Particle composition in thermal Universe

The chemistry of particle reactions in the Universe has three ‘chemical’ potentials needing to be constrained. There are also three physics constraints Michael J. Fromerth, JR etal e-Print: astro-ph /0211346; arXiv:1211.4297 → Acta Phys.Polon. B43 (2012), 2261

i. Electrical charge neutrality

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

Q_i and n_i charge and number density of species i.

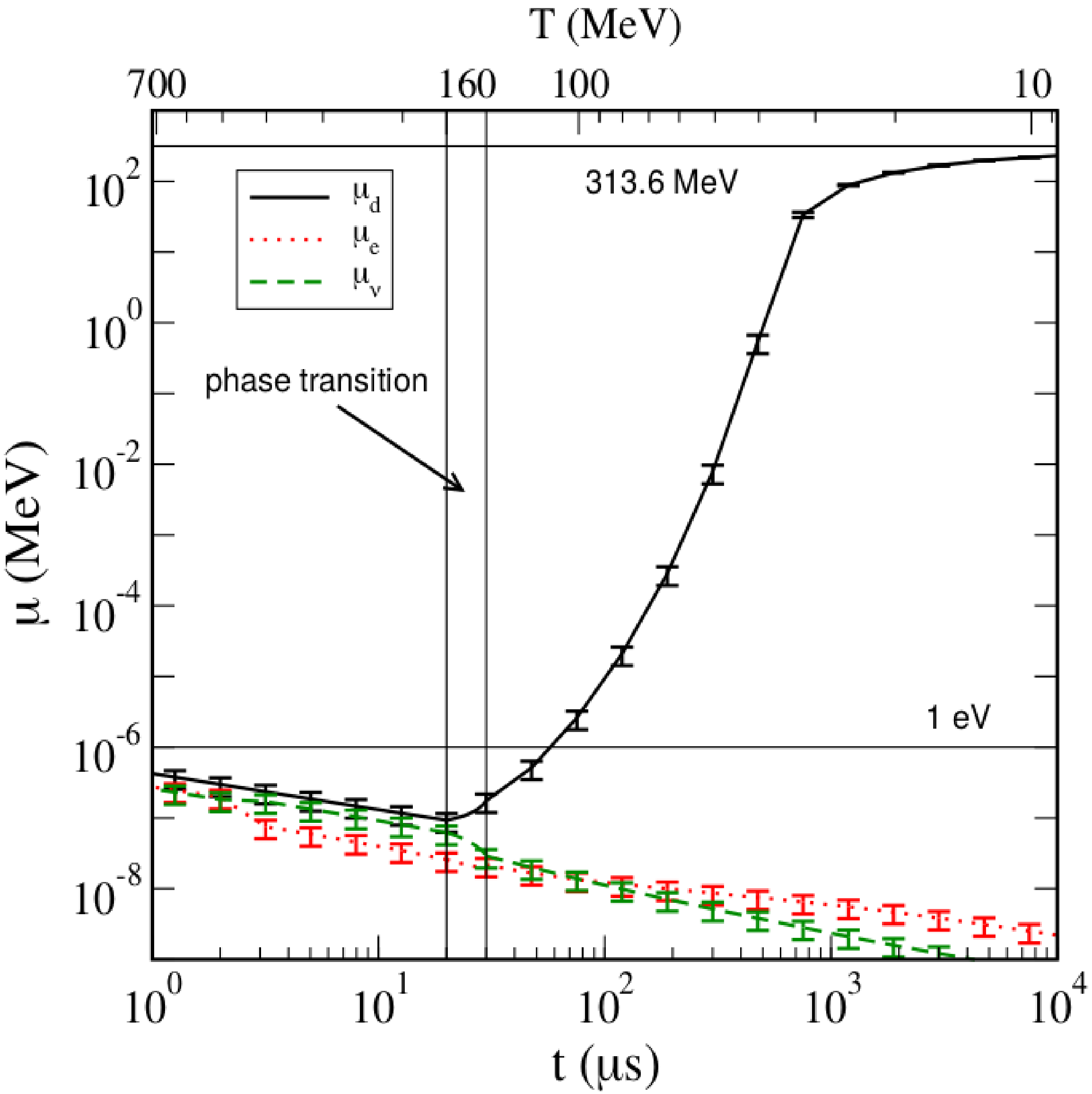
ii. Net lepton number equals(?) net baryon number
B/L-asymmetry can hide in neutrino-antineutrino imbalance

iii. Prescribed value of entropy-per-baryon $\equiv n_B/n_\gamma$

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

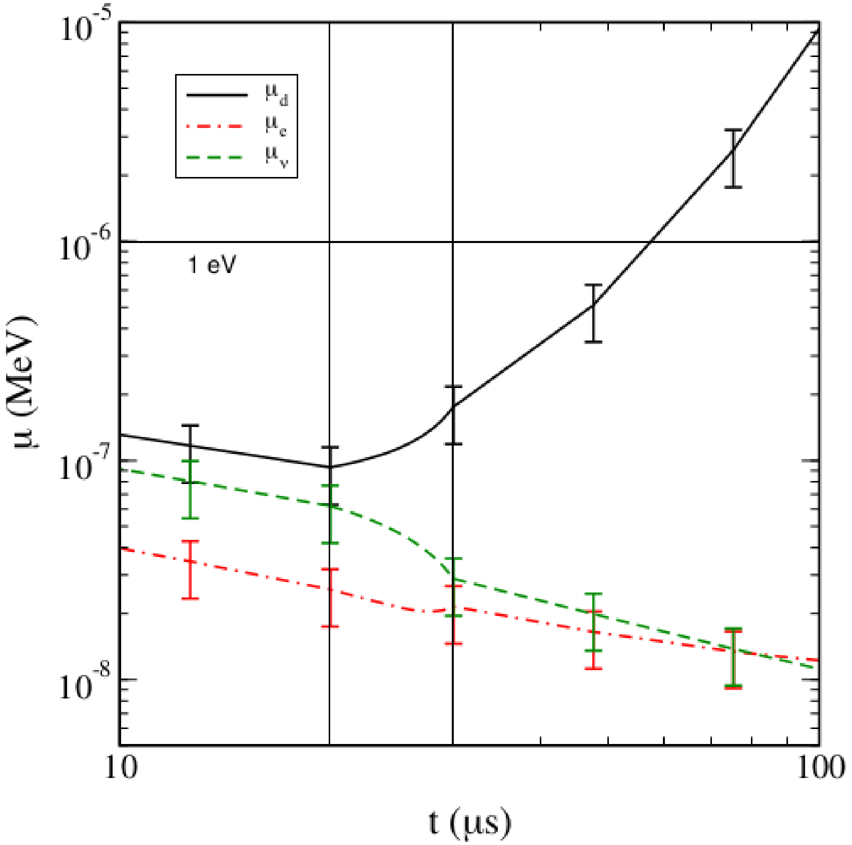
$S/B \simeq 3$–$5{\times}10^{10}$, results shown for 4.5×10^{10}

TRACING μ_d IN THE UNIVERSE

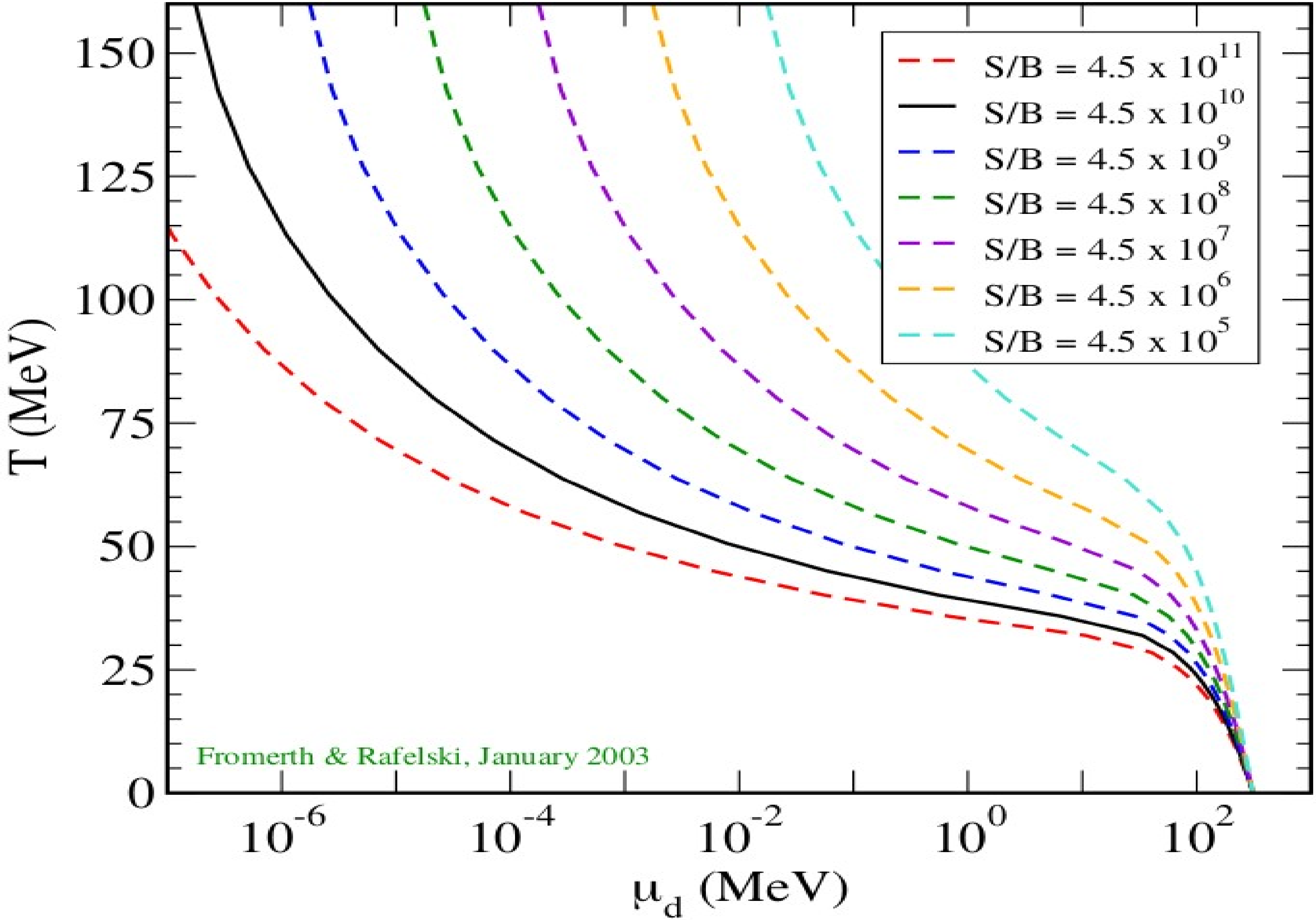


Minimum $\mu_b = 0.33^{+0.11}_{-0.08}$ eV.

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



TRACING μ_d IN A UNIVERSE



Fromerth & Rafelski, January 2003

Mixed Phase – Case differs from RHI hadronization

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 $Q = 0$:

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

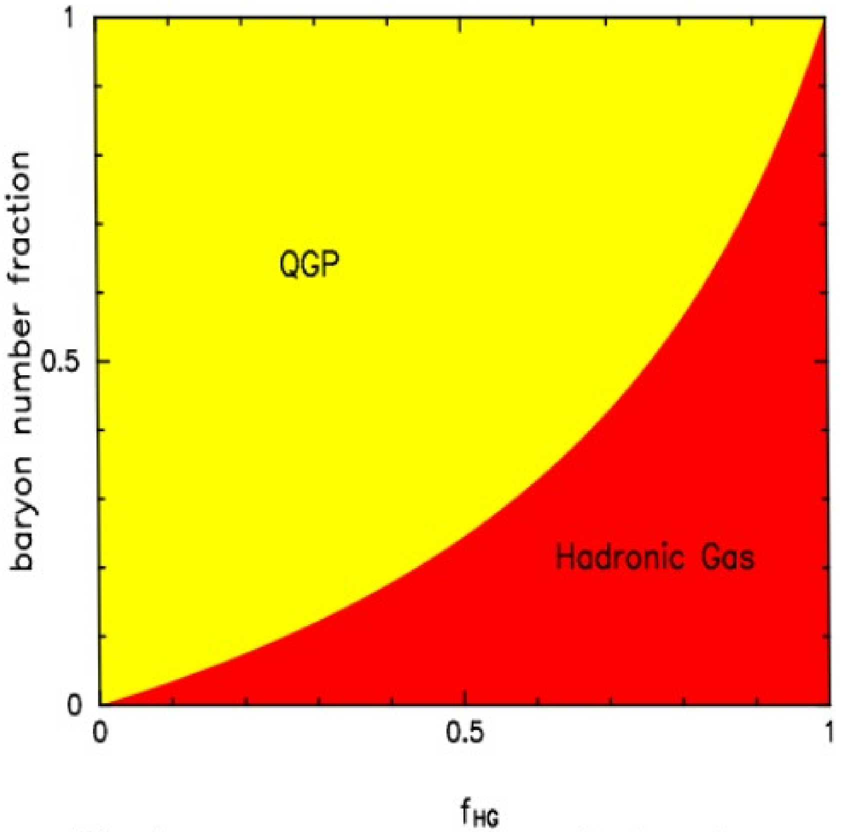
where the total volume $V_{\rm tot}$ is irrelevant to the solution. Analogous expressions are used for $L - B$ and S/B constraints. Note that $f_{\rm HG}(t)$ is result of dynamics of nucleation, assumed not generated here

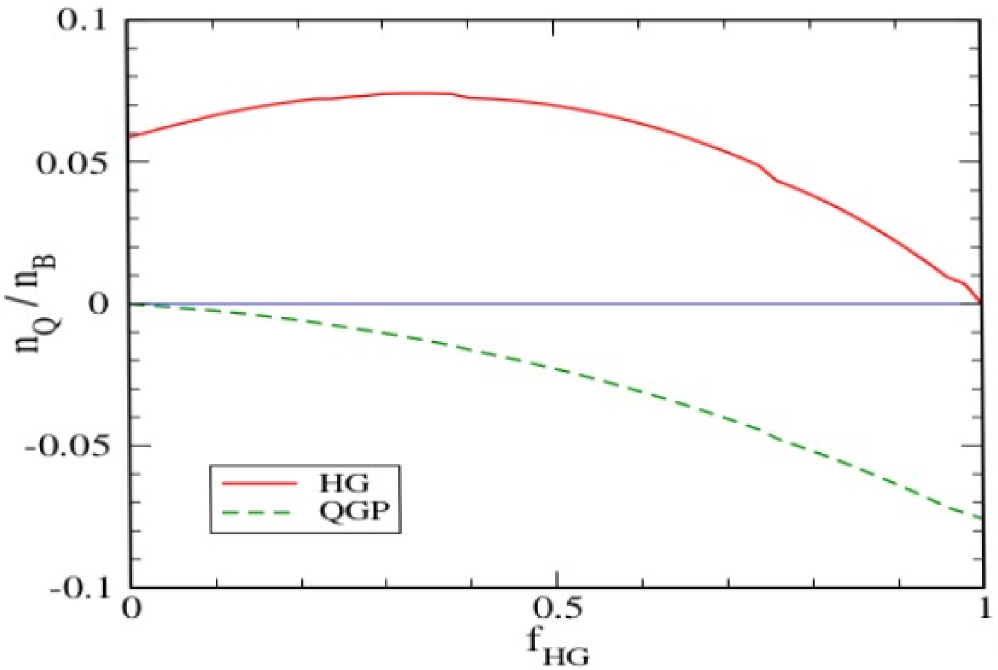
We assume that mixed phase exists $10\,\mu s$ and that $f_{\rm HG}$ changes linearly in time. Actual values will require dynamic nucleation transport theory description.

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%.

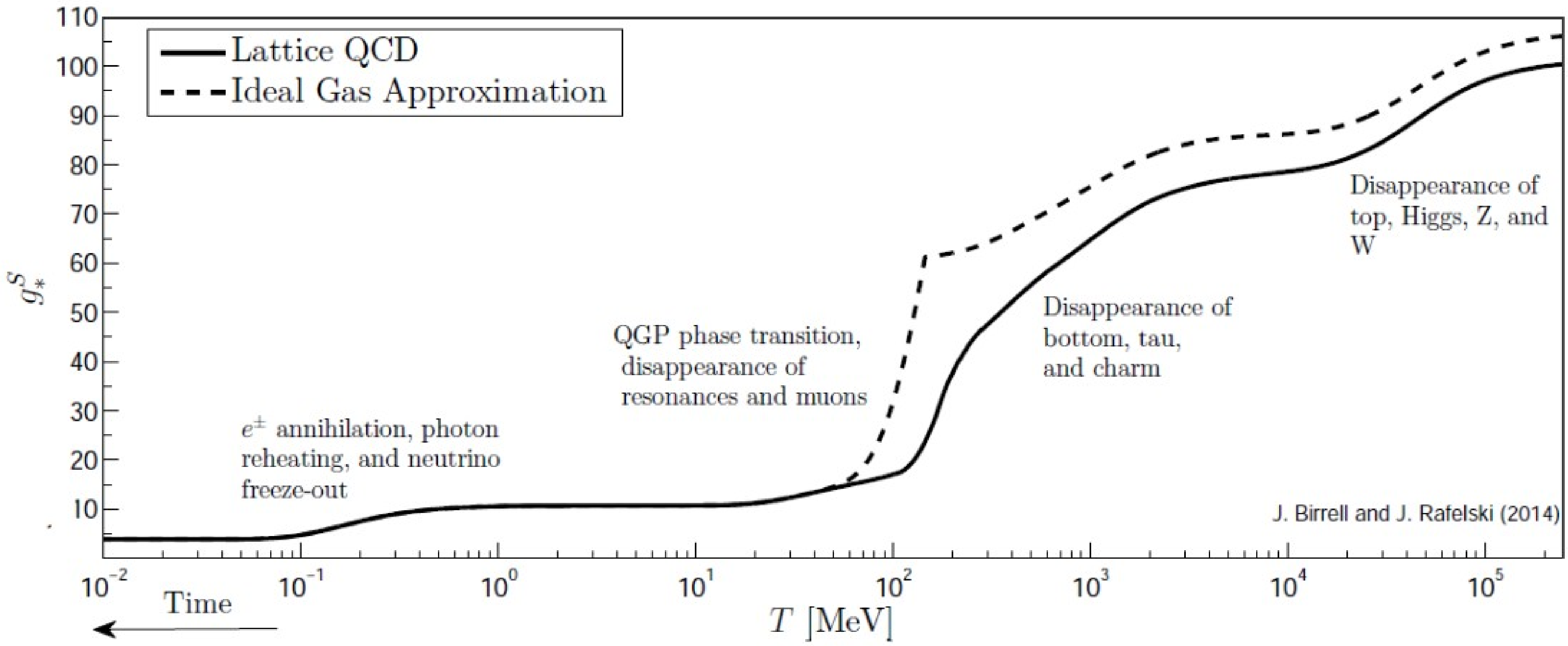
The constraint to a charge neutral universe conserves sum-charge in both fractions. Charge in each fraction can be finite. SAME for baryon number and strangeness: distillation!





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.

Count of Degrees of Freedom



Distinct Composition Eras visible. Equation of state from lattice-QCD, and at high T thermal-QCD must be used [1,2].

[1] *S. Borsanyi, Nucl. Phys. A904-905, 270c (2013)*

[2] *Mike Strickland (private communication of results and review of thermal SM).*

Reheating

Once a family ‘i’ of particles decouples at a photon temperature of T_i, a difference in its temperature from that of photons will build up during subsequent reheating periods as other particles feed their entropy into photons. This leads to a temperature ratio at $T_\gamma < T_i$ of

$$R \equiv T_i/T_\gamma = \left(\frac{g_*^S(T_\gamma)}{g_*^S(T_i)}\right)^{1/3} .$$

This determines the present day reheating ratio as a function of decoupling temperature T_i throughout the Universe history.

Example: neutrinos colder compared to photons.

Reheating ‘hides’ early freezing particles: darkness

Mechanisms assuring hadrons in thermal equilibrium

The key doorway reaction to abundance (chemical) equilibrium of the fast diluting hadron gas in Universe:

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

The lifespan $\tau_{\pi^0} = 8.4 \times 10^{-17}$ sec defines the strength of interaction which beats the time constant of Hubble parameter of the epoch. Inga Kuznetsova and JR, Phys. Rev. C82, 035203 (2010) and D78, 014027 (2008) (arXiv:1002.0375 and 0803.1588).

Equilibrium abundance of π^0 assures equilibrium of charged pions due to charge exchange reactions; heavier mesons and thus nucleons, and nucleon resonances follow:

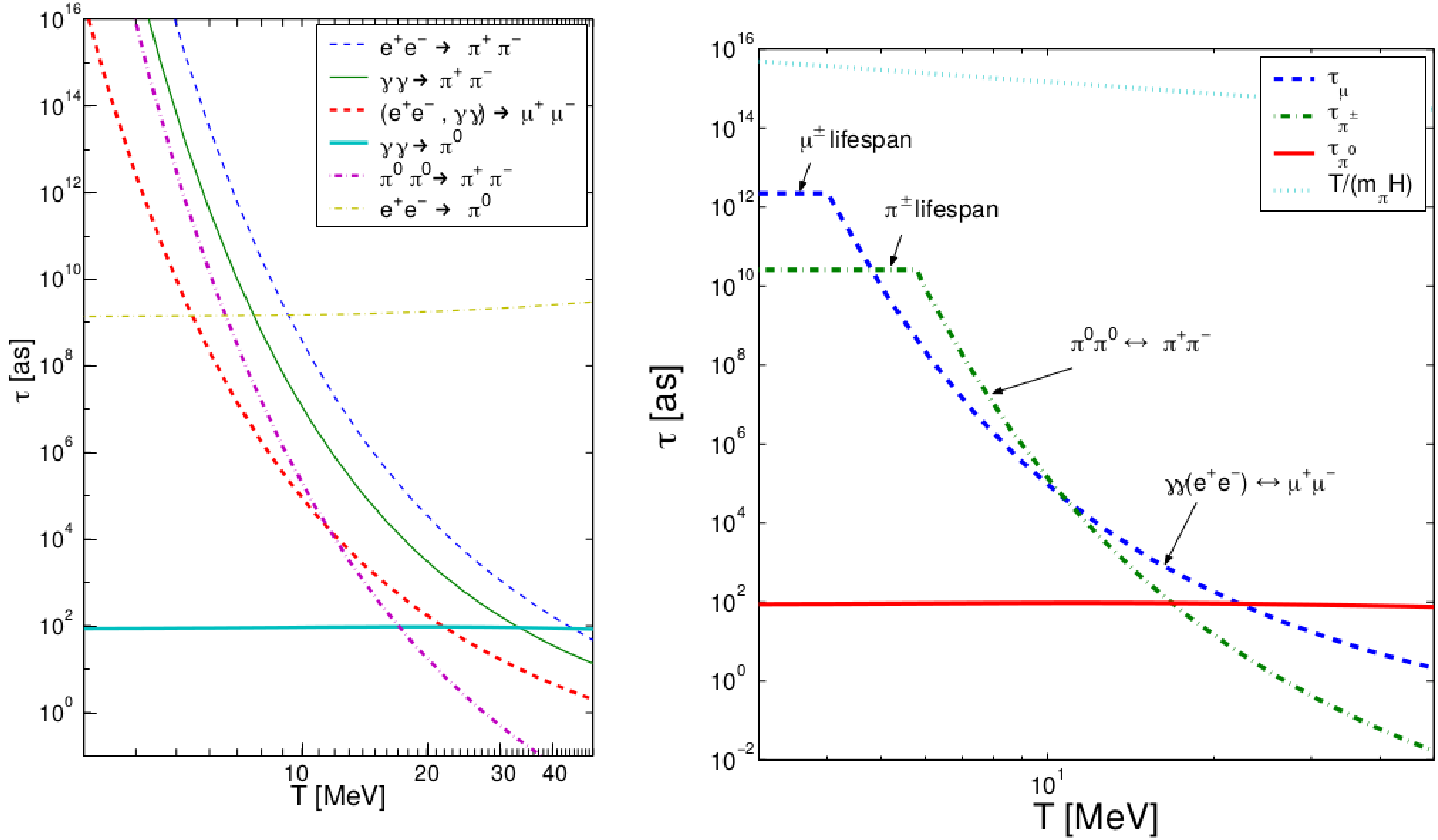
$$\pi^0 + \pi^0 \leftrightarrow \pi^+ + \pi^-. \quad \rho \leftrightarrow \pi + \pi, \quad \rho + \omega \leftrightarrow N + \bar{N}, \quad etc$$

The π^0 remains always in chemical equilibrium All charged leptons always in chemical equilibrium – with photons

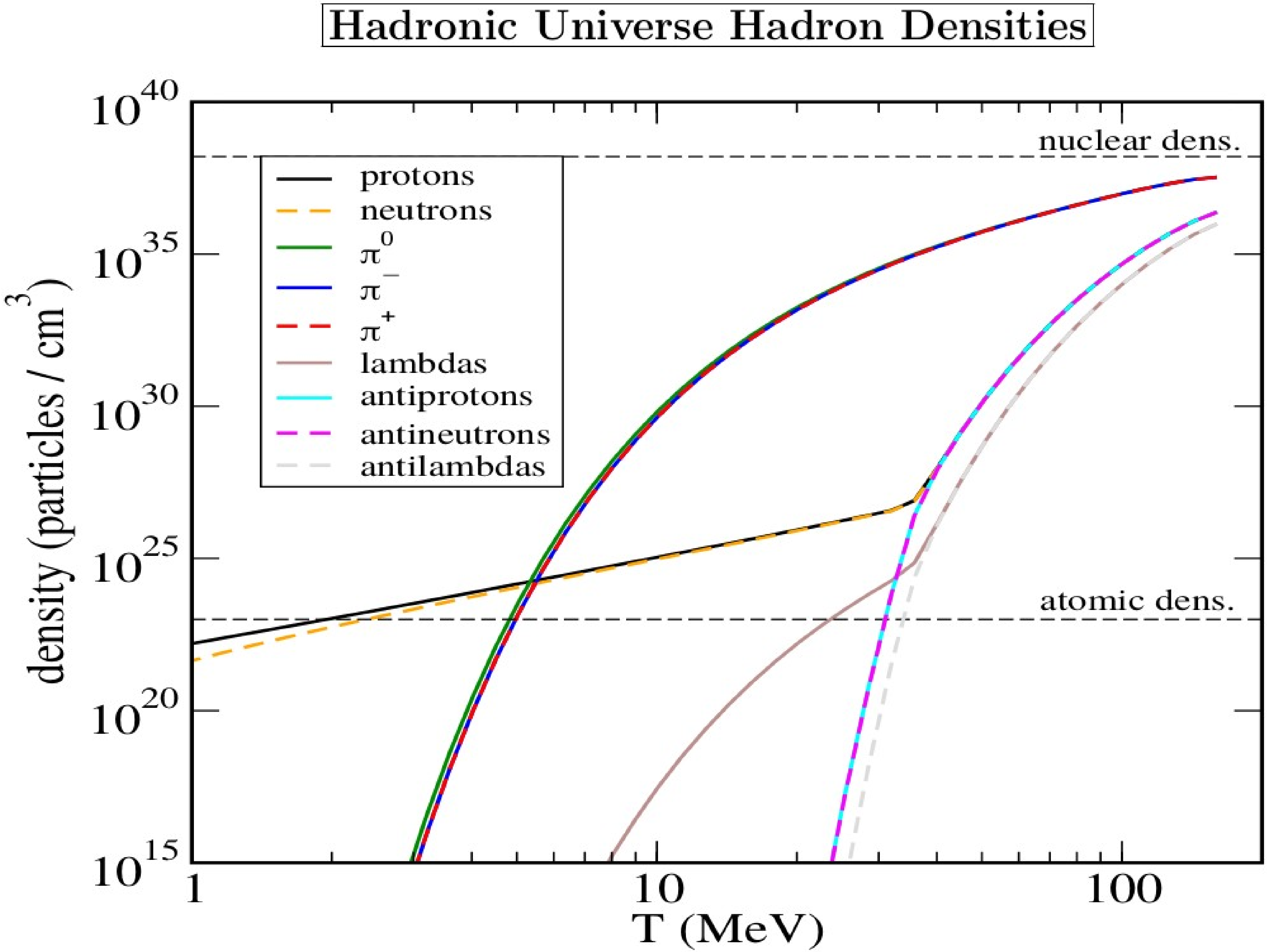
Neutrinos freeze-out at $T = \mathcal{O}$2-4MeV, more discussion follows

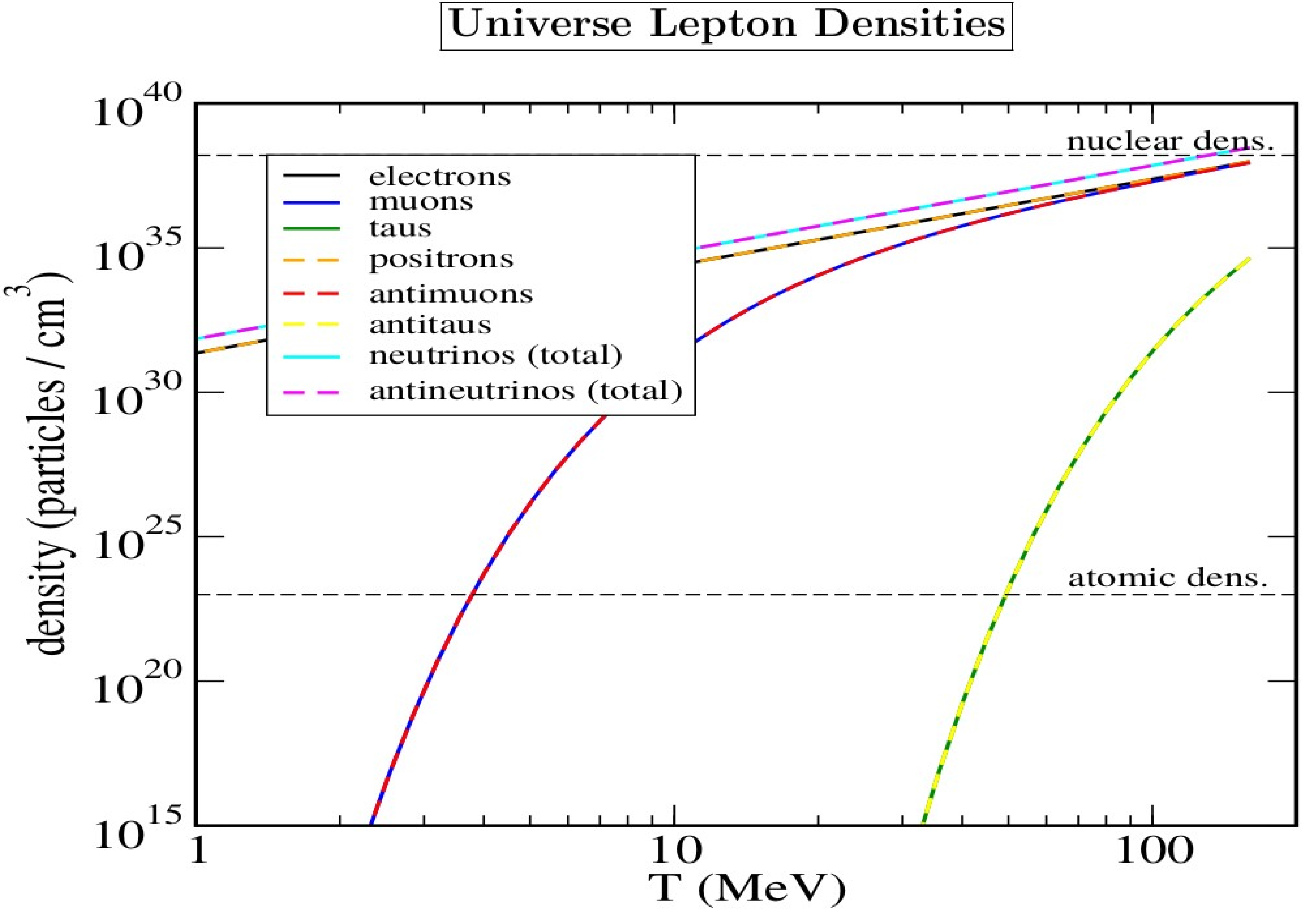
Photons freeze-out at $T = 0.25$ eV

But is the early Universe really made of hadrons?



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
nuclear dens.
atomic dens.
protons
neutrons
π^0
π^-
π^+
lambdas
antiprotons
antineutrons
antilambdas
density (particles / cm^3)
10^{40}
10^{35}
10^{30}
10^{25}
10^{20}
10^{15}
1
10
100
T (MeV)


Universe Lepton Densities
density (particles / cm^3)
10^{40}
10^{35}
10^{30}
10^{25}
10^{20}
10^{15}
1
10
100
T (MeV)
nuclear dens.
atomic dens.
electrons
muons
taus
positrons
antimuons
antitaus
neutrinos (total)
antineutrinos (total)

Free-streaming matter in the Universe: solution of kinetic equations with decoupling boundary conditions at T_k (kinetic freeze-out).

$$\rho = \frac{g}{2\pi^2}\int_0^\infty \frac{\left(m^2+p^2\right)^{1/2} p^2 dp}{\Upsilon^{-1} e^{\sqrt{p^2/T^2+m^2/T_k^2}}+1}, \quad P = \frac{g}{6\pi^2}\int_0^\infty \frac{\left(m^2+p^2\right)^{-1/2} p^4 dp}{\Upsilon^{-1} e^{\sqrt{p^2/T^2+m^2/T_k^2}}+1},$$

$$n = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\Upsilon^{-1} e^{\sqrt{p^2/T^2+m^2/T_k^2}}+1}.$$

These differ from the corresponding expressions for an equilibrium distribution by the replacement $m \rightarrow mT(t)/T_k$ *only* in the exponential. Only for massless photons free-streaming = thermal distributions (absence of mass-energy scale). For CDM (cold dark matter) $m_{\mathrm{CDM}} >> T_k$; for neutrinos $m_\nu << T_k$.

C. Cercignani, and G. Kremer. The Relativistic Boltzmann Equation: Basel, (2000).
H. Andreasson, “The Einstein-Vlasov System”Living Rev. Rel. **14***, 4 (2011) Y. Choquet-Bruhat. General Relativity and the Einstein Equations, Oxford (2009).*

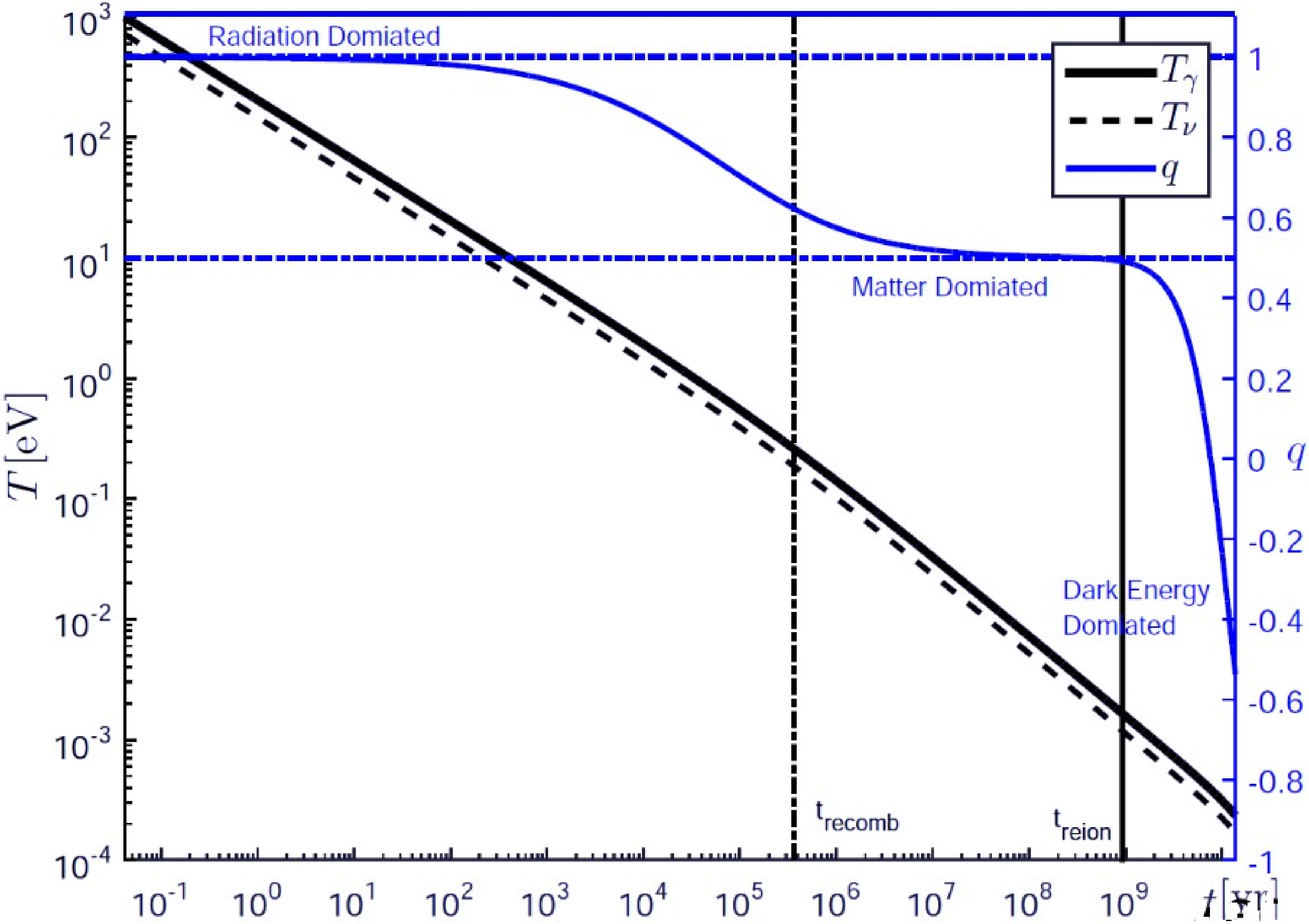
Evolution Eras and Deceleration Parameter q

Using Einsteins equations solving for $G_N = G_N$

$$q \equiv -\frac{\ddot{a}a}{\dot{a}^2} = \frac{1}{2}\left(1 + 3\frac{P}{\rho}\right)\left(1 + \frac{k}{\dot{a}^2}\right) \quad k = 0 \text{ favored}$$

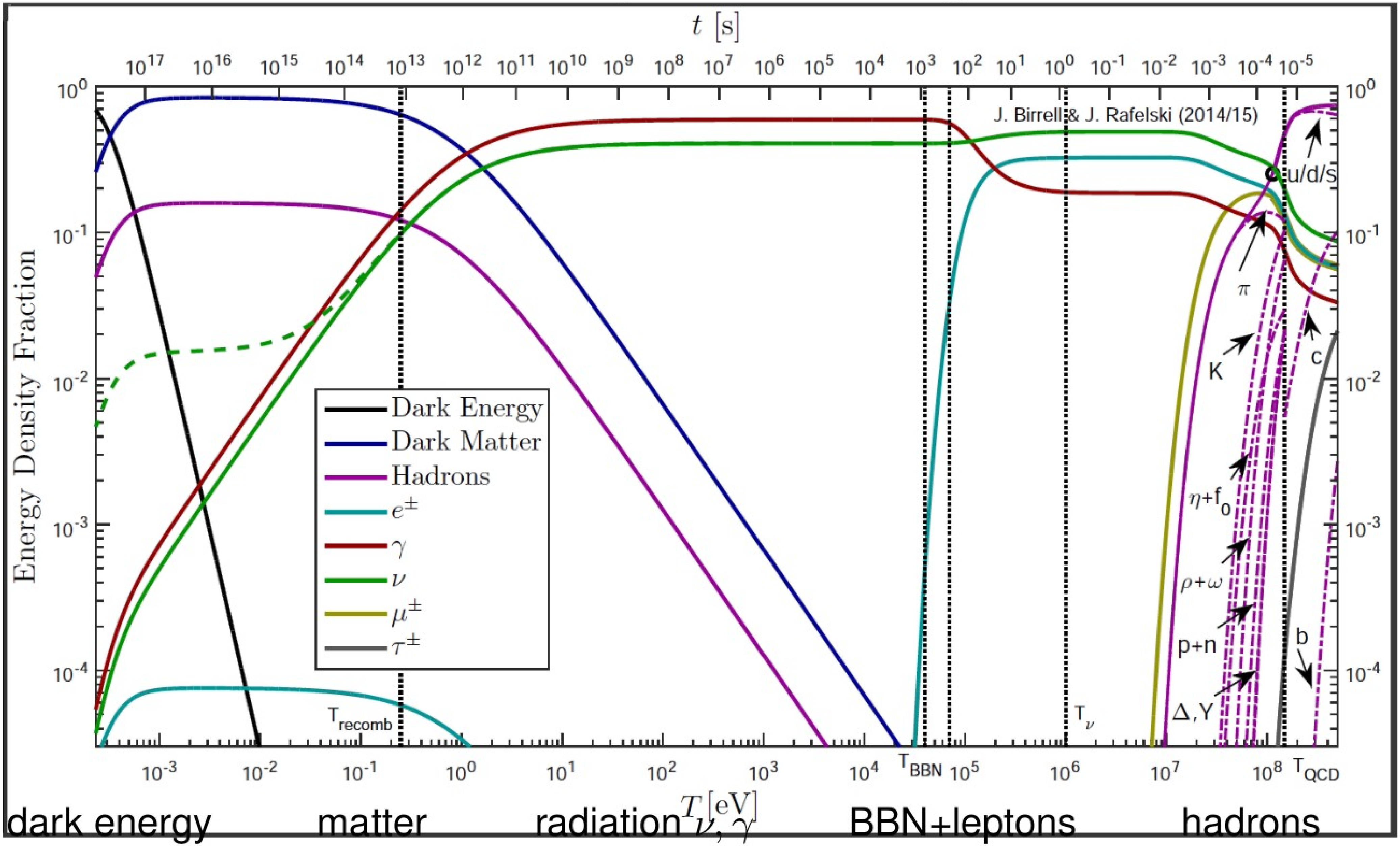
- Radiation dominated universe: $P = \rho/3 \implies q = 1.$
- Matter dominated universe: $P \ll \rho \implies q = 1/2.$
- Dark energy (Λ) dominated universe: $P = -\rho \implies q = -1.$
  Accelerating Universe

‘Recent’ evolution



Evolution of temperature T and acceleration parameter q from near/after BBN to the present day: time grows to right

The Universe Composition in Single View



Different dominance eras: Temperature grows to right

Summary

- 50 years ago particle production in pp reactions prompted introduction of Hagedorn Temperature T_{H} along with singular energy density – linked to the Big-Bang;
- By 1980 T_{H} critical temperature at which vacuum 'melts', matter surrounding us dissolves; This prompts CERN and BNL experimental program to recreate pre-matter in laboratory.
- Today: In laboratory: We explore the phase diagram of QGP and strangeness; In cosmology: we study the evolution of the Quark-Universe across many domains to the present day.
- We have detailed understanding how quark Universe evolves and the matter Universe arises
- Comprehensive view allows diverse consistency studies: we set limits on variation of natural constants in early Universe, constrain any new radiance (darkness); characterize cosmic microwave neutrinos. Interface to vacuum bi-stability issue.