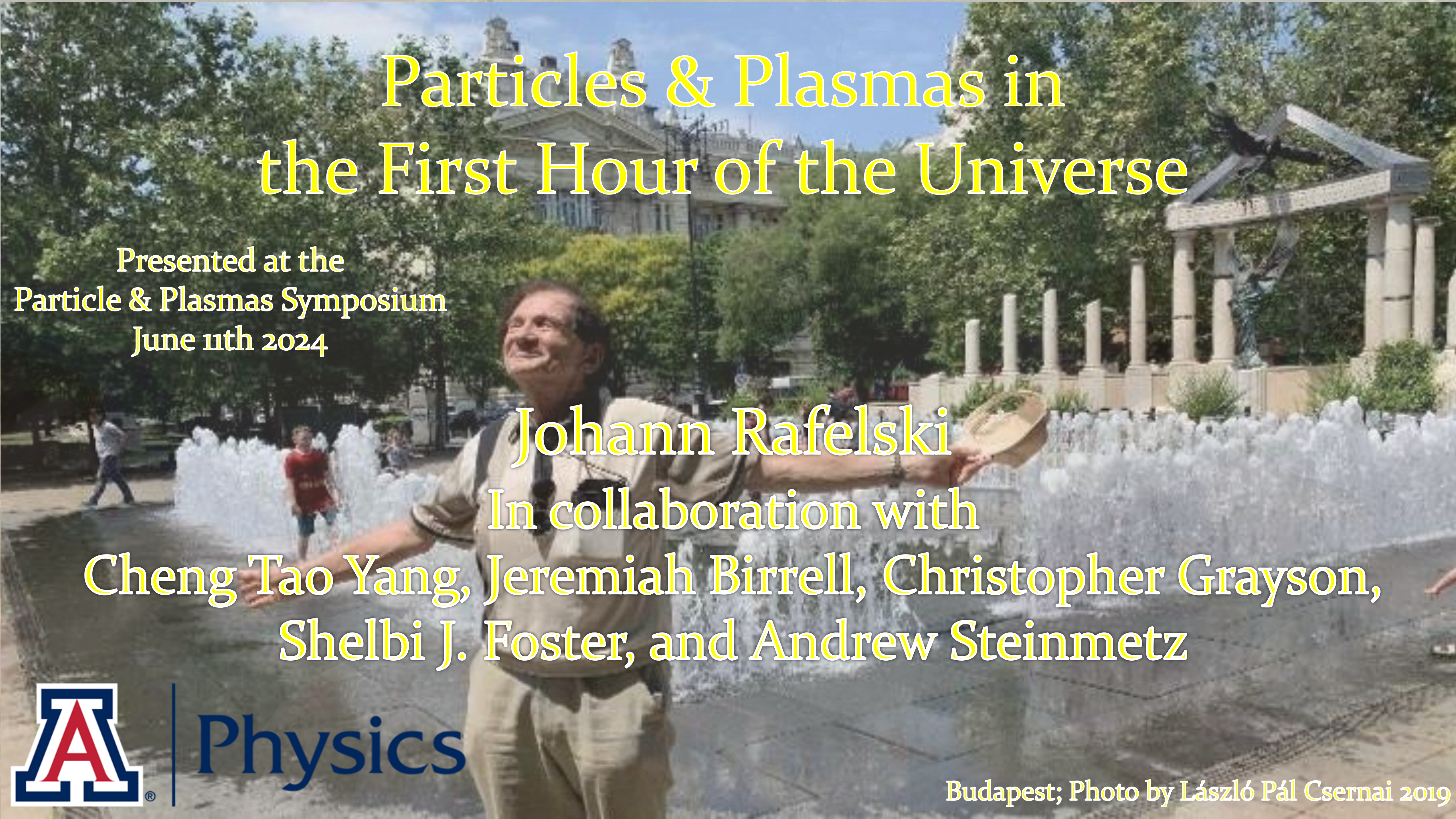
Particles & Plasmas in the First Hour of the Universe

Presented at the
Particle & Plasmas Symposium
June 11th 2024

Johann Rafelski

In collaboration with
Cheng Tao Yang, Jeremiah Birrell, Christopher Grayson,
Shelbi J. Foster, and Andrew Steinmetz

Physics



Budapest; Photo by László Pál Csernai 2019

Abstract and colleagues

We deepen the understanding of the primordial composition of the Universe in the temperature range 130 GeV > T > 0.02 MeV within the Big Bang model. Massive elementary particles: t, b, c-quarks, τ, μ-leptons, and W, Z-gauge bosons emerged at about T = 130 GeV. These elementary particles in the following were abundantly present as the Universe expanded and cooled – our interest is to search for periods of possible chemical non-equilibrium of great importance in baryogenesis. Once the temperature dropped below T = 150 MeV quarks and gluons hadronize into matter. We follow the Universe evolution in depth and study near T = O(2) MeV the emergence of the free-streaming neutrino era and develop methods to understand speed of the Universe expansion. We subsequently follow the early universe pass through the hot dense electron-positron plasma epoch and we analyze the paramagnetic characteristics of the electron-positron plasma when exposed to an external primordial magnetic field. The high density of positron antimatter persisted into the Big Bang Nucleosynthesis era which thus requires study of nuclear reactions in the presence of a highly mobile plasma phase, a topic of the following lecture by Chris.

Prof. Johann Rafelski

Dr. Andrew Steinmetz

Dr. Jeremiah Birrell

Dr. Christopher Grayson

Dr. Cheng Tao Yang

Shelbi J. Foster

Our recent and forthcoming work

Chris's lecture

ELSEVIER
Annals of Physics
Volume 458, Part 1, November 2023, 169453

Electron–positron plasma in BBN: Damped-dynamic screening

Christopher Grayson [a], Cheng Tao Yang [a], Martin Formanek [b], Johann Rafelski [a]

PHYSICAL REVIEW D 108, 123522 (2023)

Matter-antimatter origin of cosmic magnetism

Andrew Steinmetz, Cheng Tao Yang, and Johann Rafelski
Department of Physics, The University of Arizona, Tucson, Arizona 85721, USA

(Received 30 August 2023; accepted 15 November 2023; published 11 December 2023)

We explore the hypothesis that the abundant presence of relativistic antimatter (positrons) in the primordial Universe is the source of the intergalactic magnetic fields we observe in the Universe today. We evaluate both Landau diamagnetic and magnetic dipole moment paramagnetic properties of the very dense primordial electron-positron e^+e^--plasma, and obtain in quantitative terms the relatively small magnitude of the e^+e^- magnetic moment polarization asymmetry required to produce a consistent self-magnetization in the Universe.

DOI: 10.1103/PhysRevD.108.123522

universe · Open Access · Review

A Short Survey of Matter-Antimatter Evolution in the Primordial Universe

by Johann Rafelski *, Jeremiah Birrell, Andrew Steinmetz and Cheng Tao Yang
Department of Physics, The University of Arizona, Tucson, AZ 85721, USA

Universe 2023, 9(7), 309; https://doi.org/10.3390/universe9070309

Submission received: 28 April 2023 / Revised: 16 June 2023 / Accepted: 19 June 2023 / Published: 27 June 2023

(This article belongs to the Special Issue Remo Ruffini Festschrift)

We offer a survey of the matter-antimatter evolution within the primordial Universe. While the origin of the tiny matter-antimatter asymmetry has remained one of the big questions in modern cosmology, antimatter itself has played a large role for much of the Universe's early history. In our study of the evolution of the Universe we adopt the position of the standard model Lambda-CDM Universe implementing the known baryonic asymmetry. We present the composition of the Universe across its temperature history while emphasizing the epochs where antima essential to our understanding. Special topics we address include the heavy quarks in quark-gluon pl the creation of matter from QGP, the free-streaming of the neutrinos, the vanishing of the muons, the the electron-positron cosmos, and a better understanding of the environment of the Big Bang Nucleosy producing the light elements. We suggest but do not explore further that the methods used in explo Universe may also provide new insights in the study of exotic stellar cores, magnetars, as well as gan (GRB) events. We describe future investigations required in pushing known physics to its extremes laboratory of the matter-antimatter early Universe.

Keywords: particles; plasmas and electromagnetic fields in cosmology; quarks to cosmos

ELSEVIER
Physics Letters B
Volume 827, 10 April 2022, 136944

Cosmological strangeness abundance

Cheng Tao Yang, Johann Rafelski

https://doi.org/10.1016/j.physletb.2022.136944
Get rights and content

We investigate the strange particle composition of the expanding early Universe n the hadron epoch $T_h \approx 150 \geq T \geq 10$ MeV. We study strangeness yield in hermal and chemical equilibrium constrained by prescribed conserved entropy per baryon in a charge neutral and strangeness neutral $\langle s - \bar{s} \rangle$ Universe. Turning to kinetic processes in a Hubble expanding Universe, we determine the conditions at which at decreasing temperature T individual strangeness producing reactions fall out of detailed balance between decay and back-reaction strangeness production rates: This is done by comparing the relevant reaction rates to the Hubble expansion rate. We allow for weak, electromagnetic, and strong interaction processes. The weak interaction $\mu^+ + \nu_\mu \to K^+$ freezeout is at $T_f^{K^+} = 33.8$ MeV; the electromagnetic process $l^- + l^+ \to \phi$ freezeout is at $T_f^\phi = 23 \sim 25$ MeV; and the hadronic reaction $\pi + \pi \to K$ freezeout is at $T_f^K = 19.8$ MeV

Forthcoming work

Nonequilibrium Higgs Abundance in Primordial Quark-Gluon Plasma

Cheng Tao Yang[a], Shelbi Foster[a], Johann Rafelski[a]
[a] *Department of Physics University of Arizona Tucson Arizona 85721 USA*

Abstract

We investigate dynamic abundance of Higgs in the primordial Quark-Gluon Plasma (QGP). By examining the reaction strength for Higgs production and decay, we demonstrate that Higgs exhibits prolonged nonequilibrium behavior within temperature range $1\,\text{GeV} > T > 0.3\,\text{GeV}$ due to the detailed balance between production and decay reactions. At temperatures below $T < 0.3\,\text{GeV}$, the Higgs abundance diminishes to zero due to the lack of bottom quarks in QGP. The rapid Higgs decay and production speed ensures that there are about 10^{17} of cycles of Higgs production processes occur during QGP. In this scenario, a small baryon violation at the level of 10^{-18} associated with cycling can result in the observed baryon number today.

Prof. Johann Rafelski

Dr. Andrew Steinmetz

Dr. Jeremiah Birrell

Dr. Christopher Grayson

Dr. Cheng Tao Yang

Shelbi J. Foster

Overview of primordial cosmic plasma

After "Big-Bang " the universe began as a fireball with extremely high temperature and high energy density.

Primordial quark-gluon plasma (the standard model of particle physics epoch):

At the early time when 130GeV > T > 150MeV, the standard model particles define the property and evolution of the Universe

Hadronic matter plasma epoch begins:

After hadronization quarks and mesons become confined within baryon and mesons, the visible matter in the Universe.

Lepton-photon plasma emerges as dominant energy content:

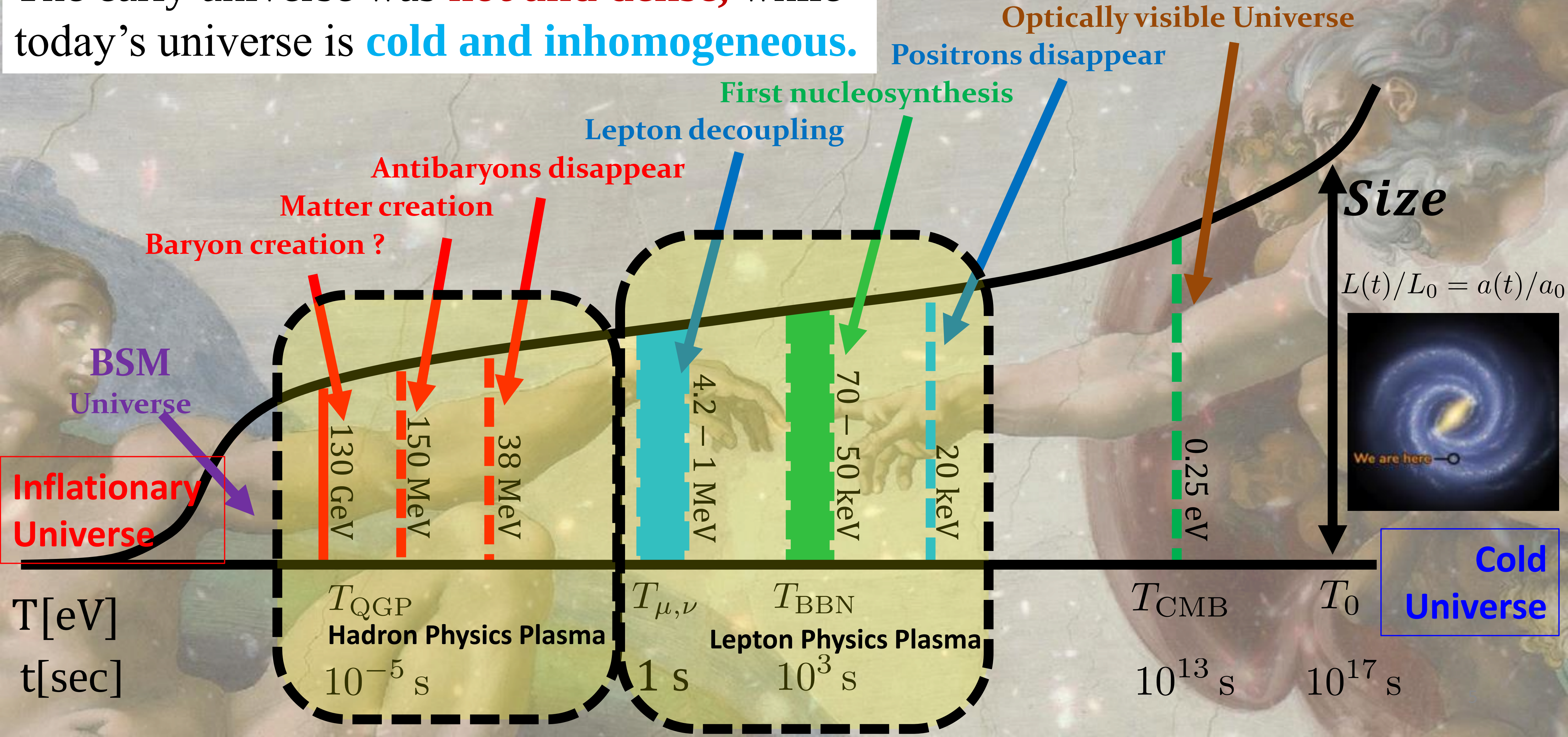
For temperature 10 MeV > T > 2 MeV, the Universe contained relativistic electrons, positrons, photons, and three species of (anti)neutrinos.

Electron-positron plasma persists:

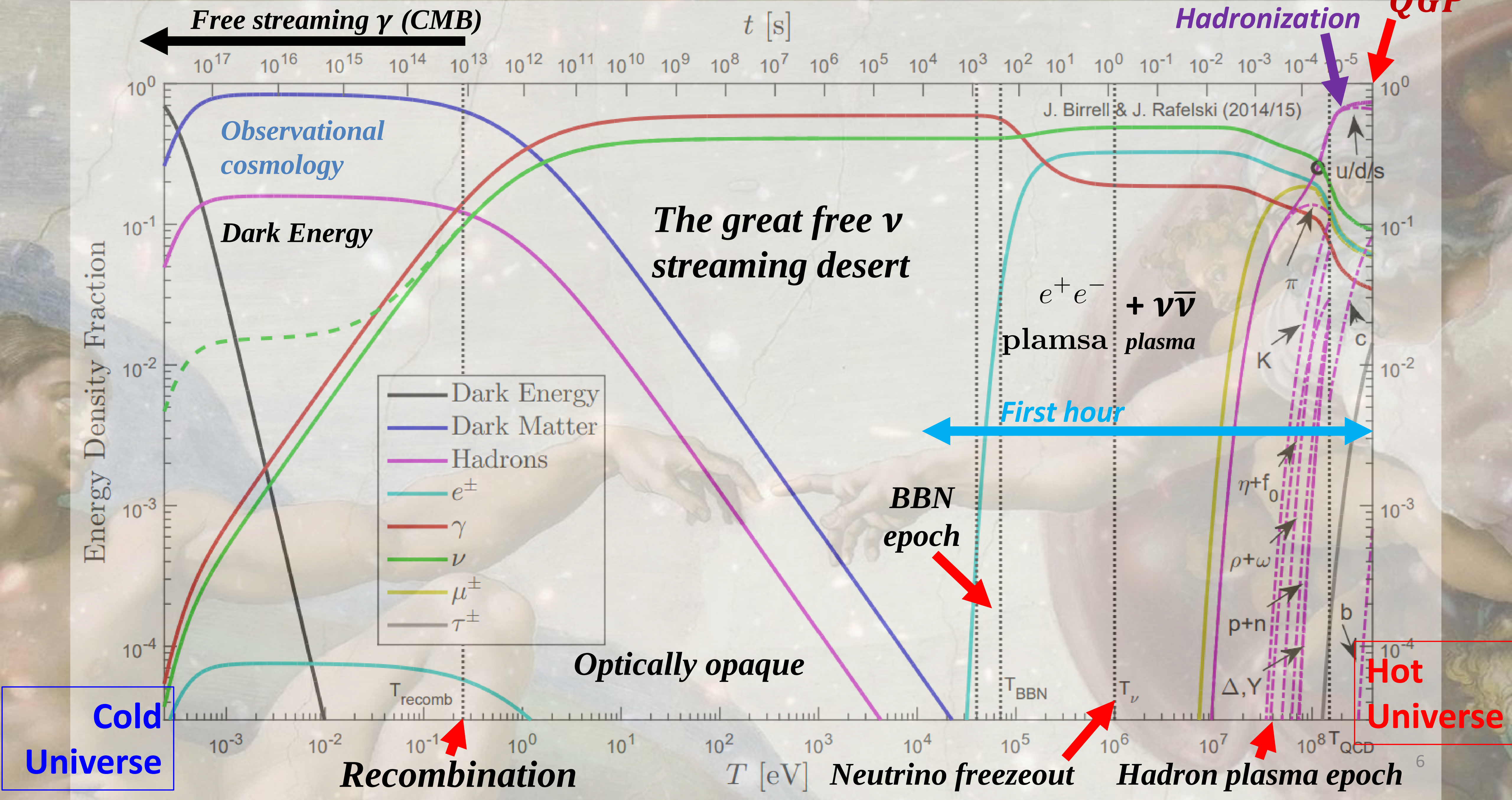
After neutrinos freeze-out, the cosmic plasma was dominated by electrons, positrons, and photons. Positrons existed until T=0.02MeV.

Major **events** in the early universe

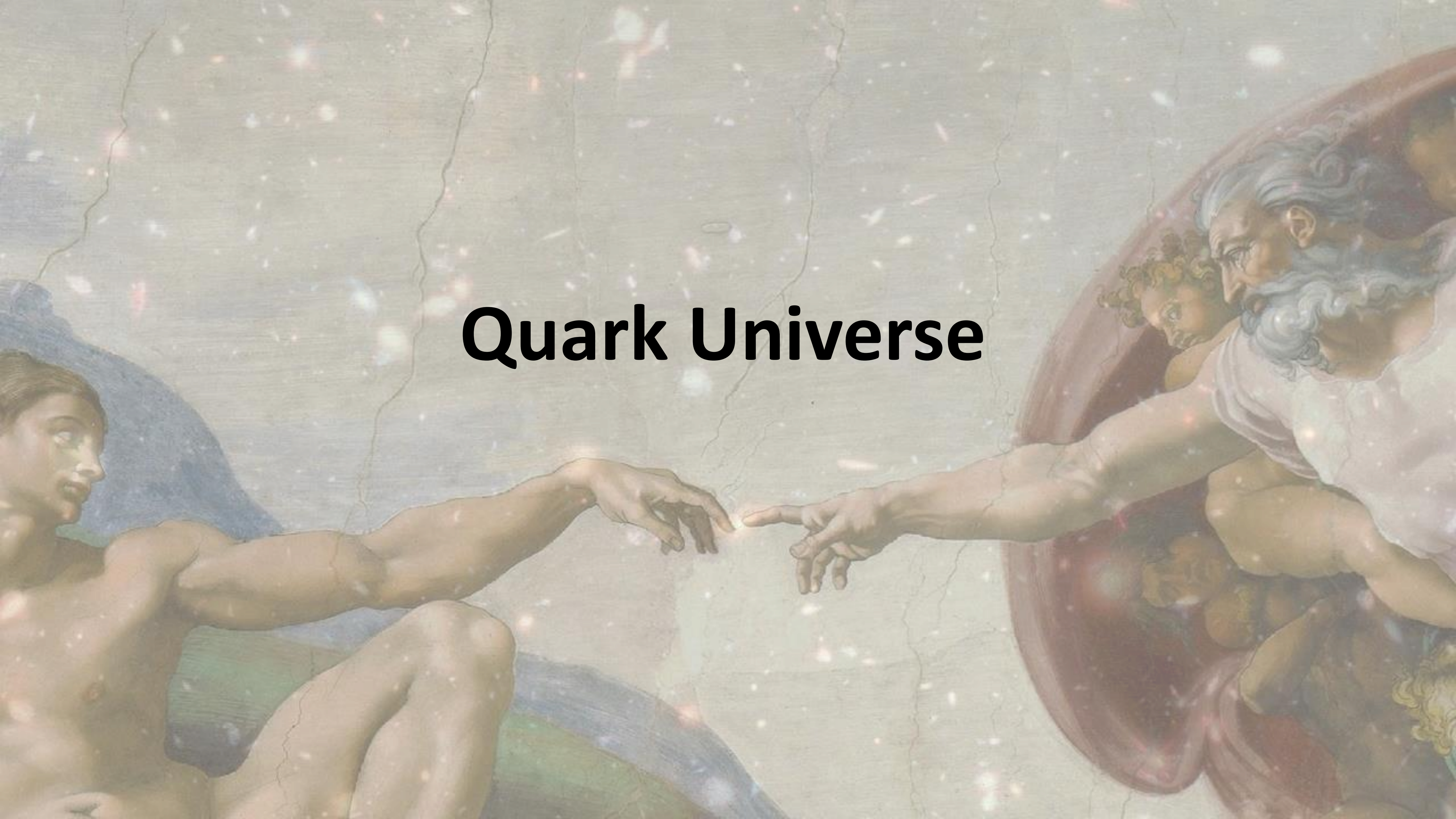
The early universe was **hot and dense,** while today's universe is **cold and inhomogeneous.**



Chemical equilibrium: A quick look at the Universe's composition



Quark Universe



The SM Universe: Primordial Quark-Gluon Plasma 130GeV to 150MeV

The primordial QGP epoch begins after the electroweak phase transition and ends when the universe reach the hadronization.

T=130 GeV — Primordial Quark-Gluon Plasma — T=150 MeV

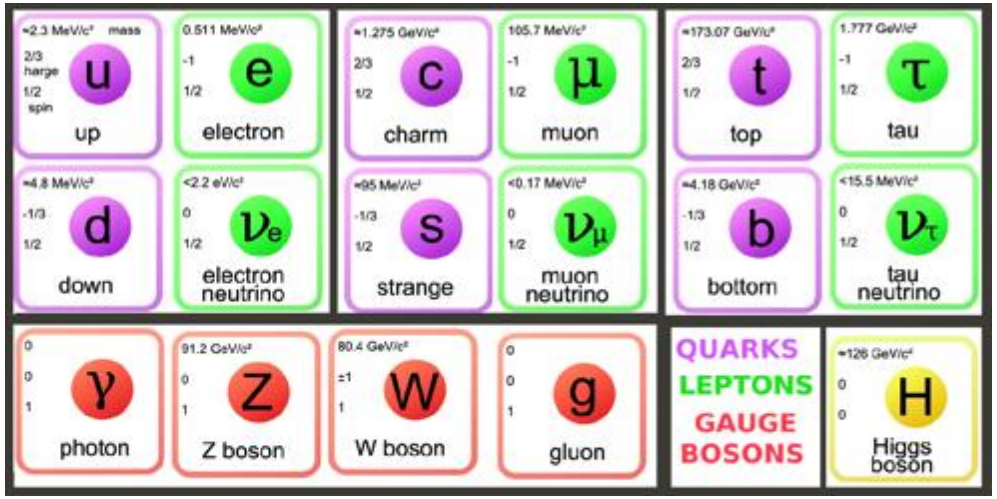
Electroweak phase transition

Top quark T=7.0GeV | Higgs T=5.7GeV | Z boson T=3.9GeV | W boson T=3.3GeV

condition where $n_i = (n_B - n_{\overline{B}})$

Hadronization

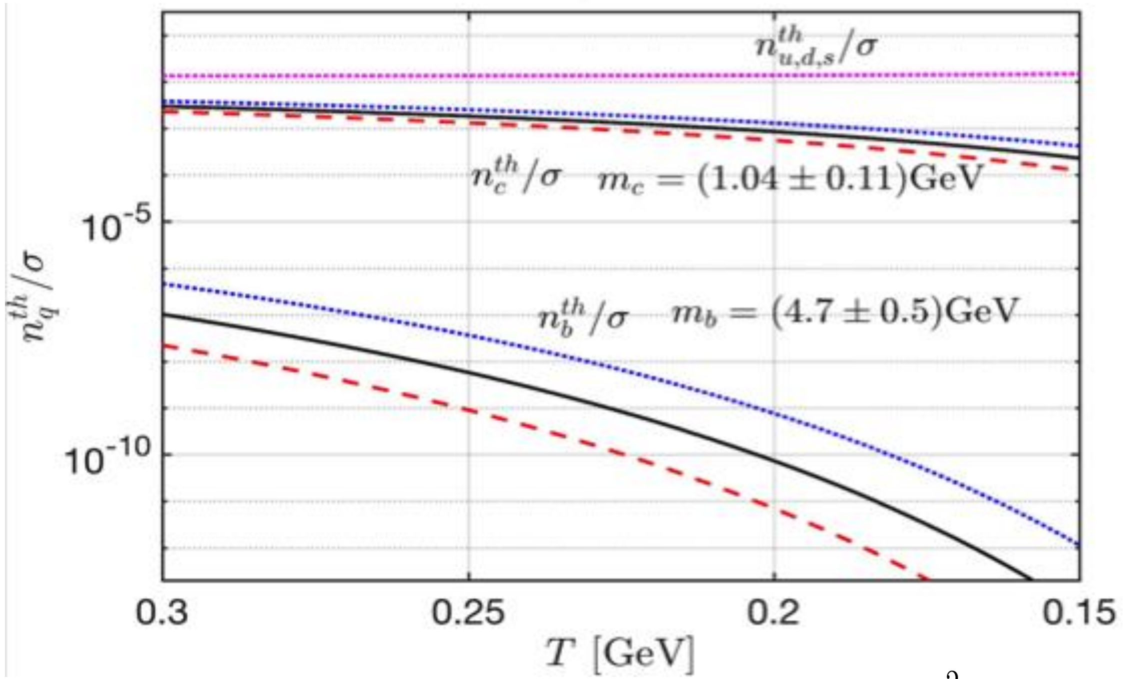
We are interested in temperature range 300MeV>T>150MeV



- Up/down are massless quarks and retain the equilibrium via gluon/quark fusion. Jean Letessier, JR, "Hadrons and Quark-Gluon Plasma"
- Strangeness retain the equilibrium via weak, electromagnetic, and strong interaction until T~13MeV

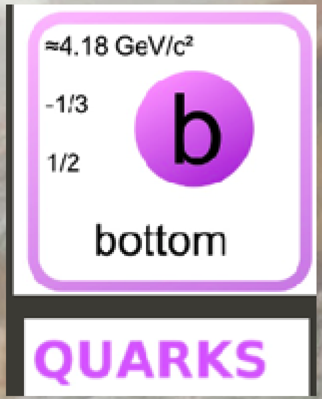
C.T. Yang and JR,``Cosmological strangeness abundance,'' Phys. Lett. B 827, 136944 (2022)

- We are working on the top quark, massive bosons W, Z and Higgs.



$$n_q = \frac{3}{4\pi^2} g_q \zeta(3) T^3 \qquad n^{th}_{b,c} = \frac{g_{b,c}}{2\pi^2} T^3 \left(\frac{m_{b,c}}{T}\right)^2 K_2(m_{b,c}/T)$$

Chemical nonequilibrium: Bottom production/decay

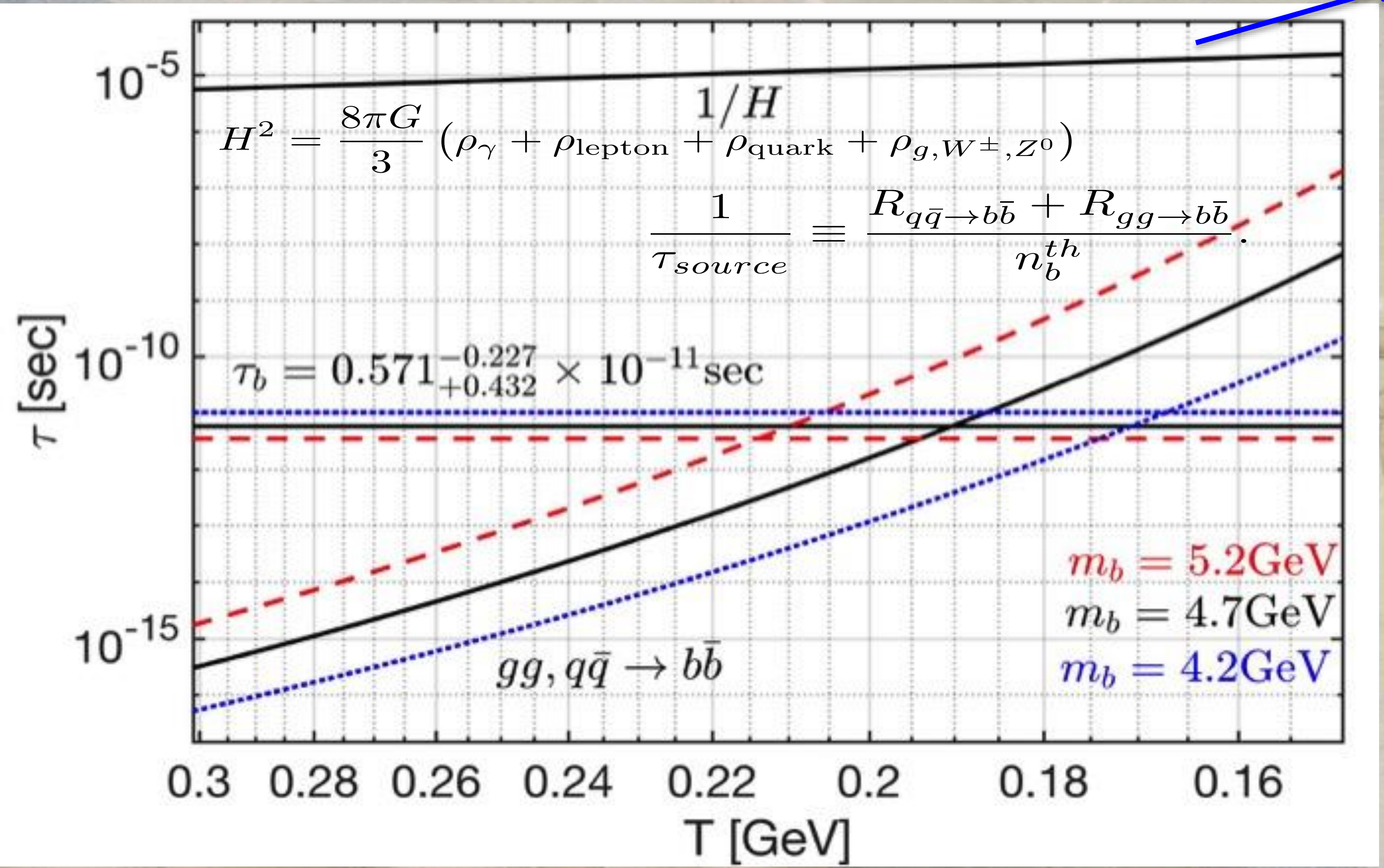


In the primordial QGP, the bottom quarks can be produced via the strong interaction gluon/quark pair fusion processes and disappear via the weak interaction decay .

$$b \longrightarrow c + l + \overline{\nu_l} \qquad q + \bar{q} \longleftrightarrow b + \bar{b}$$

$$b \longrightarrow c + q + \bar{q} \qquad g + g \longleftrightarrow b + \bar{b}$$

Assuming that three-body decay breaks detailed balance.



The universe expand 10^6 order slower compare to the bottom reaction at T=200MeV

The competition between decay and production reactions →Dynamic bottom abundance in QGP

Number of bottom quark

Fugacity: the parameter to study nonequilibrium bottom

$$\frac{1}{V}\frac{dN_b}{dt} = \left(1 - \Upsilon_b^2\right) R_b^{\text{Source}} - \Upsilon_b\, R_b^{\text{Decay}}$$

Thermal decay rates per volume of bottom quark:
The bottom lifespan weighted with density of particles

$$R_b^{\text{Decay}} = \frac{dn_b/d\Upsilon_b}{\tau_b}$$

Kuznetsova, I., D. Habs, and JR (2008). Pion and muon production in e-, e+,gamma plasma. Phys. Rev. D, 78, p. 014027.

Chemical nonequilibrium: Bottom Quark in QGP

Considering the **expansion of the universe** and the **number density of bottom quarks in Boltzmann limit**, the population equation for bottom quark can be written as

$$\frac{1}{V}\frac{dN_b}{dt} = \left(1-\Upsilon_b^2\right) R_b^{\rm Source} - \Upsilon_b\, R_b^{\rm Decay}$$

$$\frac{1}{V}\frac{dN_b}{dt} = \frac{dn_b}{d\Upsilon_b}\frac{d\Upsilon_b}{dt} + \frac{dn_b}{dT}\frac{dT}{dt} + 3Hn_b$$

$$n_b = \Upsilon_b\left[\frac{g_b}{2\pi^2}T^3\left(\frac{m_b}{T}\right)^2 K_2(m_b/T)\right] = \Upsilon_b\, n_b^{th}$$

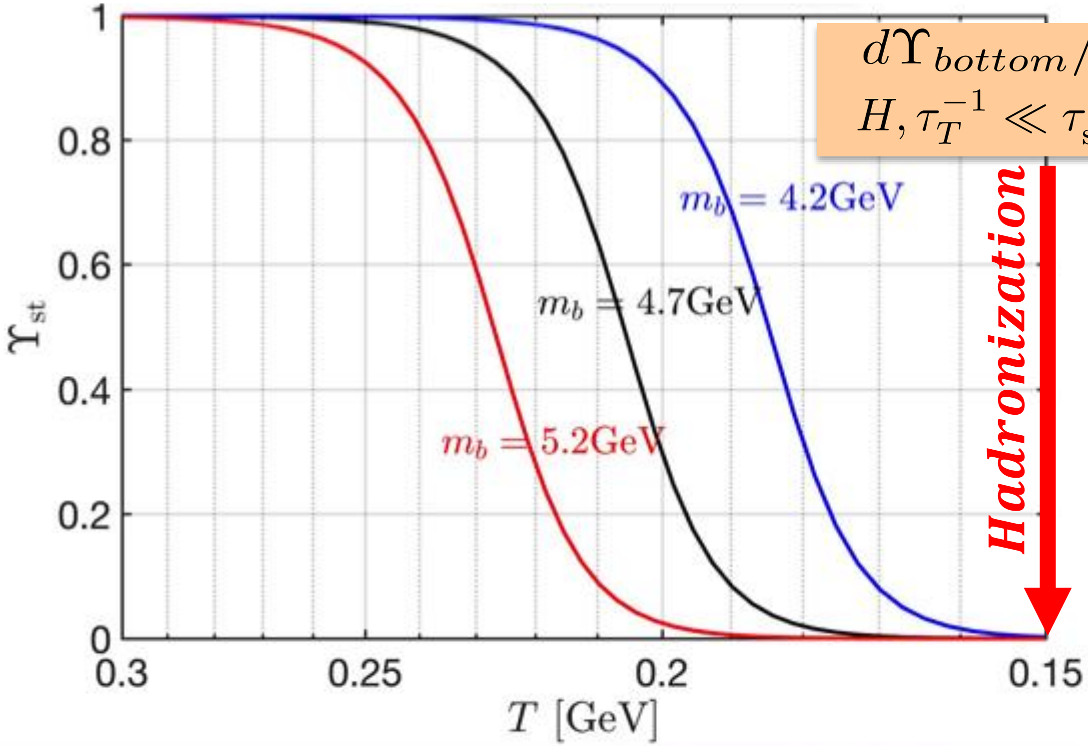
$$\frac{d\Upsilon_b}{dt} = (1-\Upsilon_b^2)\frac{1}{\tau_b^{\rm Source}} - \Upsilon_b\left(\frac{1}{\tau_b^{\rm Decay}} + 3H - \frac{1}{\tau_T}\right)$$

$$\frac{1}{\tau_T} \equiv -\frac{dn_b^{th}/dT}{n_b^{th}}\frac{dT}{dt} \qquad \frac{1}{\tau_{source}} \equiv \frac{R_{q\bar{q}\to b\bar{b}} + R_{gg\to b\bar{b}}}{n_b^{th}}.$$

Considering the dynamic equilibrium condition between production and decay reactions in adiabatic approximation:

$$d\Upsilon_{bottom}/dt = 0$$
$$H, \tau_T^{-1} \ll \tau^{-1}_{\rm source,decay}$$

$$\Upsilon_{\rm st} = \sqrt{1+\left(\frac{\tau_{source}}{2\tau_{decay}}\right)^2} - \left(\frac{\tau_{source}}{2\tau_{decay}}\right)$$



- The fugacity is a function of time because of the competition between the strong interaction production and WI decay
- Smaller mass of bottom quark allows nonequilibrium condition to move near to the transformation of QGP to HG phase.

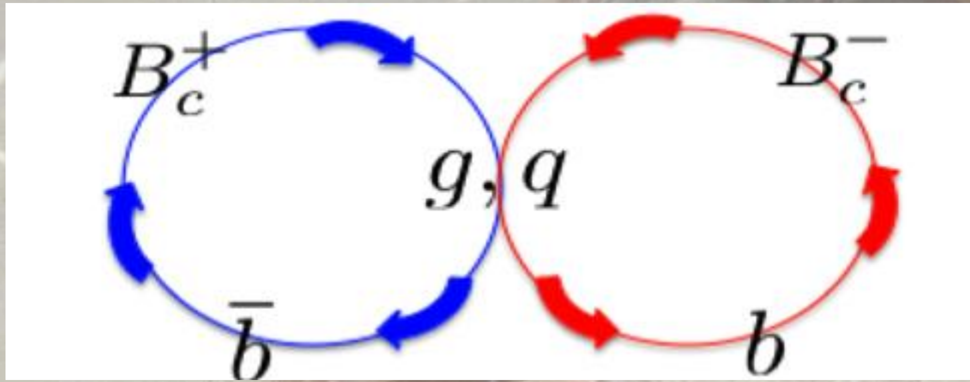
The bottom quark nonequliibrium occurs near to QGP – hadronization around the temperature T = 0.3 ~ 0.15GeV.

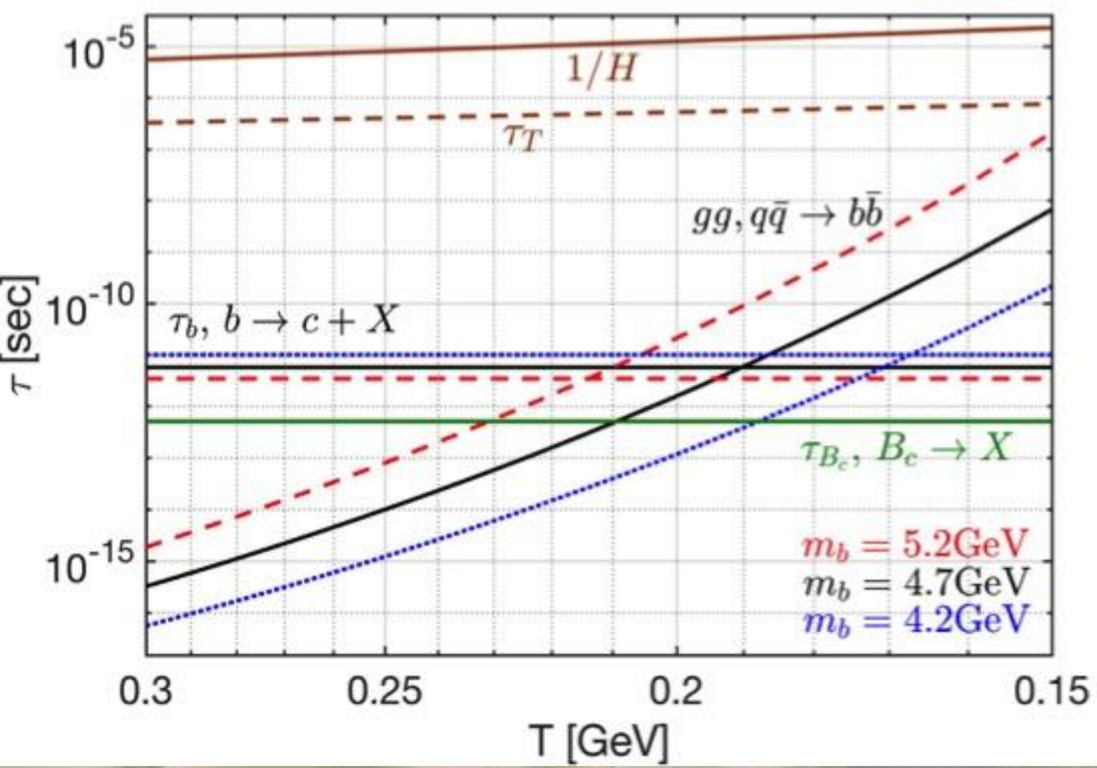
Nonequilibrium effects amplification: Urca cycle process

The off-equilibrium of bottom quark around the temperature windows T = 0.3 ~ 0.15 GeV is amplified by reaction cycling.

$$g+g, q+q \longleftrightarrow b+\bar{b}\,[b(\bar{b})+\bar{c}(c)] \longrightarrow \mathrm{B}_c^{\pm} \longrightarrow \text{anything.}$$

The rapid decay and reformation at picosecond scale assures that there are millions of individual microscopic processes involving bottom quark production and decay at the hadronization epoch of QGP → **Urca process**





At low temperature, the number of bottom quark cycling can be estimated as

$$\tau_H = \frac{1}{H} = 1.272 \times 10^{-5}$$

$$\mathrm{C_{cycle}}\Big|_{T=0.2\mathrm{GeV}} = \frac{\tau_H}{\tau_{B_c}} \approx 2 \times 10^{7}$$

$$\tau_{\mathrm{B}_c} = 0.510 \times 10^{-12}\mathrm{sec}$$

M_{bc}=6274.5MeV

Any small and yet not observed violation of baryon number associated with bottom quarks can be amplified by the Urca process to required strength for today's observation

Chemical nonequilibrium: Higgs Abundance

Bottom nonequilibrium idea could apply to other heavy particles in QGP as well. **We search for other competition conditions between the production and decay in the early Universe of relevance to the baryon abundance-creation.**

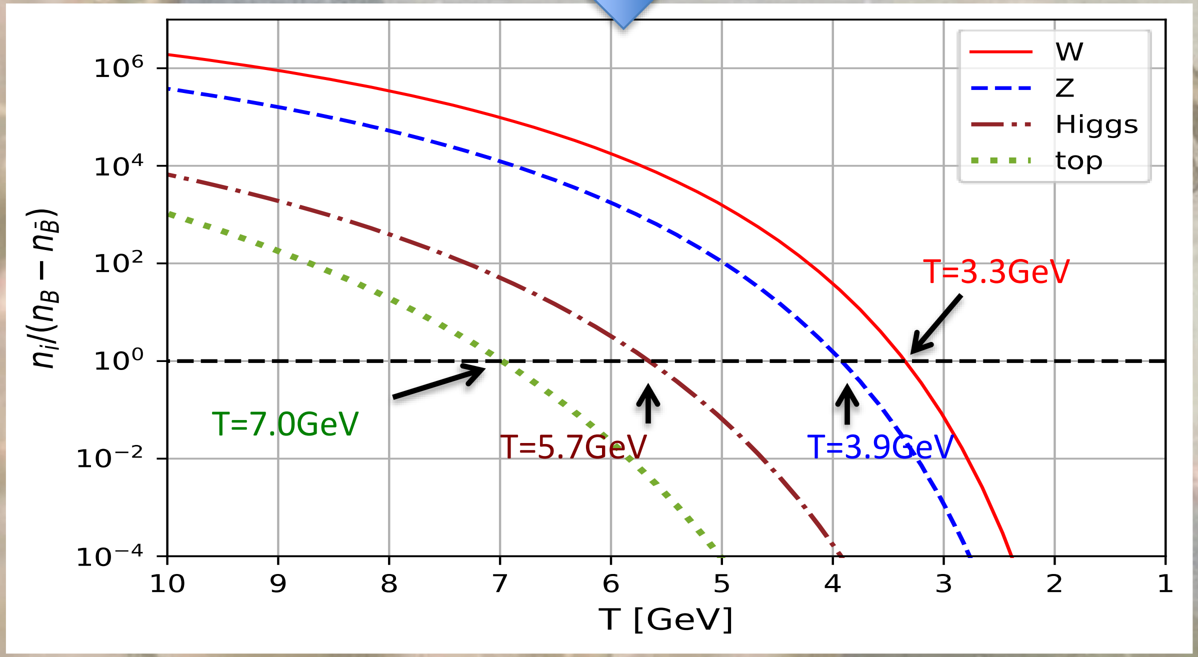
This time we focus on Higgs boson in QGP in temperature range 10GeV>T>0.15GeV.

Physical relevant down to "low" temperature:

The Higgs number density is comparable to the baryon number density when T=5.7GeV

$$\frac{n_H}{(n_B - n_{\bar{B}})} = \frac{n_H}{s_{tot}} \frac{s_{tot}}{(n_B - n_{\bar{B}})} = \frac{n_H}{s_{tot}} \left(\frac{s_{tot}}{(n_B - n_{\bar{B}})}\right)_{t_0}$$

$$n_H = \frac{\Upsilon_H}{2\pi^2} T^3 \left(\frac{m_H}{T}\right)^2 K_2(m_H/T) \qquad s_{tot} = \frac{2\pi^2}{45} g^s_* T^3$$



The competition between decay and production reactions →Dynamic Higgs abundance in QGP

$$b + \bar{b} \longleftrightarrow H$$

$$H \longrightarrow WW^*, ZZ^* \longrightarrow \text{anything}$$

Full width of Higgs $\Gamma = 3.2\ \text{MeV}$

These particles rapidly interact and re-equilibrate with the cosmic plasma.

→ Difficult to overcome the energy for inverse decay

H DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	*p* (MeV/c)
WW^*	(25.7 ±2.5) %		–
ZZ^*	(2.80±0.30) %		–
$\gamma\gamma$	(2.50±0.20) × 10^{-3}		62625
$b\bar{b}$	(53 ±8) %		–

Hadronic Matter Universe

Chemical equilibrium: Composition of hadronic matter universe

We show that the Universe in the range T>20 MeV is rich in physics phenomena involving strange mesons, (anti)baryons including (anti)hyperon abundances.

For a given chemical potential the number density in Boltzmann limit is:

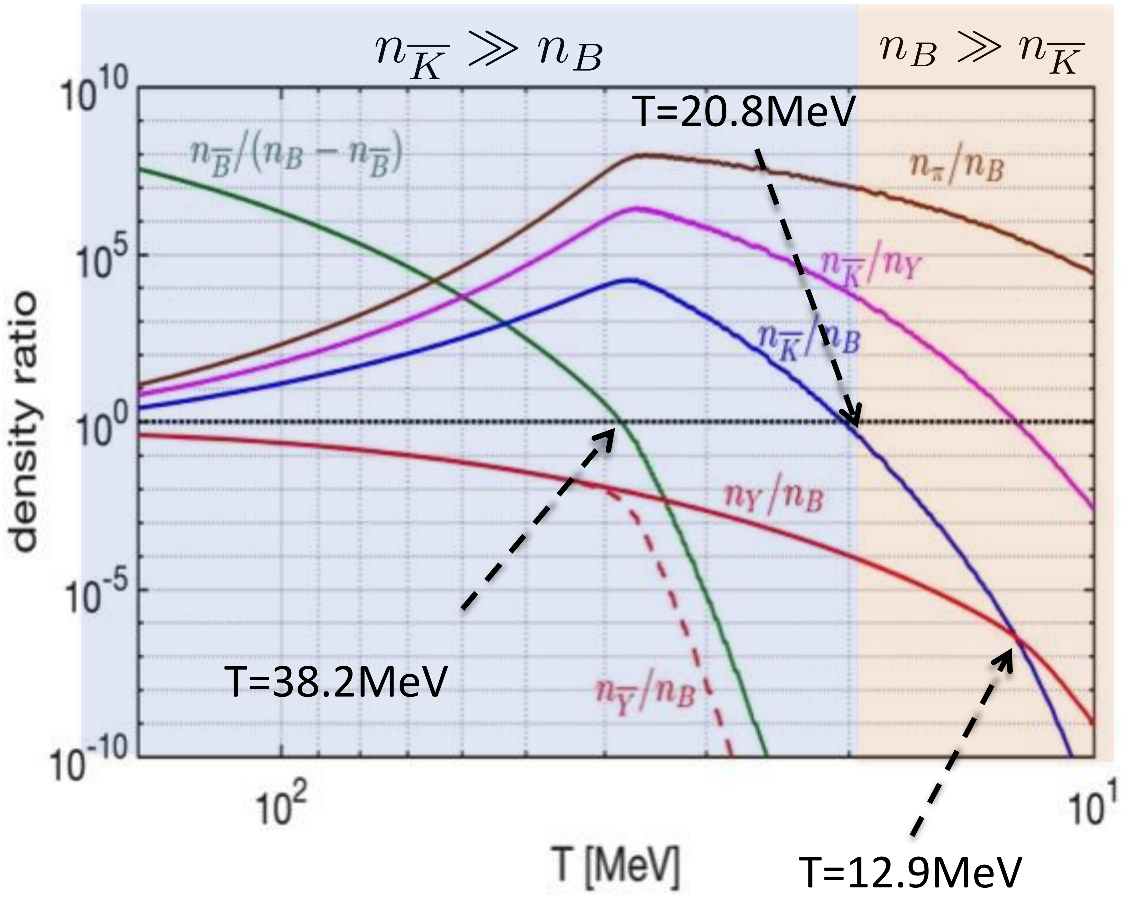
Requirement: Charge neutrality

Prescribe value of entropy-per-baryon $S/B = 3.5\times 10^{10}$

Assume: Net lepton number equals net baryon number

$$n_K = \frac{T^3}{2\pi^2}\left(\lambda_s\lambda_q^{-1}\right)\sum_{K_i} g_{K_i}\left(\frac{m_{K_i}}{T}\right)^2 K_2(m_{K_i}/T) \qquad n_Y = \frac{T^3}{2\pi^2}\left(\lambda_q^2\lambda_s\right)\sum_{Y_i} g_{Y_i}\left(\frac{m_{Y_i}}{T}\right) K_2(m_{Y_i}/T)$$

$$\mu_s = T\ln\lambda_s$$
$$\mu_B = 3T\ln\lambda_q$$



For T=38.2 MeV antibaryons disappear from the Universe inventory $n_{\overline{B}}/(n_B - n_{\overline{B}}) = 1 \longrightarrow T = 38.2\,\mathrm{MeV}$

In qualitative agreement with Kolb and Turner T=40MeV

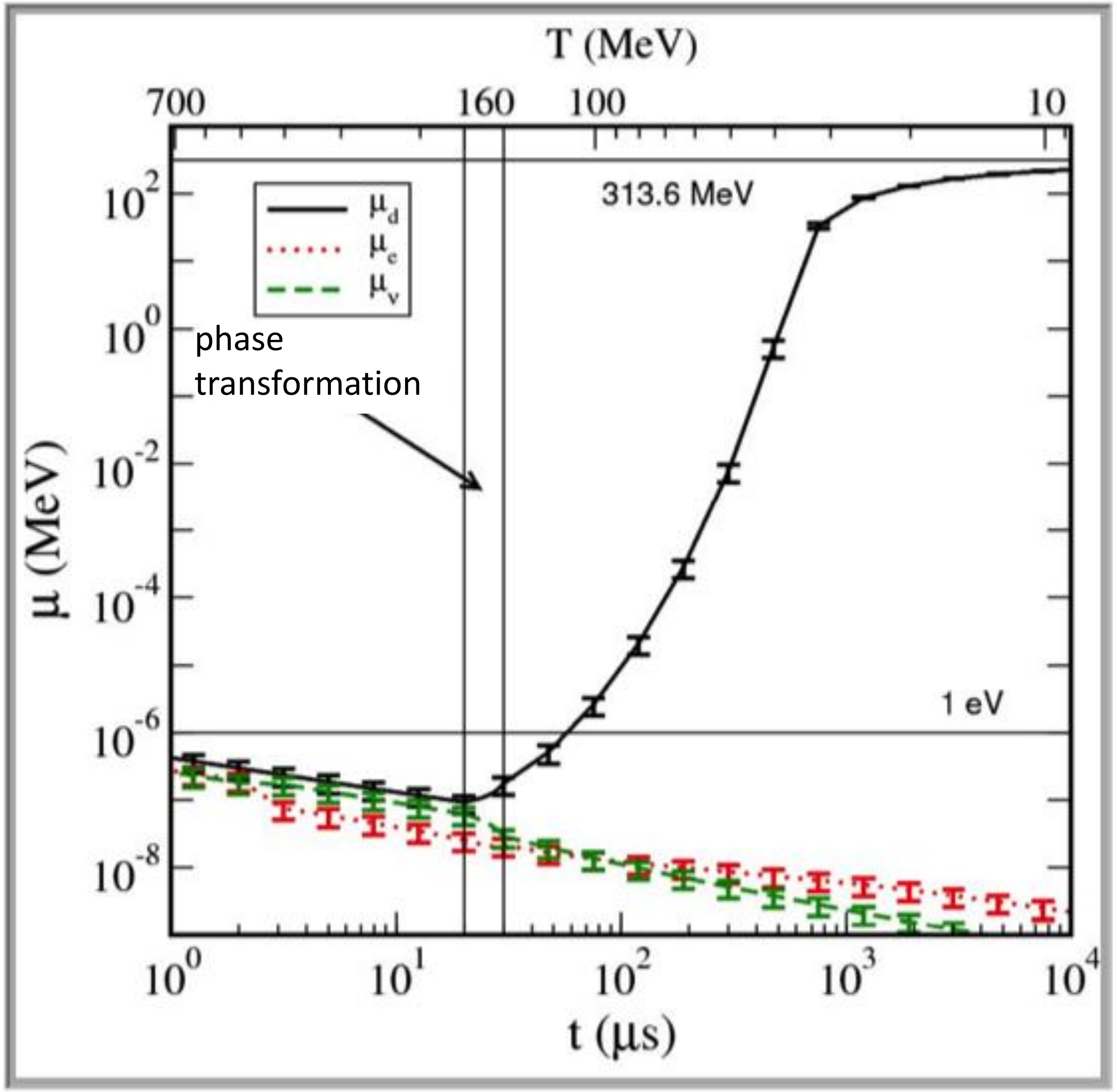
Kolb, E.W.; Turner, M.S. The early universe; CRC Press, 1990

For T>20.8 MeV, strangeness is dominantly in meson

For 20.8 MeV >*T* > 12.9 MeV, strangeness present in hyperons and anti-strangeness in kaon keeping strangeness symmetry $\overline{K} + N \rightarrow \Lambda + \pi$

For 12.9MeV>T strangeness is dominantly present in hyperons

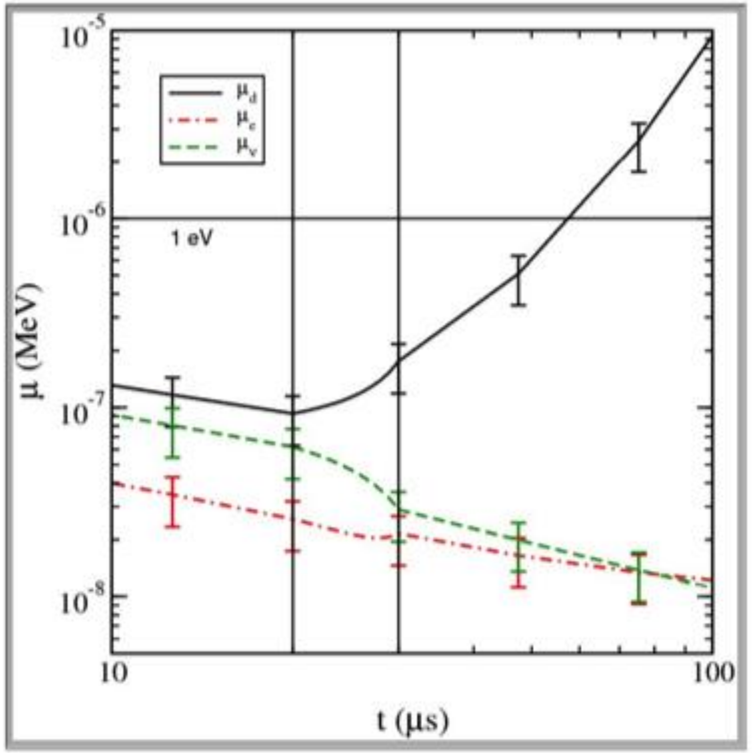
Chemical potential created by baryon asymmetry



2002 input data:
Changes in 2022 data nearly within the error bars and hardly visible

Minimum:

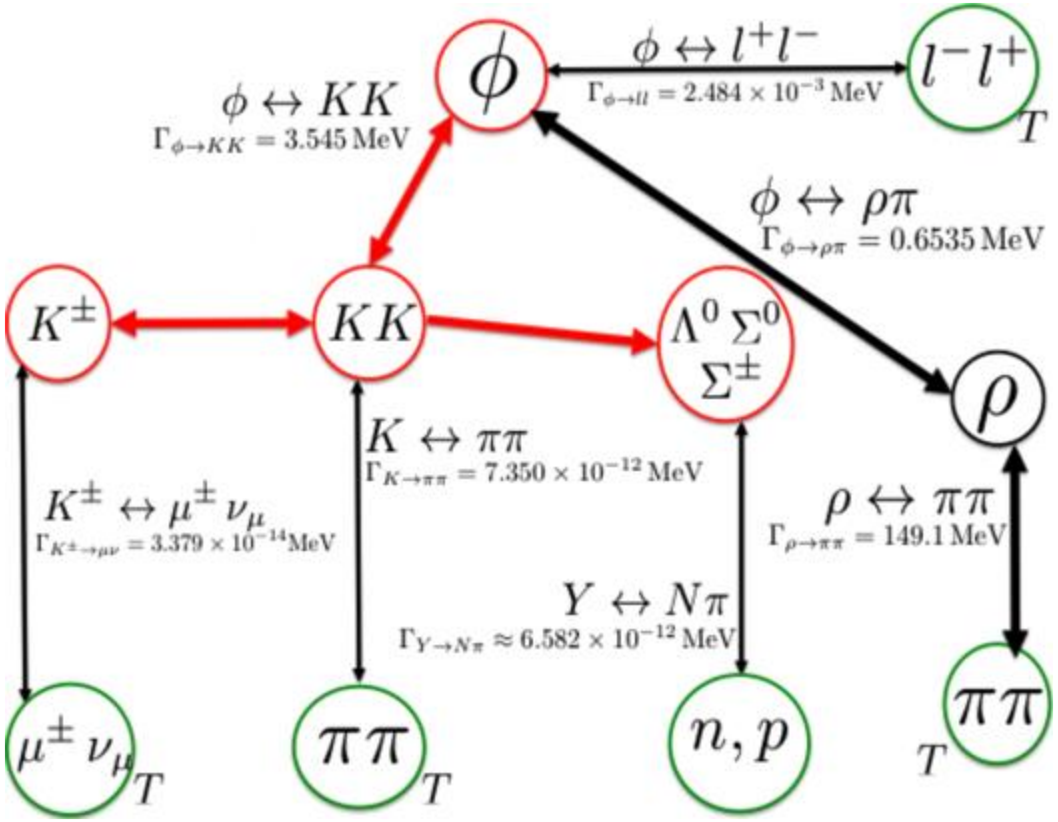
$$\mu_B = 0.33^{+0.11}_{-0.08}\,\text{eV}$$



$\Longrightarrow$ μ_B defines remainder of matter after annihilation

Strangeness network reactions

The chemical non-equilibrium can be achieved by breaking the detailed balance between particle production reaction and decay processes. The relevant reactions following QGP hadronization in the temperature interval 150> T > 10 MeV range.



Strangeness in mesons:

$$\pi + \pi \leftrightarrow K, \qquad \mu^\pm + \nu \leftrightarrow K^\pm$$
$$l^+ + l^- \leftrightarrow \phi, \qquad \rho + \pi \leftrightarrow \phi,$$
$$\pi + \pi \leftrightarrow \rho$$

Competition between Hubble and production

Strangeness in hyperons:

$$\pi + N \leftrightarrow K + \Lambda,$$
$$K + N \leftrightarrow \Lambda + \pi,$$
$$\Lambda \leftrightarrow N + \pi$$

Competition between production and decay

Pions retain their chemical equilibrium until T=3~5MeV

I. Kuznetsova, D.Habs and JR. Phys. Rev. D 78, 014027 (2008)

Muons retain their chemical equilibrium until T = 4.135 MeV.

JR and C. T. Yang (2021). The muon abundance in the primordial Universe. Acta Phys. Polon. B, 52, p. 277.

Chemical nonequilibrium: partial freezeout due to Hubble expansion

Once the reactions decouple from the cosmic plasma, the corresponding detailed balance can be broken and the **inverse decay reactions are acting like a "hole" in the abundance "pot".**

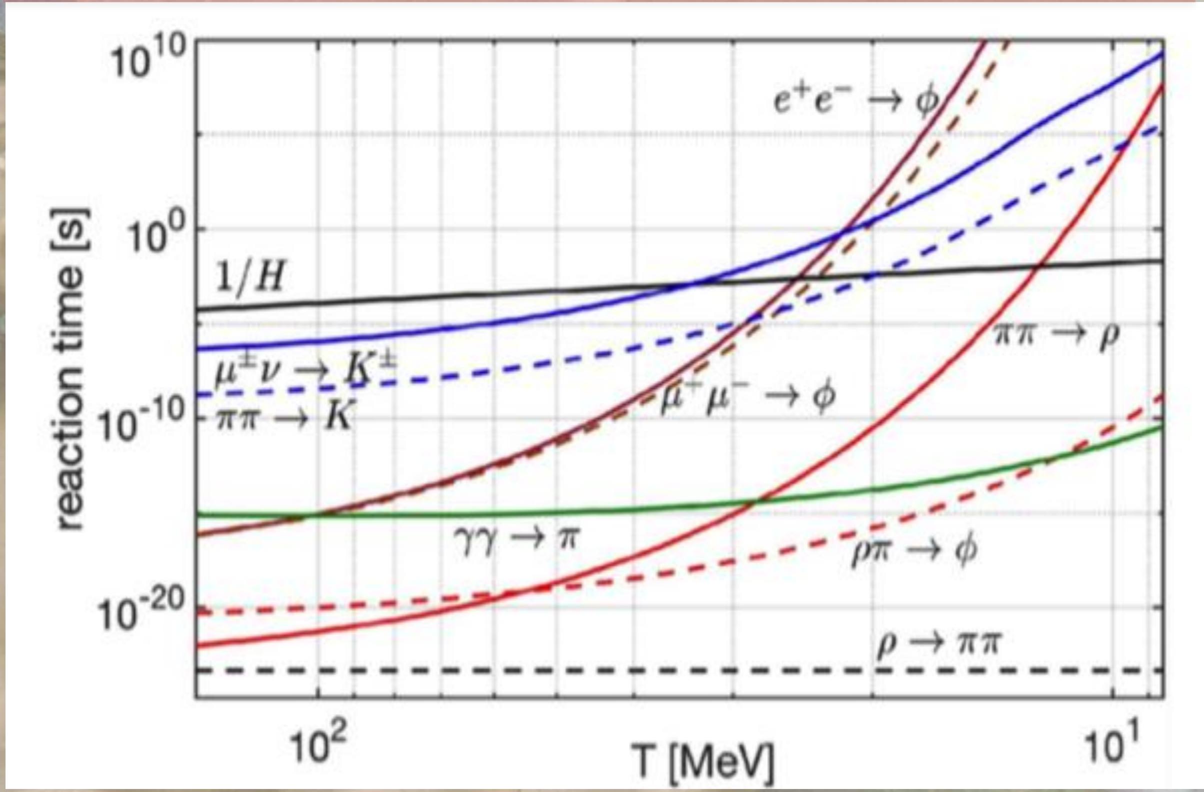
Relaxation time $\tau_{12\to3} \equiv \dfrac{n_1^{eq}}{R_{12\to3}}$

P.Koch, B.Muller and JR, `Strangeness in Relativistic Heavy Ion Collisions', Phys. Rept. 142 167-262 (1986)

$$H^2 = H^2_{rad}\left(1 + \frac{\rho_{\pi,\,\mu,\,\rho}}{\rho_{\rm rad}} + \frac{\rho_{\rm strange}}{\rho_{\rm rad}}\right) \quad H^2_{\rm rad} = \frac{8\pi G_{\rm N}}{3}\left(\rho_\gamma + \rho_\nu + \rho_{e^\pm}\right)$$

$$\frac{1}{\Delta T_f} \equiv \left[\frac{1}{(\Gamma_{12\to3}/H)}\frac{d(\Gamma_{12\to3}/H)}{dT}\right]_{T_f}, \quad \Gamma_{12\to3} \equiv \frac{1}{\tau_{12\to3}}$$

Freezeout Condition $\tau_{12\to3}(T_f) = 1/H(T_f)$

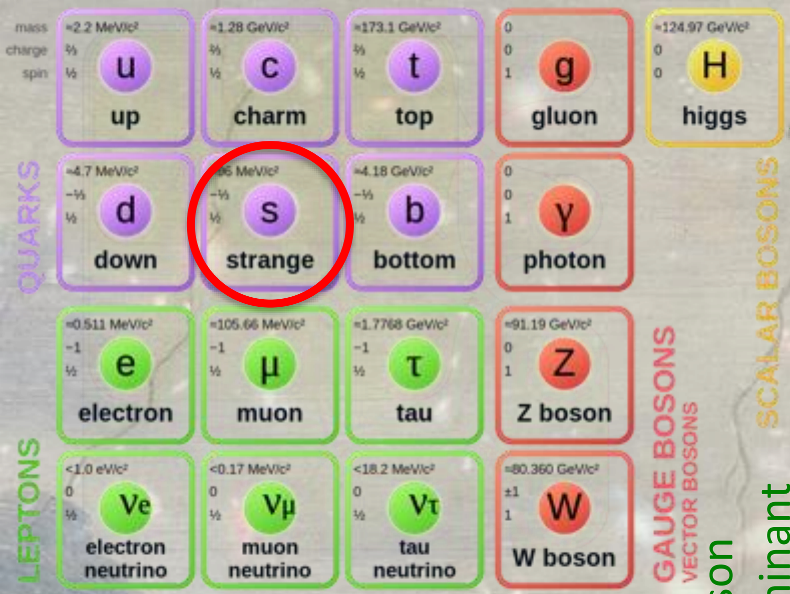


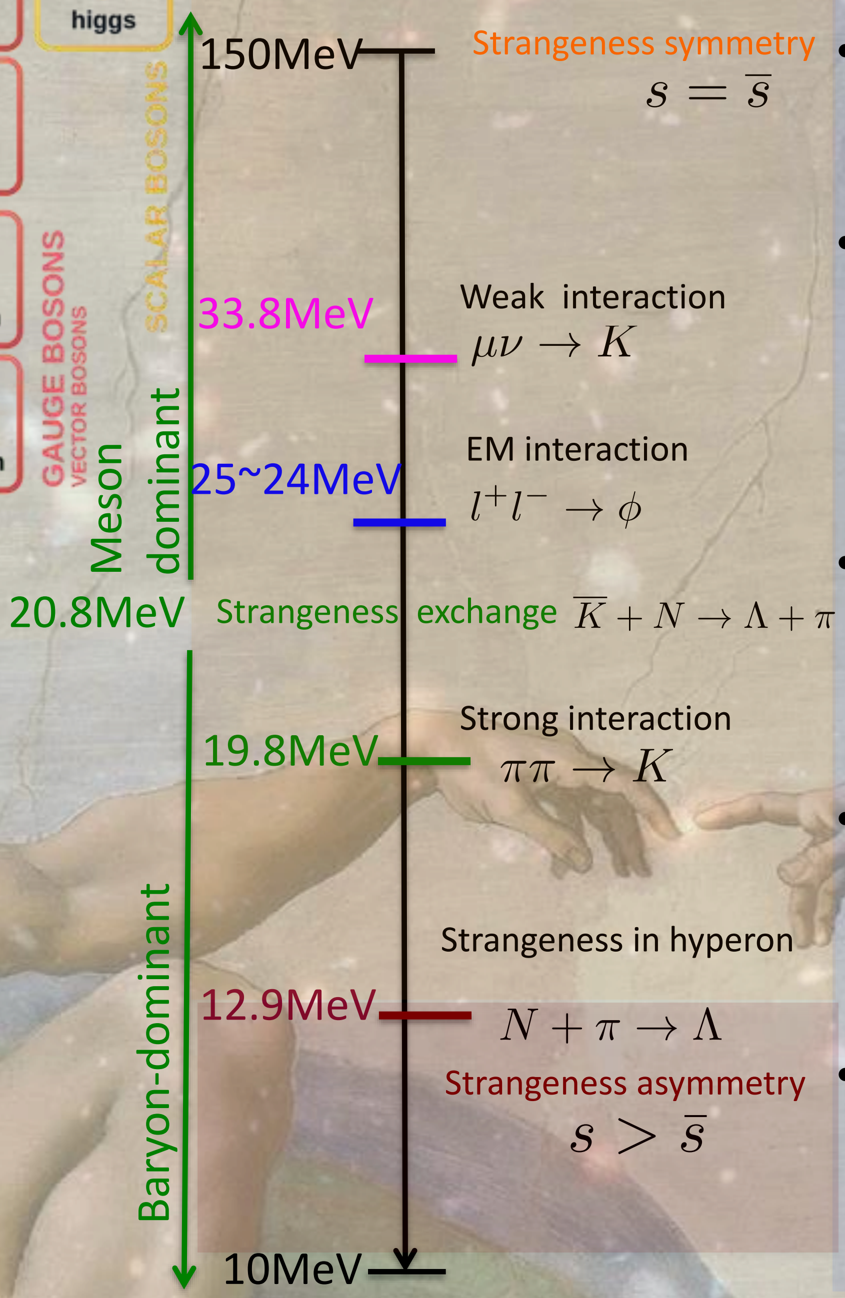
Reactions	Freezeout Temperature (MeV)	ΔT_f (MeV)
$\mu^\pm\nu \to K^\pm$	T_f = 33.8 MeV	3.5 MeV
$e^+e^- \to \phi$	T_f = 24.9 MeV	0.6 MeV
$\mu^+\mu^- \to \phi$	T_f = 23.5 MeV	0.6 MeV
$\pi\pi \to K$	T_f = 19.8 MeV	1.2 MeV
$\pi\pi \to \rho$	T_f = 12.3 MeV	0.2 MeV

Most of ρ-mesons decay faster before they can convert to ϕ-meson: Strangeness nonequilibrium

Below the temperature T < 20 MeV, all the detail balances in the strange meson reactions are broken.

Summary of strangeness in the universe





- For temperature T > 20.8 MeV, the strangeness is predominantly present in the mesons with $s = \bar{s}$
- Strange mesons can be produced by the inverse decay reactions are in equilibrium via weak, electromagnetic, and strong interactions in the early universe until T=20MeV
- Below the temperature T < 20 MeV, all the detail balances in the strange meson reactions are broken and the strangeness in the meson sector should disappear rapidly
- For temperature 20.8 >T > 12.8MeV, the strangeness is predominantly present in the hyperons and anti-strangeness in kaon, then keep $s = \bar{s}$
- For T< 12.9 MeV the reaction K + N → Λ + π becomes slower than the strangeness decay N + π ↔Λ, and we have $s > \bar{s}$

Lepton Universe

Lepton Universe: Muon persistence temperature

We establish the range of temperature in which production processes exceed in speed the decay process that keep muons in abundance (chemical) equilibrium

Muon Production

$$\gamma + \gamma \longrightarrow \mu^+ + \mu^-$$

$$e^+ + e^- \longrightarrow \mu^+ + \mu^-$$

$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$

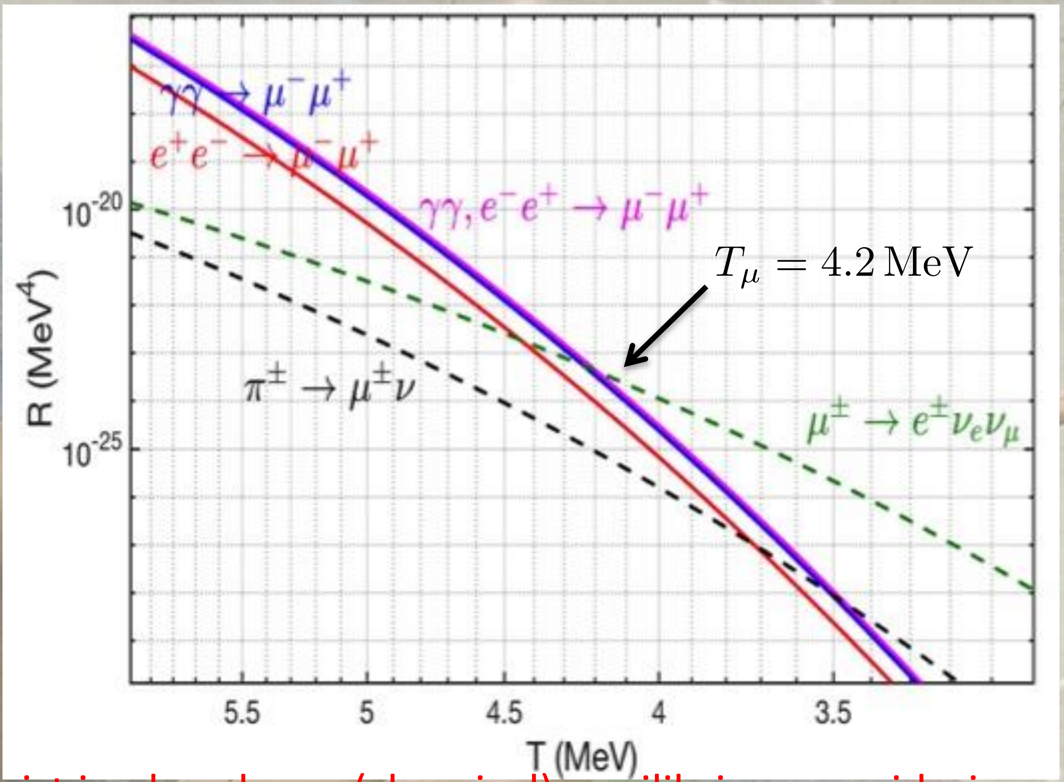
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

$$\tau_\pi = 2.6033 \times 10^{-8} \text{ sec}$$

Muon Decay $\tau_\mu = 2.197 \times 10^{-6} \text{sec}$

$$\mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e$$

$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$



$$R_{a\bar{a}\to b\bar{b}} = \frac{g_a g_{\bar{a}}}{1+I}\frac{T}{32\pi^4}\int_{s_{th}}^{\infty} ds \frac{s(s-4m_a^2)}{\sqrt{s}}\sigma_{a\bar{a}\to b\bar{b}} K_1(\sqrt{s}/T)$$

$$R_c = \frac{g_c}{2\pi^2}\left(\frac{T^3}{\tau_c}\right)\left(\frac{m_c}{T}\right)^2 K_1(m_c/T)$$

Vacuum decay rate applies because the T>m_e, decay blocking is small.

As the temperature decreases in the expanding Universe, the muon abundance disappears as soon as any decay rate is faster than the fastest production rate.

Specifically after the Universe cools below the temperature T=4.2 MeV , the dominant reaction is the muon decay.

Muons persist in abundance (chemical) equilibrium considering electromagnetic and weak interaction processes until T = 4.2 MeV.

Electroweak 2-2 processes in progress.

JR and C. T. Yang (2021). The muon abundance in the primordial Universe. Acta Phys. Polon. B, 52, p. 277. doi:10.5506/APhysPolB.52.277.

Accidental degeneracy of muon abundance with baryon abundance

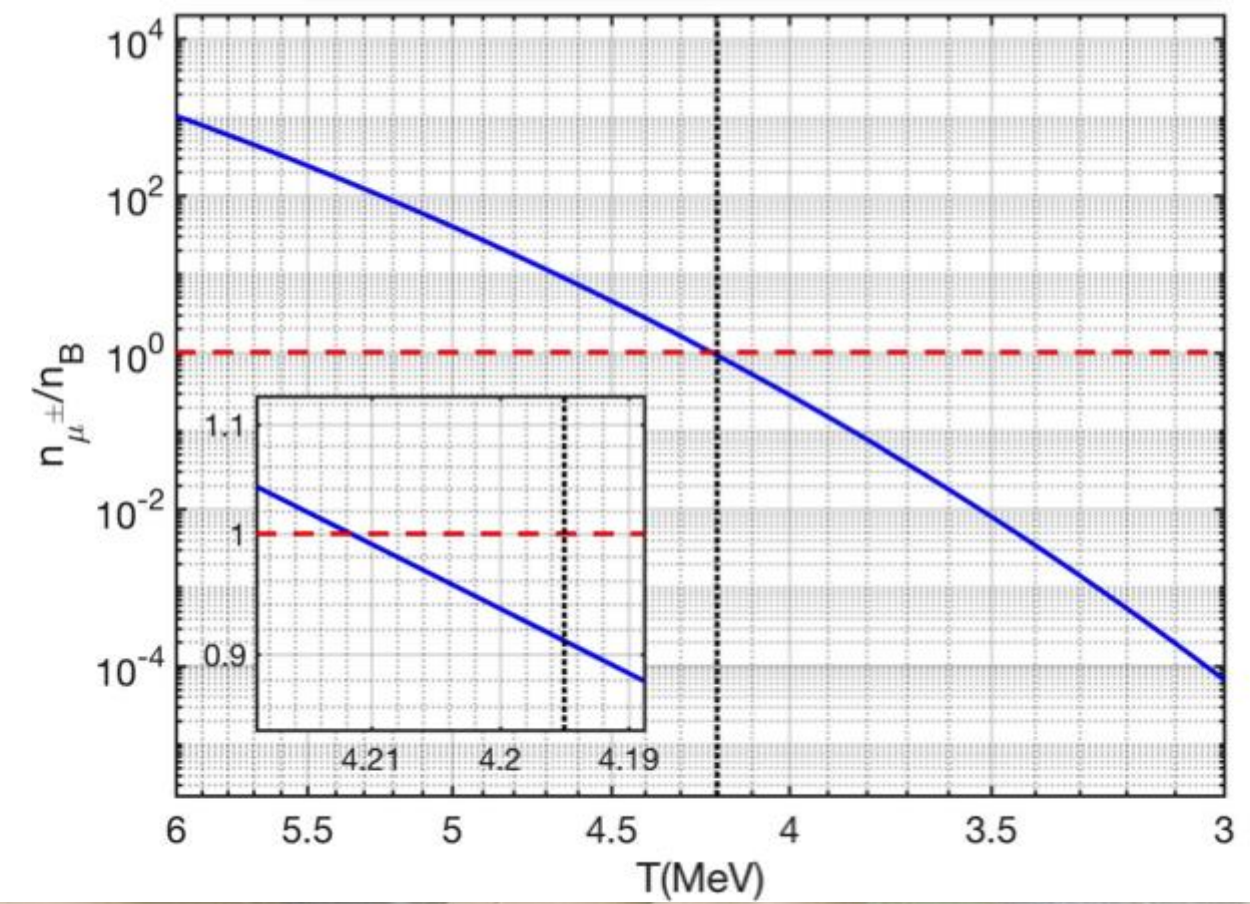
Using constant baryon-per-entropy ratio, the density between muon and baryon can be written as

$$\frac{n_{\mu^\pm}}{n_\mathrm{B}} = \frac{n_{\mu^\pm}}{s}\frac{s}{n_\mathrm{B}} = \frac{n_{\mu^\pm}}{s}\left(\frac{s_{\gamma e}(1+s_\nu/s_{\gamma e})}{n_\mathrm{B}}\right)_{t_0}$$

$$\left(n_B - n_{\overline{B}}\right)/n_\gamma = (0.609 \pm 0.06)\times 10^{-9}(\mathrm{CMB})$$

$$s = \frac{2\pi^2}{45} g_*^s T^3$$

$$n_{\mu^\pm} = \frac{g_{\mu^\pm}}{2\pi^2} T^3 \left(\frac{m_\mu}{T}\right)^2 K_2(m_\mu/T)$$



Muon-baryon density ratio at persistence temperature:

$$T_\mu = 4.2\,\mathrm{MeV} \qquad n_{\mu^\pm}/n_\mathrm{B}(T_\mu) \approx 0.911$$

The temperature for unity muon-to-baryon density ratio:

$$T_\mathrm{equal} \approx 4.212\ \mathrm{MeV} \qquad n_{\mu^\pm}/n_\mathrm{B}(T_\mathrm{equal}) = 1$$

This means that the muon abundance could influence baryon evolution because muon number density is comparable to the baryon number density.

JR and C. T. Yang (2021). The muon abundance in the primordial Universe. Acta Phys. Polon. B, 52, p. 277.

Long lasting muons could disappear just before neutrino freezeout coincidentally with the same abundance as baryon number

Boltzmann Equation and Neutrino freeze-out

The Boltzmann equation describe the evolution of distribution function in phase space. In general, the Boltzmann equation in FLRW universe in the absence of electromagnetic field can be written as

$$\frac{\partial f}{\partial t} - \frac{(E^2 - m^2)}{E} H \frac{\partial f}{\partial E} = \frac{1}{E} \sum_q \mathcal{C}_q[f]$$

As the Universe expanded, the interactions gradually became too slow to maintain equilibrium and particles freeze-out from the cosmic plasma.

Freeze-out condition $\tau_{rel}^{-1} \leqslant H$ $\qquad \tau_{rel}^{-1} = \frac{g}{(2\pi)^3 n} \int d^3p \frac{1}{E} \mathcal{C}_q[f]$

The freeze-out process involves several steps that lead to the free streaming

Extension of the textbook knowledge

Chemical freeze-out :
Freeze-out of inelastic scattering

Kinetic freeze-out :
Freeze-out of elastic scattering

Free-streaming:
Particles had fully decoupled from the cosmic plasma

Prior to the chemical freeze-out :

$$f_{th} = \frac{1}{\exp((E-\mu)/T) + 1} \longrightarrow$$

Between chemical and kinetic freeze-out

$$f_k = \frac{1}{\Upsilon^{-1} \exp((E-\mu)/T) + 1} \longrightarrow$$

Fugacity : controlling overall abundance of given particles and antiparticle

After kinetic freeze-out, free-streaming distribution

$$f_{fs} = \frac{1}{\Upsilon_f^{-1} \exp\left(\sqrt{\frac{E^2 - m^2}{T_{fs}^2} + \frac{m^2}{T_f^2}} - \frac{\mu}{T_f}\right) + 1}$$

Effective free-streaming temperature $\quad T_{fs} \equiv \frac{a(t_f)}{a(t)} T_f$

J. Birrell, C.T Yang, P. Chen, and JR (2014a). Relic neutrinos: Physically consistent treatment of effective number of neutrinos and neutrino mass. Phys.Rev. D, 89, p. 023008. doi:10.1103/PhysRevD.89.023008.

Neutrino Freeze-out in the Early Universe

For temperature 4MeV > T > 0.02 MeV, the Universe contained relativistic electrons, positrons, photons, and three species of (anti)neutrinos

Cosmic plasma: $\{\gamma, e^{\pm}, \nu_l, \bar{\nu}_l\}$

Neutrino freeze-out temperature:

The freeze-out temperature **impact the energy and entropy transfer from electron-positron annihilation to neutrinos**

→ impact $N_\nu^{\rm eff}$

Effective number of neutrino

$$N_\nu^{\rm eff} \equiv \frac{\rho_\nu^{\rm tot}}{\frac{7}{8}\rho_\gamma\left(\frac{4}{11}\right)^{4/3}} = \frac{\rho_\nu^{\rm tot}}{\frac{7\pi^2}{120}\left(\frac{4}{11}\right)^{4/3} T_\gamma^4}$$

The Planck collaboration 2013 result:

$$N_\nu^{\rm eff} = 3.36 \pm 0.34\,({\rm CMB})$$

$$N_\nu^{\rm eff} = 3.62 \pm 0.25\,({\rm CMB} + H_0)$$

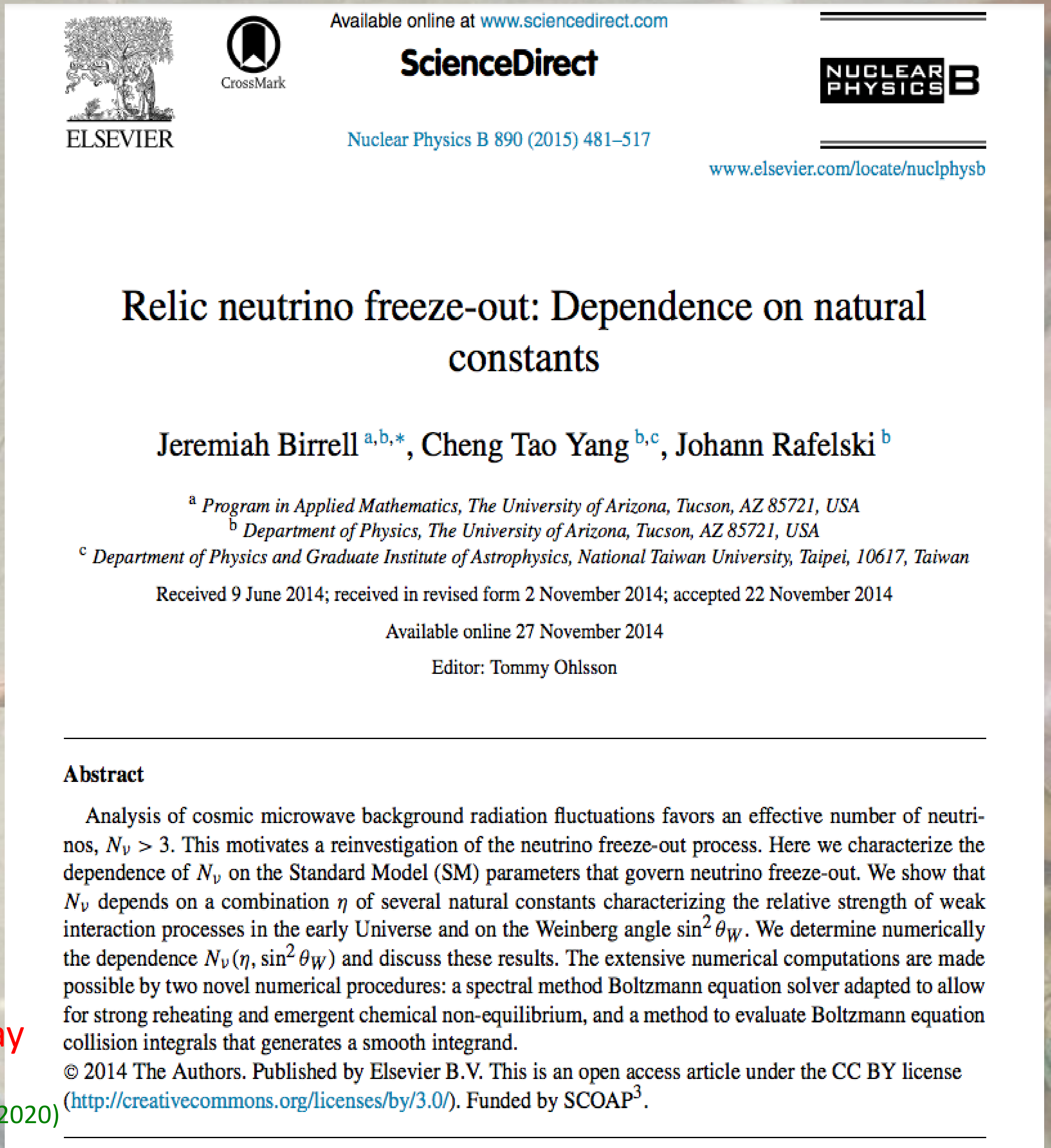
Ade, P. A. R. et al. (2014). Planck 2013 results. XVI.. Astron. Astrophys., 571, p. A16.

The Planck collaboration 2018 result:

$$N_\nu^{\rm eff} = 2.99 \pm 0.17$$

In contradiction to present day Universe dynamics

N.Aghanim, et al.,``Planck 2018 results. VI. Cosmological parameters,’’Astron. Astrophys. 641, A6 (2020)



Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics B 890 (2015) 481–517

www.elsevier.com/locate/nuclphysb

Relic neutrino freeze-out: Dependence on natural constants

Jeremiah Birrell [a,b,*], Cheng Tao Yang [b,c], Johann Rafelski [b]

[a] Program in Applied Mathematics, The University of Arizona, Tucson, AZ 85721, USA
[b] Department of Physics, The University of Arizona, Tucson, AZ 85721, USA
[c] Department of Physics and Graduate Institute of Astrophysics, National Taiwan University, Taipei, 10617, Taiwan

Received 9 June 2014; received in revised form 2 November 2014; accepted 22 November 2014

Available online 27 November 2014

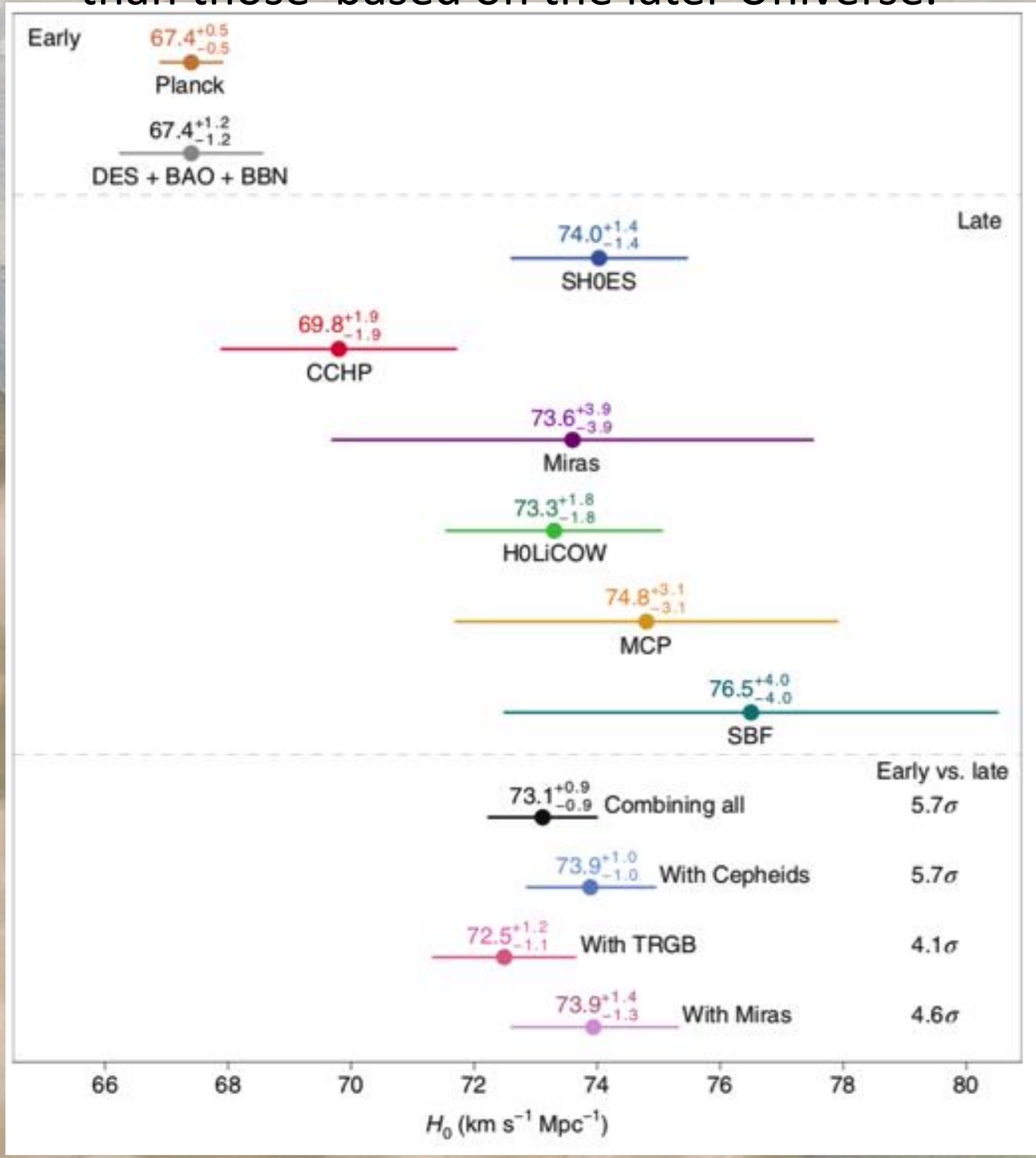
Editor: Tommy Ohlsson

Abstract

Analysis of cosmic microwave background radiation fluctuations favors an effective number of neutrinos, $N_\nu > 3$. This motivates a reinvestigation of the neutrino freeze-out process. Here we characterize the dependence of N_ν on the Standard Model (SM) parameters that govern neutrino freeze-out. We show that N_ν depends on a combination η of several natural constants characterizing the relative strength of weak interaction processes in the early Universe and on the Weinberg angle $\sin^2\theta_W$. We determine numerically the dependence $N_\nu(\eta, \sin^2\theta_W)$ and discuss these results. The extensive numerical computations are made possible by two novel numerical procedures: a spectral method Boltzmann equation solver adapted to allow for strong reheating and emergent chemical non-equilibrium, and a method to evaluate Boltzmann equation collision integrals that generates a smooth integrand.

Hubble tensions between the early and late Universe

Estimates of the universe's expansion rate based on physics of the early Universe tend to have lower values than those based on the later Universe.



L. Verde, T. Treu and A. G. Riess,``Tensions between the Early and the Late Universe,'' Nature Astron. 3, 891

After neutrinos decoupled from the cosmic plasma and become free-streaming, it still continue to play a significant role in the evolution of the Universe

$$H^2 = \frac{8\pi G_N}{3}\left[\rho_{\rm matter} + \rho_\gamma + \rho_\nu\right] + \frac{\Lambda}{3}$$
$$= \frac{8\pi G_N}{3}\left[\rho_{\rm matter} + \rho_\gamma + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_\nu^{\rm eff}\rho_\gamma\right] + \frac{\Lambda}{3}$$

Effective number of neutrinos related to observed Universe dynamics

$$N_\nu^{\rm eff} = \frac{\rho_\nu^{\rm tot}}{\frac{7}{8}\rho_\gamma\left(\frac{4}{11}\right)^{4/3}} = \frac{\rho_\nu^{\rm tot}}{\frac{7\pi^2}{120}\left(\frac{4}{11}\right)^{4/3} T_\gamma^4}$$

Dr. Cheng Tao Yang

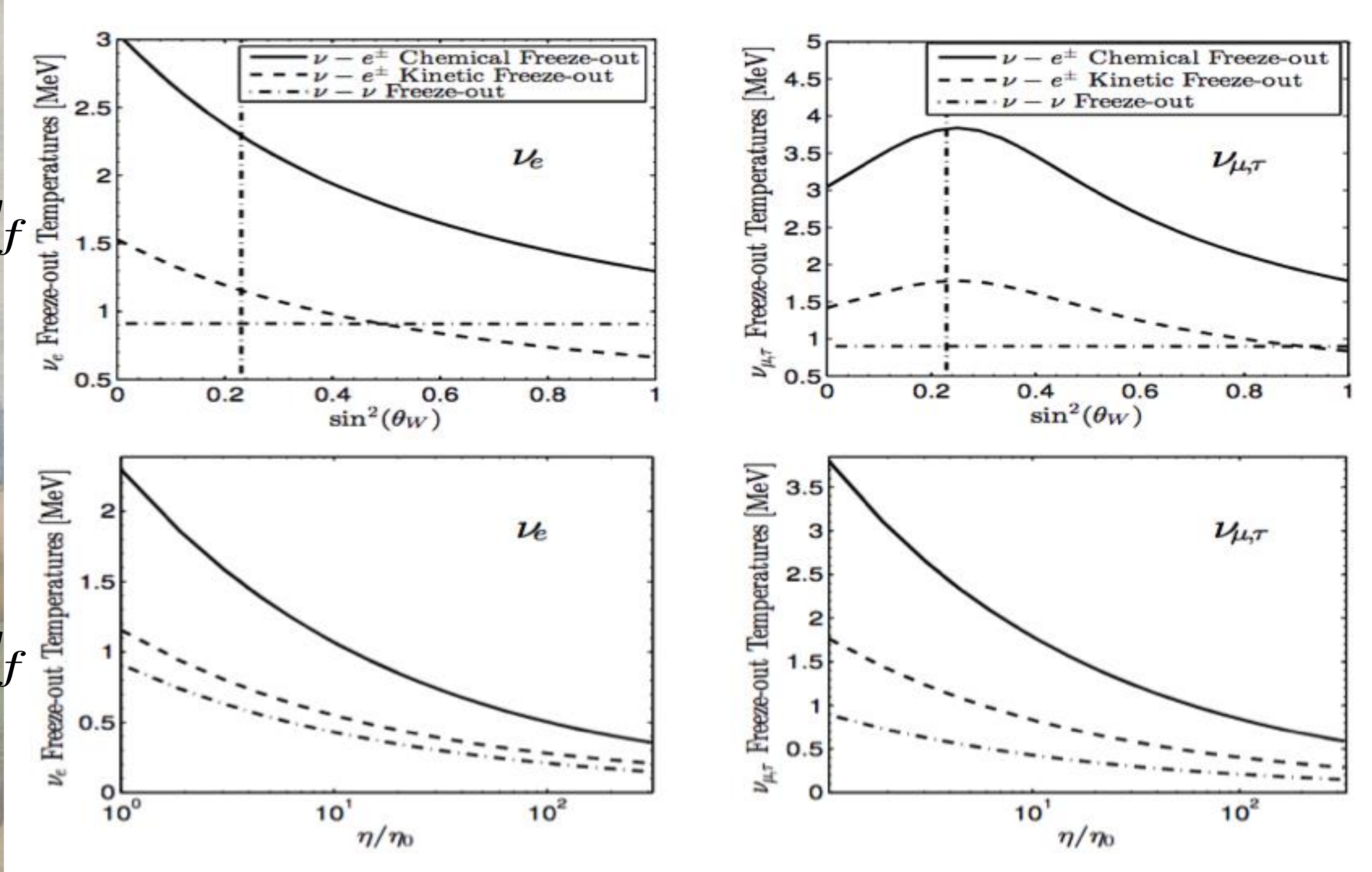
Neutrino freeze-out temperature

We show that the neutrino freeze-out temperature is controlled by standard model parameters which can be modified in high temperature or plasma environment.

SM parameters: **Weinberg angle** $\sin^2\theta_W = 0.231$

Interaction strength parameter $\eta \equiv M_p m_e^3 G_F^2$ $\quad \eta_0 \equiv M_p m_e^3 G_F^2\big|_0 = 0.04421$

T_f



T_f

Lepton asymmetry: $B \neq L$ Effective number of neutrinos and μ_ν

We study in a quantitative manner the lepton asymmetry L in the Universe and its impact on Universe expansion.

To be specific we explore how the large cosmological lepton asymmetry relates to the effective number of neutrinos.

$$N_\nu^{\mathrm{eff}} \equiv \frac{\rho_\nu^{\mathrm{tot}}(\mu_\nu)}{\frac{7\pi^2}{120}\left(\frac{4}{11}\right)^{4/3} T_\gamma^4} \quad \xleftrightarrow{\mu_\nu} \quad L \equiv \frac{[N_{\mathrm{L}}(\mu_\nu) - N_{\overline{\mathrm{L}}}(\mu_\nu)]}{N_\gamma}$$

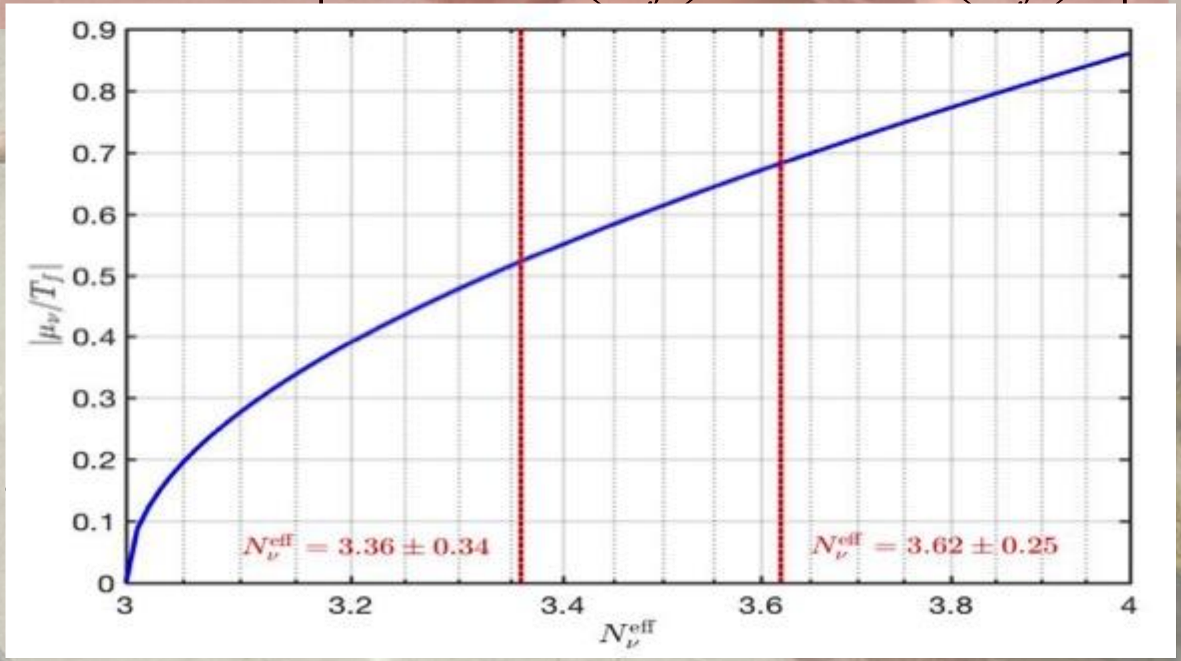
Free-streaming distribution: Birrell, J., C.-T. Yang, P. Chen, and JR (2014a). Phys.Rev. D, 89, p. 023008.

$$f_\nu = \frac{1}{\exp\left(\sqrt{\frac{E^2-m_\nu^2}{T_\nu^2} + \frac{m_\nu^2}{T_f^2}} - \sigma\frac{\mu_\nu}{T_f}\right) + 1}$$

$$T_\nu \equiv \frac{a(t_f)}{a(t)} T_f \qquad T_f = 2\,\mathrm{MeV} \qquad \sigma = \pm 1$$

Effective number of neutrino

$$N_\nu^{\mathrm{eff}} = 3\left[1 + \frac{30}{7\pi^2}\left(\frac{\mu_\nu}{T_f}\right)^2 + \frac{15}{7\pi^4}\left(\frac{\mu_\nu}{T_f}\right)^4\right]$$



The SM value of the effective number of neutrinos can be obtained when chemical potential is small:

$$N_\mu^{\mathrm{eff}} = 3 \quad \longleftrightarrow \quad \mu_\nu \ll T_f$$

To interpret the literature values of effective number of neutrino, we require

$$0.52 \leqslant \mu_\nu / T_f \leqslant 0.69$$

neutrino-antineutrino asymmetry freezeout

Effective number of neutrinos and lepton number

The density ratio between lepton-asymmetry and baryon-asymmetry at neutrino freeze-out can be written as

$$\frac{\ell_f}{b_f} \equiv \left(\frac{n_e - n_{\overline{e}}}{n_B}\right)_f + \sum_{i=e,\mu,\tau}\left(\frac{n_{\nu_i} - n_{\overline{\nu}_i}}{n_B}\right)_f \qquad (n_\nu - n_{\overline{\nu}})_f = \frac{g_\nu}{6\pi^2}T_f^3\left[\pi^2\left(\frac{\mu_\nu}{T_f}\right) + \left(\frac{\mu_\nu}{T_f}\right)^3\right]$$

Charge neutrality:
It is small compared to the 2nd term

The subscript f indicate the quantities at the neutrino freezeout temperature

Lepton-baryon number ratio

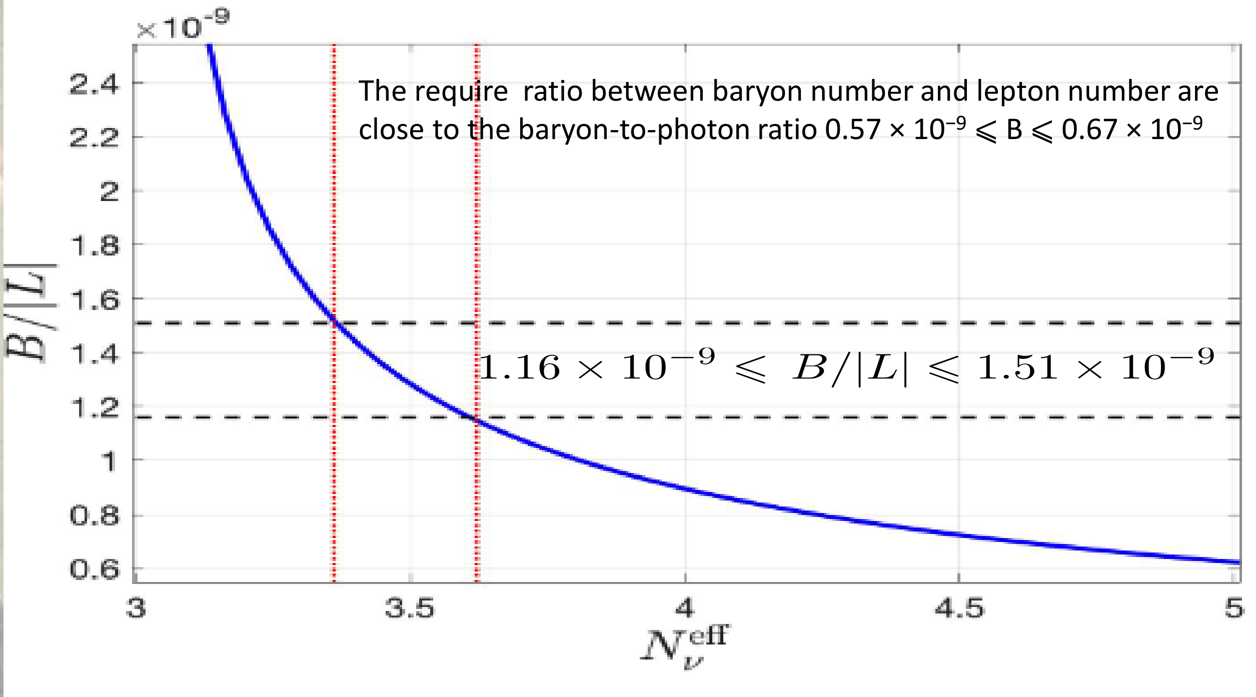
$$\frac{L}{B} \approx \sum_{i=e,\mu,\tau}\left(\frac{n_\nu - n_{\overline{\nu}}}{\sigma}\right)_f\left(\frac{\sigma}{n_B}\right)_f = \frac{45}{4\pi^4}\,\frac{\pi^2(\mu_\nu/T_f) + (\mu_\nu/T_f)^3}{10.75 + \frac{45}{4\pi^2}(\mu_\nu/T_f)^2}\left(\frac{\sigma}{n_B}\right)_{t_0}$$

$$B = \frac{[N_{\mathrm{B}} - N_{\overline{\mathrm{B}}}]}{N_\gamma} \qquad L \equiv \frac{[N_{\mathrm{L}} - N_{\overline{\mathrm{L}}}]}{N_\gamma}$$

$$\sigma_f = \frac{2\pi^2}{45}\left[10.75 + \frac{45}{4\pi^2}\left(\frac{\mu_\nu}{T_f}\right)^2\right]T_f^3$$

Effective number of neutrino

$$N_\nu^{\text{eff}} = 3\left[1 + \frac{30}{7\pi^2}\left(\frac{\mu_\nu}{T_f}\right)^2 + \frac{15}{7\pi^4}\left(\frac{\mu_\nu}{T_f}\right)^4\right]$$



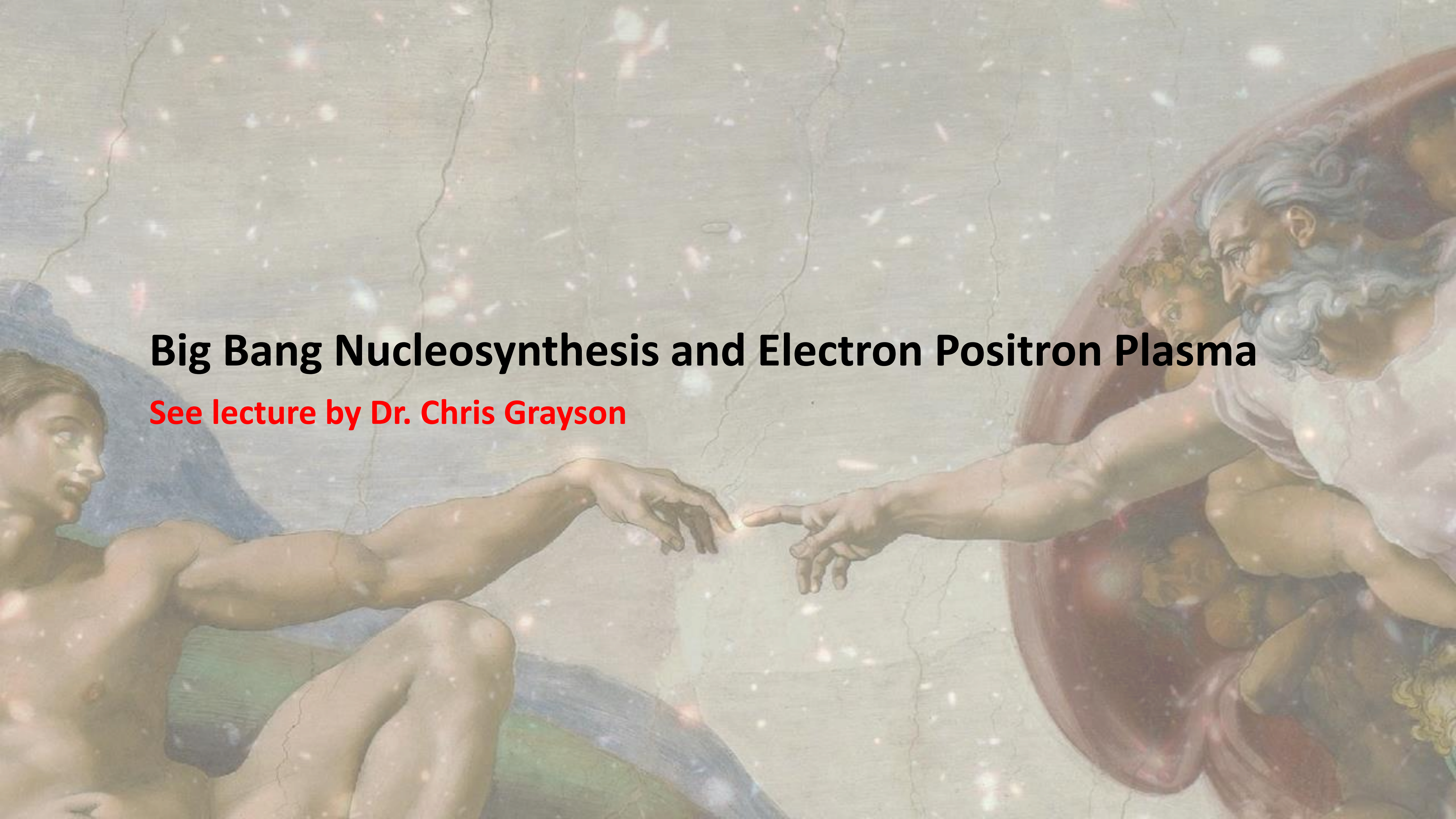
Our point of view:

Instead of B ≃ |L|, we found that 0.4 ⩽ |L| ⩽ 0.52 and B ≃ 1.33 ×10^{-9}|L| reconciles the CMB and current epoch results for the Hubble expansion parameter

Yang, C. T., J. Birrell, and JR. "Lepton Number and Expansion of the Universe." arXiv preprint arXiv:1812.05157 (2018).

Big Bang Nucleosynthesis and Electron Positron Plasma

See lecture by Dr. Chris Grayson



Electron Chemical Potential and Charge Neutrality

The dense electron/positron plasma in the early universe is neutralized by protons. The proton abundance is derived by using entropy conservation. **The presence of rich electron positron plasma can last until T=20.3 keV,** and the plasma effect needs to be accounted in study of BBN.

Charge neutrality :

$$n_e - n_{\bar{e}} = \frac{n_p}{n_B}\left(\frac{n_B}{s_{\gamma,e,\bar{e}}}\right) s_{\gamma,e,\bar{e}}$$

Constant baryon-to-entropy ratio

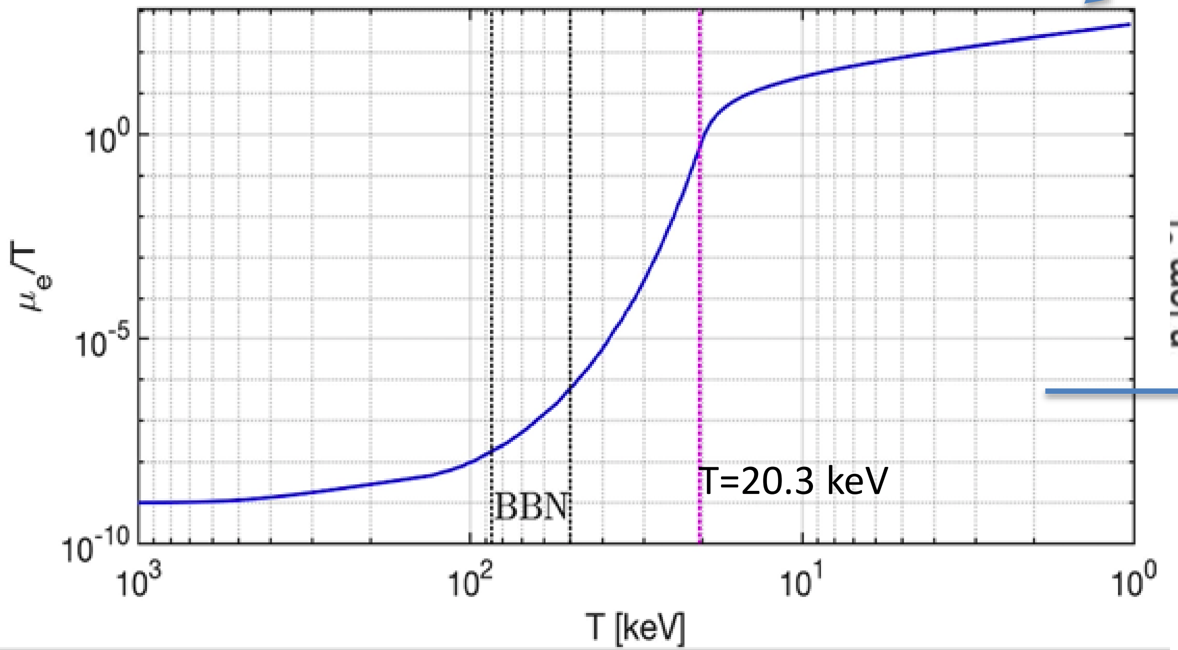
Observation

$$(n_B/n_\gamma)_{t_0} = 6.05 \times 10^{-10} \quad n_p/n_B = 0.87$$

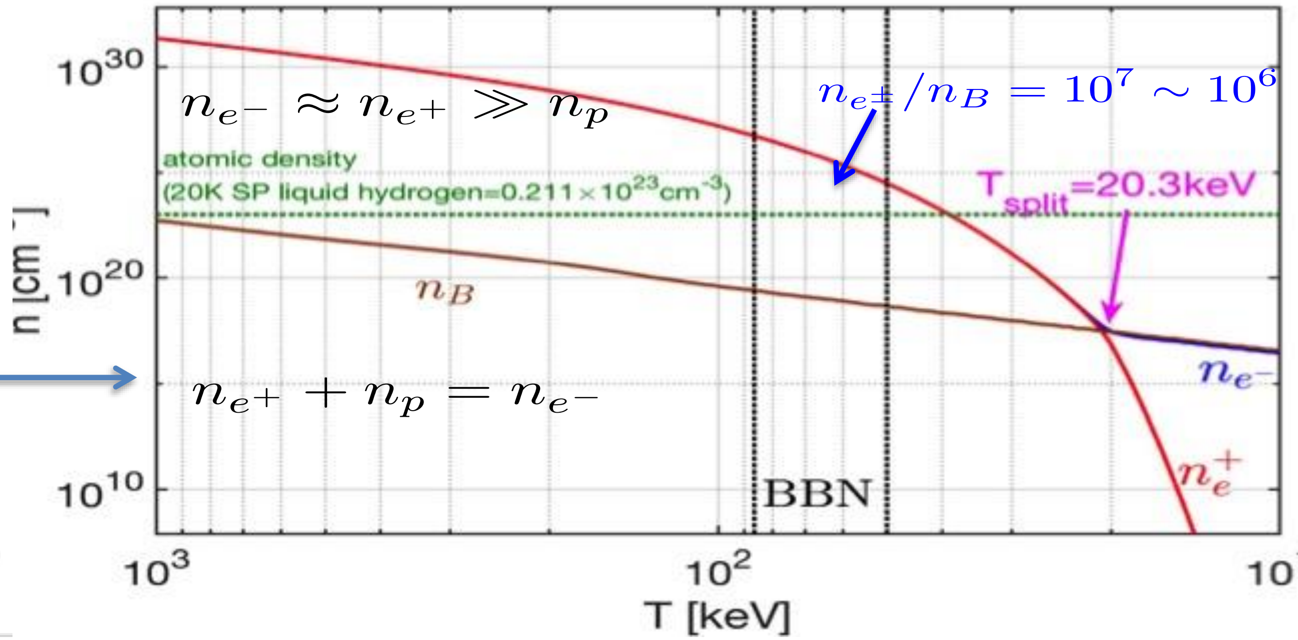
The number density of electrons over positrons

$$n_e - n_{\bar{e}} = \frac{g_e}{2\pi^2}\left[\int_0^\infty \frac{p^2 dp}{\exp\left(\left(E-\mu_e\right)\right)/T_\gamma + 1} - \int_0^\infty \frac{p^2 dp}{\exp\left((E+\mu_e)/T_\gamma\right)+1}\right]$$

$$T_{\rm BBN} = 86 \sim 50 \text{keV}$$

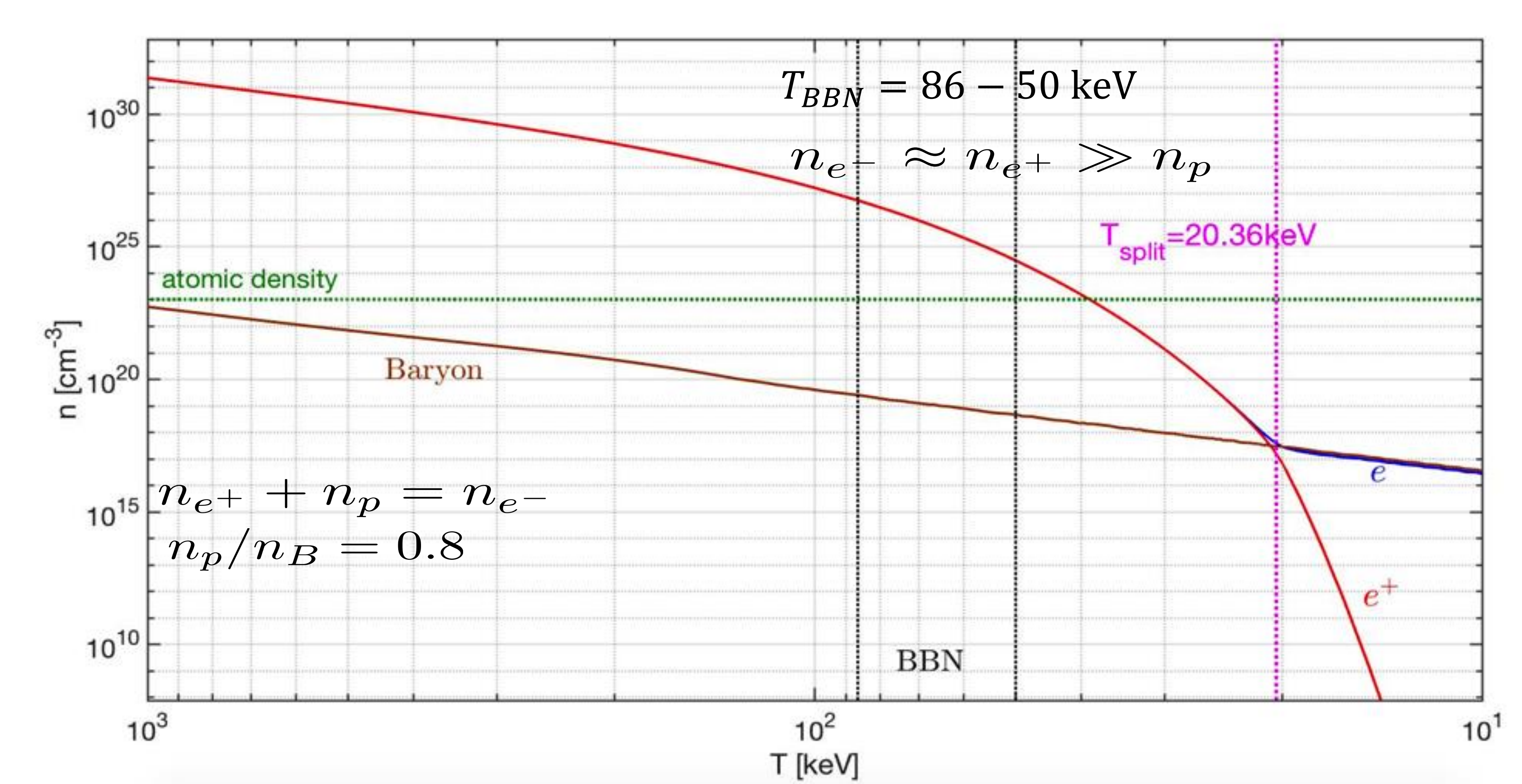


$$T_{\rm BBN} = 86 \sim 50 \text{keV}$$



Big Bang Nucleosynthesis in rich Electron/Positron Plasma

We will show that when the temperature is $T = 86$ keV, we have an abundance of electrons and positrons in cosmic plasma with $n_{e^\pm}/n_B = 10^7$



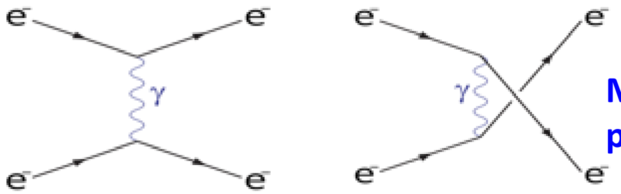
BBN happens within the rich electron-positron plasma and **plasma effects need to be accounted for in the precision study of the final abundances of light elements produced in BBN..** ← **Dr. Chris Grayson**

Microscopic evaluation of collision damping in e⁻e⁺-plasma

In electron-positron plasma the major reactions between photons and electron/positron pairs are given by

Møller scattering:

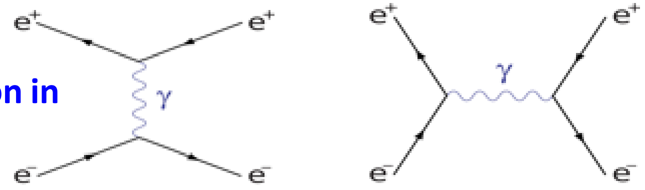
$$e^{\pm} + e^{\pm} \longrightarrow e^{\pm} + e^{\pm}$$



Massive photon in plasma

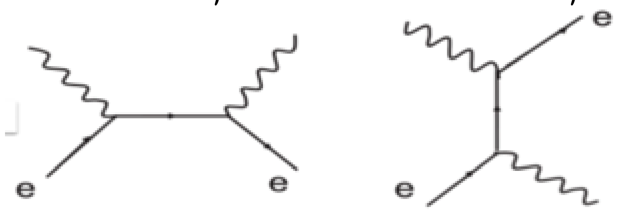
Bhabha scattering:

$$e^{\pm} + e^{\mp} \longrightarrow e^{\pm} + e^{\mp}$$

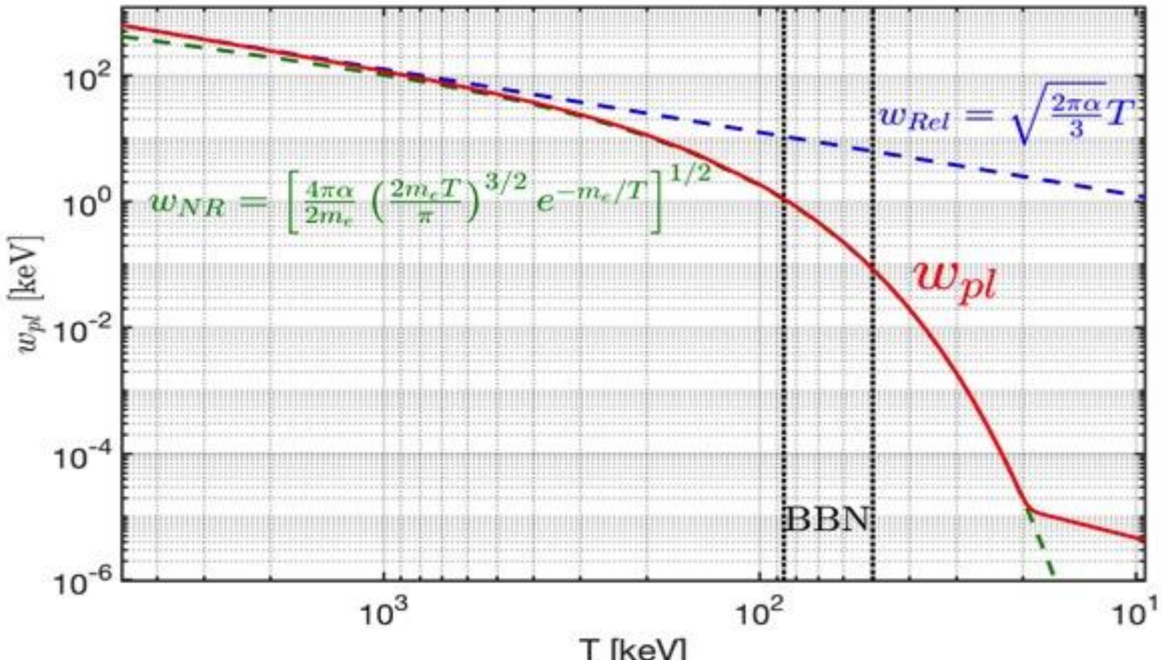


Inverse Compton scattering:

$$e^{\pm} + \gamma \longrightarrow e^{\pm} + \gamma$$



A photon propagates through a plasma of electrons and positrons, its propagation is influenced by the interactions with the medium and generate effective mass for the photon in plasma.



For the BBN temperature 50<T_{BBN}<86 keV, we can consider the Boltzmann approximation for the nonrelativistic electron/positron plasma:

$$m_\gamma^2 = w_{pl}^2 = \frac{4\pi\alpha}{2m_e}\left(\frac{2m_e T}{\pi}\right)^{3/2} e^{-m_e/T}$$

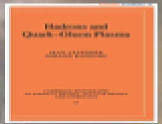
$$T_{\rm BBN} = 86 \sim 50\text{keV}$$
$$m_\gamma = w_{pl} = 1 \sim 0.1\,\text{keV}$$

Photons still remain relativistics because w_{pl}/T_{BBN}<<1.

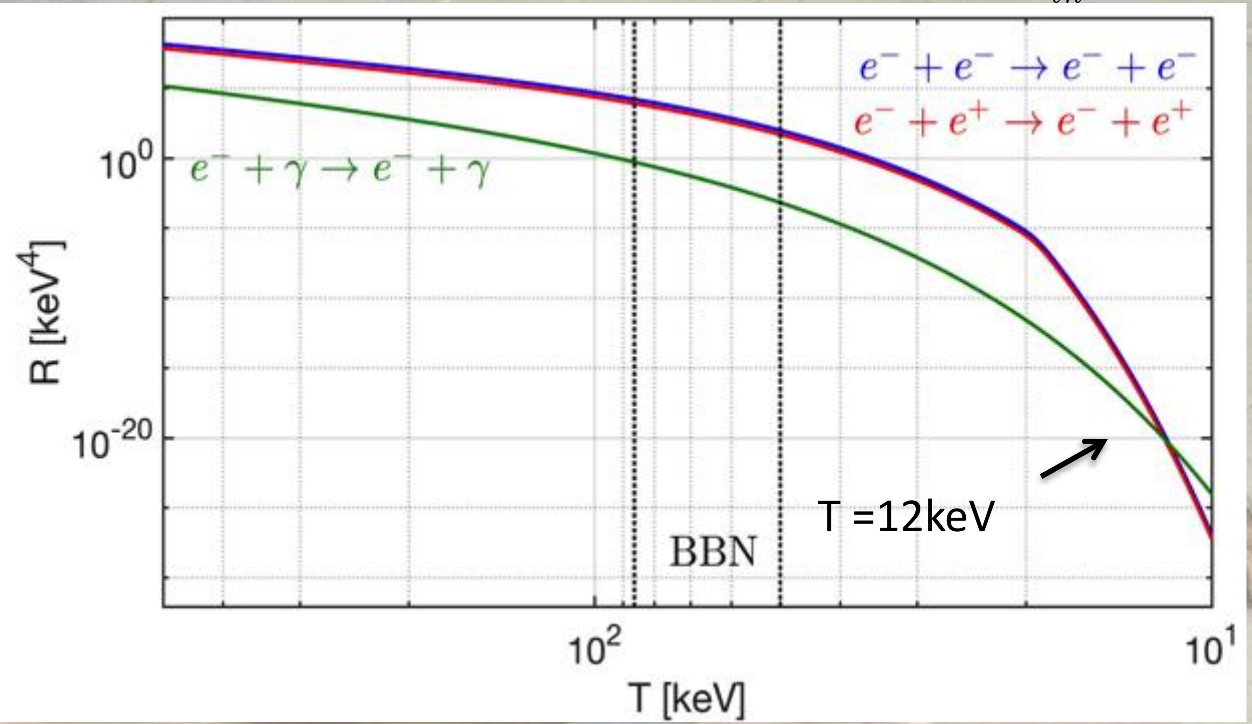
Damping rate in electron-positron plasma → Chris Grayson's Lecture

To calculate the damping rate κ in plasma, we calculate the reaction rate per volume in two-body reaction in the Boltzmann approximation first:

$$R_{12\to 34} = \langle \sigma v \rangle_T n_1 n_2 = \frac{g_1 g_2}{32\pi^4}\frac{T}{1+I_{12}}\int_{s_{th}}^{\infty} ds\,\sigma(s)\frac{\left[s-(m_1+m_2)^2\right]\left[s-(m_1-m_2)^2\right]}{\sqrt{s}}K_1(\sqrt{s}/T)\,,$$



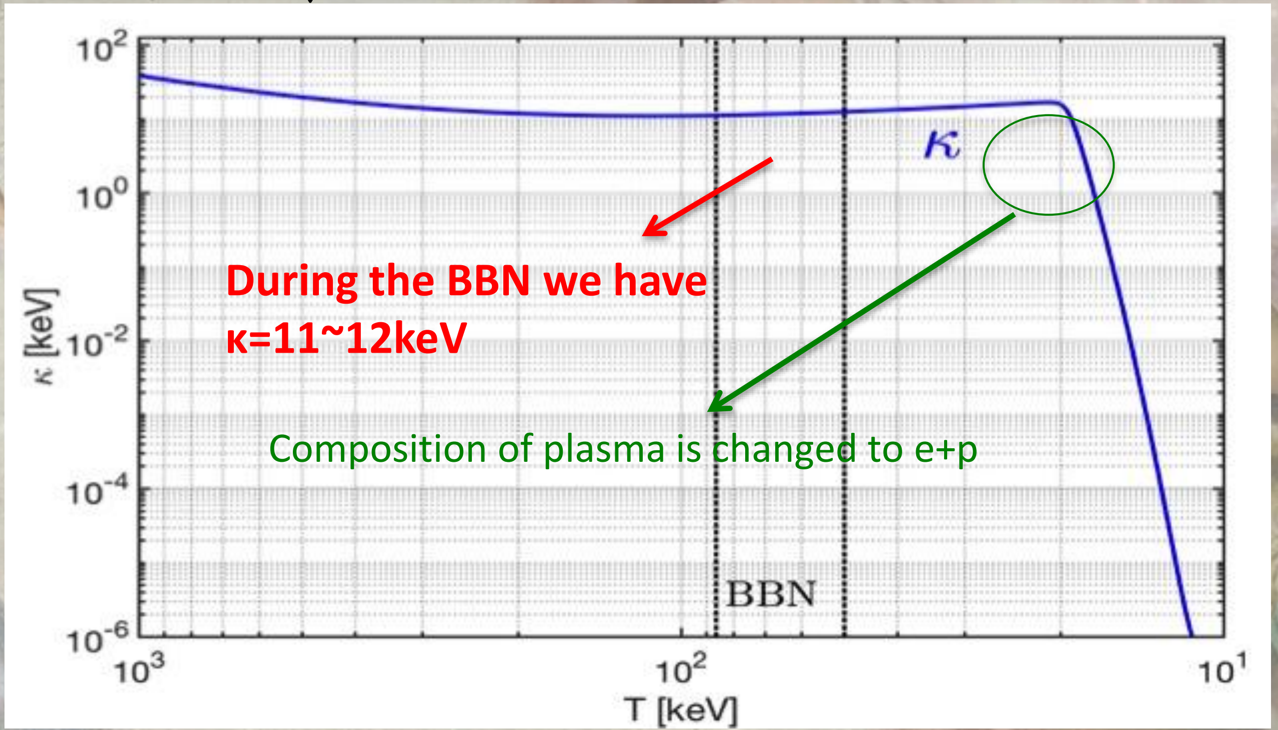
Jean Letessier, Johann Rafelski, "Hadrons and Quark-Gluon Plasma"



For T>12keV, the dominate reactions in plasma are Møller and Bhabha scatterings

The electron(positron) damping rates can be defined as

$$\kappa = \frac{R_{e\bar{e}\to e\bar{e}} + R_{ee\to ee}}{\sqrt{n_e n_{\bar{e}}}} \qquad \sqrt{n_e n_{\bar{e}}} = \frac{g_e}{2\pi^3}T^3\left(\frac{m_e}{T}\right)^2 K_2(m_e/T)$$



For comprehensive discussion and the application of the damped e^-e^+-plasma and dynamic screening during BBN see paper:**C. Grayson, C.T.Yang, M.Formanek and J.Rafelski, ``Electron-positron plasma in BBN: Damped-dynamic screening,'' Annals Phys. 458, 169453 (2023)**

Improving damping rate in e^-e^+-plasma: self-consistence approach

The photon mass is one of important parameters in the calculation of the relaxation rate for Møller and Bhabha scattering in electron positron plasma.

M. Formanek, C. Grayson, J. Rafelski and B. Müller, ``Current-conserving relativistic linear response for collisional plasmas,'' Annals Phys. 434, 168605 (2021)

Considering the linear response theory, the dispersion relation for the photon in nonrelativistic e± plasma is given by

$$w^2 = |k|^2 + \frac{w}{w + i\kappa} w_{pl}^2$$

Solving the dispersion relation with k=0 →

$$w_{\pm} = -i\frac{\kappa}{2} \pm \sqrt{w_{pl}^2 - \frac{\kappa^2}{4}}$$

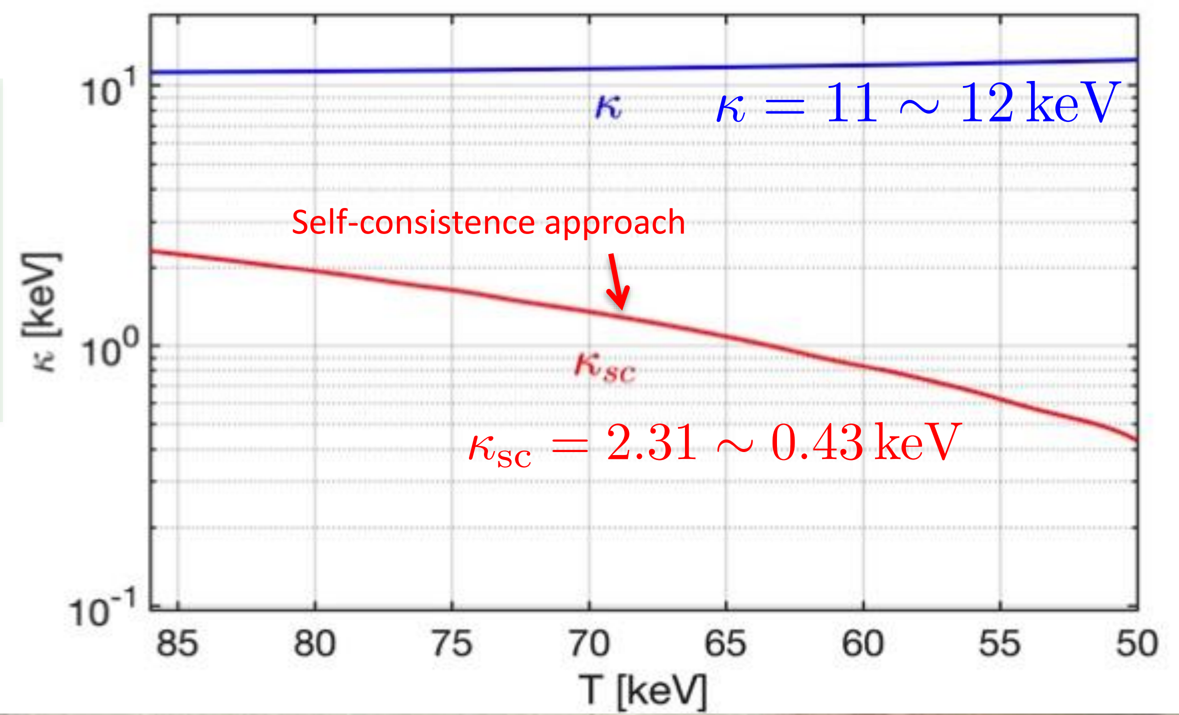
The effective plasma frequency in damped plasma

The effective photon mass in damped plasma is a function of the scattering rate. $m_\gamma(\kappa, w_{pl})$

we need to solve the self-consistent equation for scattering rate:

$$\kappa \left[\frac{g_e}{2\pi^3} T^3 \left(\frac{m_e}{T}\right)^2 K_2(m_e/T)\right]$$
$$= \frac{g_e g_e}{32\pi^4} T \int_{4m_e^2}^{\infty} ds \frac{s(s-4m_e^2)}{\sqrt{s}} K_1(\sqrt{s}/T) \left[\sigma_{e\pm e\pm}(s, w_{pl}, \kappa) + \sigma_{e\pm e\mp}(s, w_{pl}, \kappa)\right]$$

To solve the self-consistent equation we need to know the transition amplitude for Møller and Bhabha scattering with imaginary photon mass which requires detail study.



Magnetism in primordial cosmology

PHYSICAL REVIEW D **108**, 123522 (2023)

Matter-antimatter origin of cosmic magnetism

Andrew Steinmetz, Cheng Tao Yang, and Johann Rafelski
Department of Physics, The University of Arizona, Tucson, Arizona 85721, USA

(Received 30 August 2023; accepted 15 November 2023; published 11 December 2023)

We explore the hypothesis that the abundant presence of relativistic antimatter (positrons) in the primordial Universe is the source of the intergalactic magnetic fields we observe in the Universe today. We evaluate both Landau diamagnetic and magnetic dipole moment paramagnetic properties of the very dense primordial electron-positron e^+e^--plasma, and obtain in quantitative terms the relatively small magnitude of the e^+e^- magnetic moment polarization asymmetry required to produce a consistent self-magnetization in the Universe.

Steinmetz, Andrew, Cheng Tao Yang, and Johann Rafelski. "Matter-antimatter origin of cosmic magnetism." Physical Review D 108.12 (2023): 123522.

universe **For Remo Ruffini Festschrift** MDPI

Review

A Short Survey of Matter-Antimatter Evolution in the Primordial Universe

Johann Rafelski *, Jeremiah Birrell, Andrew Steinmetz and Cheng Tao Yang
Department of Physics, The University of Arizona, Tucson, AZ 85721, USA
* Correspondence: johannr@arizona.edu

Abstract: We offer a survey of the matter-antimatter evolution within the primordial Universe. While the origin of the tiny matter-antimatter asymmetry has remained one of the big questions in modern cosmology, antimatter itself has played a large role for much of the Universe's early history. In our study of the evolution of the Universe we adopt the position of the standard model Lambda-CDM Universe implementing the known baryonic asymmetry. We present the composition of the Universe across its temperature history while emphasizing the epochs where antimatter content is essential to our understanding. Special topics we address include the heavy quarks in quark-gluon plasma (QGP), the creation of matter from QGP, the free-streaming of the neutrinos, the vanishing of the muons, the magnetism in the electron-positron cosmos, and a better understanding of the environment of the Big Bang Nucleosynthesis (BBN) producing the light elements. We suggest but do not explore further that the methods used in exploring the early Universe may also provide new insights in the study of exotic stellar cores, magnetars, as well as gamma-ray burst (GRB) events. We describe future investigations required in pushing known physics to its extremes in the unique laboratory of the matter-antimatter early Universe.

Rafelski J, Birrell J, Steinmetz A, Yang CT. A Short Survey of Matter-Antimatter Evolution in the Primordial Universe. Universe. 2023; 9(7):309.

e^- e^+ e^- e^+ e^- e^+ e^- e^+ e^- e^+ e^- e^+ e^- e^+ e^- e^+ e^- e^+ e^- e^+ e^-

Electron-positron magnetization in early Universe

The Universe today filled with magnetic fields at various scales and strengths both within galaxies and in deep extra-galactic space far and away from matter sources

Pshirkov, M. S., P. G. Tinyakov, and F. R. Urban. "New limits on extragalactic magnetic fields from rotation measures". Phys. Rev. Lett., 116(19), p. 191302(2016)

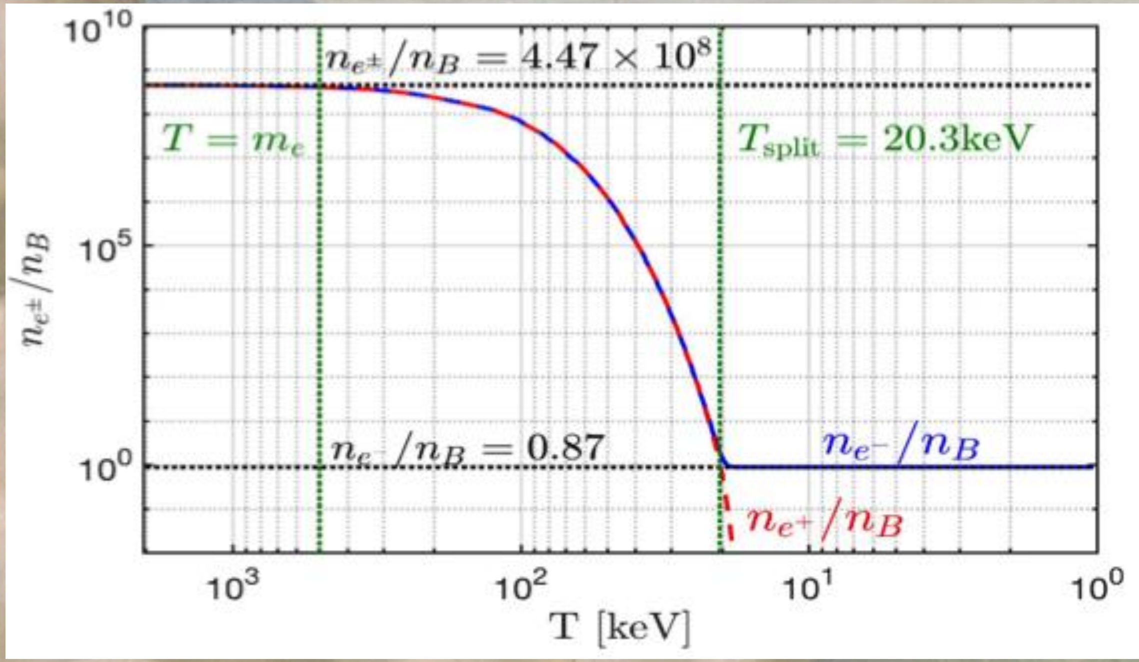
Jedamzik, K. and A. Saveliev," Stringent limit on primordial magnetic fields from the cosmic microwave background radiation". Physical review letters, 123(2), p. 021301. (2019).

Observation: Extra-galactic magnetic fields (EGMF)

$$10^{-8}\ \mathrm{G} > \mathcal{B}_{\mathrm{EGFM}} > 10^{-16}\ \mathrm{G}$$

- Electrons and positrons have **the largest magnetic moments** in nature.

This very dense electron-positron plasma could be the origin of cosmic magnetism.



The partition of the electron-positron plasma in a uniform magnetic field B pointing along the z-axis

$$\ln \mathcal{Z}_{e^+e^-} = \frac{eBV}{(2\pi)^2} \sum_{\sigma}^{\pm} \sum_{s}^{\pm} \sum_{n=0}^{\infty} \int_{-\infty}^{\infty} dp_z \left[\ln \left(1 + \lambda_\sigma \xi_s e^{-E_n^s/T} \right) \right]$$

$$E_n^{\pm} = \sqrt{p_z^2 + \tilde{m}_{\pm}^2 + 2eBn} \qquad \tilde{m}_{\pm}^2 = m_e^2 + eB\left(1 \mp \frac{g}{2}\right)$$

Particle chemical potential $\lambda_{\pm} = \exp\left(\pm\mu_e/T\right)$

Spin chemical potential $\xi_{\pm} = \exp\left(\pm\eta_s/T\right)$

We study the magnetization process within dense electron-positron plasma via fundamental quantum statistical analysis:

JR, J.Birrell, A.Steinmetz and C.T.Yang, ``A short survey of matter-antimatter evolution in the primordial universe,'' Universe 9, 309 (2023)

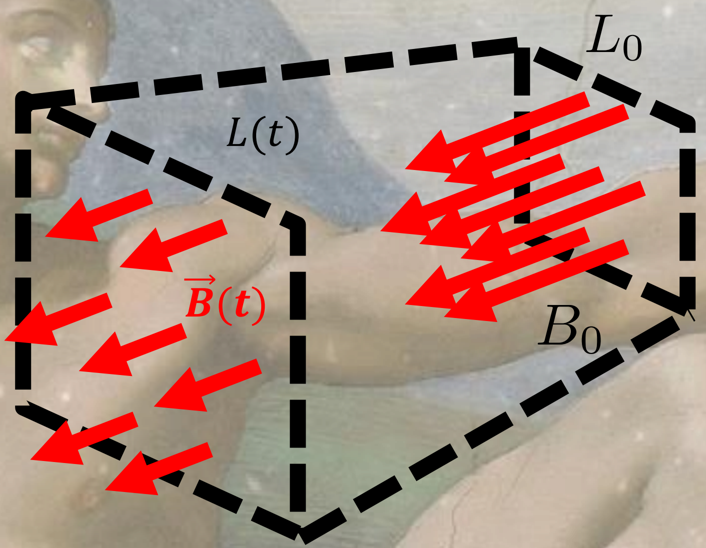
Example: How magnetism is function of temperature

Magnetic flux is conserved over a comoving surface

$$L(t)^2 = L_0^2 a(t)^2/a(t_0)^2$$

The magnetic field then dilutes over time as

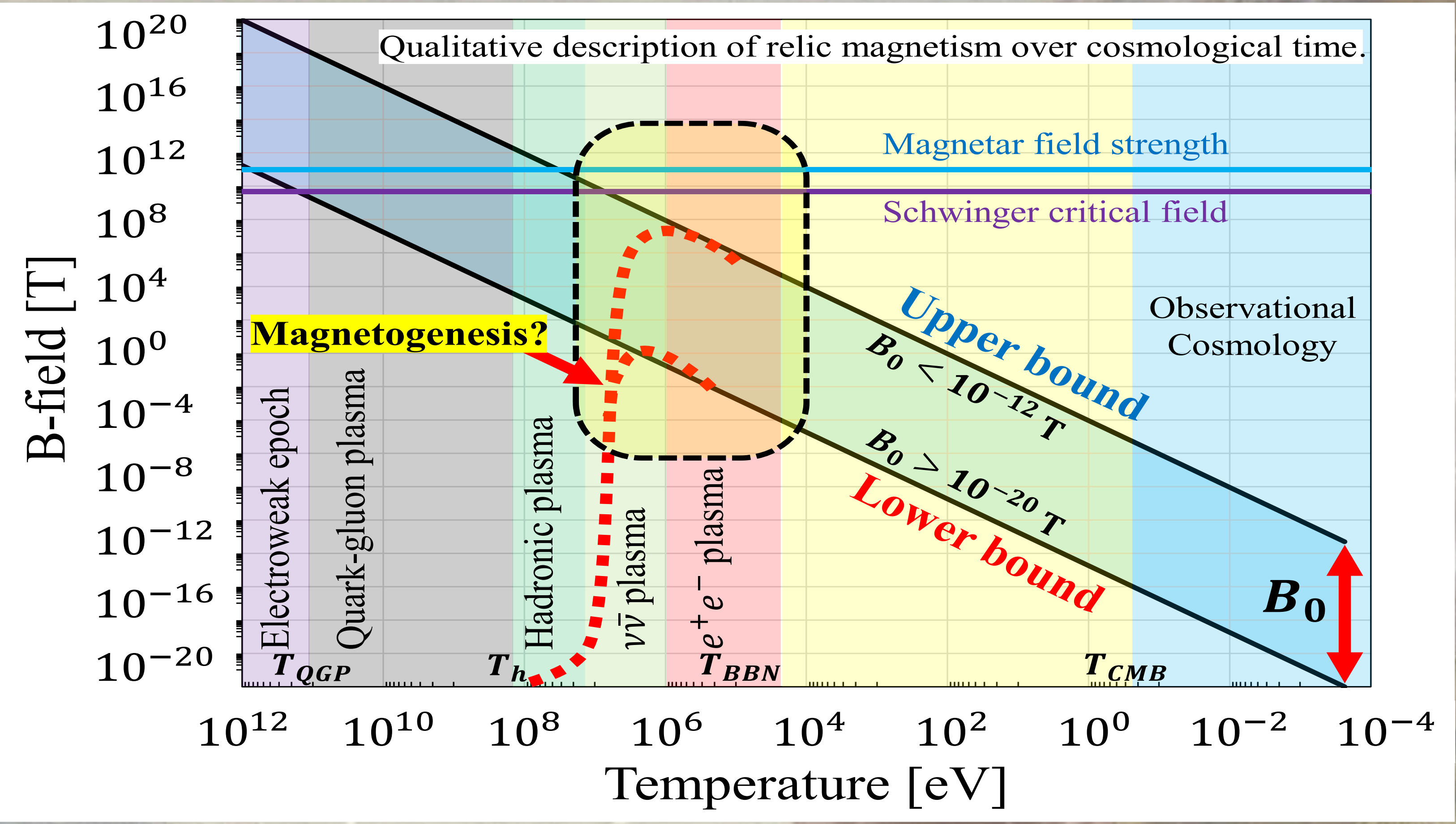
$$B(t)^2 = B_0^2\, a(t_0)^2/a(t)^2$$



Magnetic flux:

$$\Phi_B = B(t)L^2(t) = B_0 L_0^2$$

Cosmic relic magnetism – Pre-CMB signal



The upper and lower bounds on inter-galactic magnetic fields (IGMF) coherent over Mpc scales is shown.

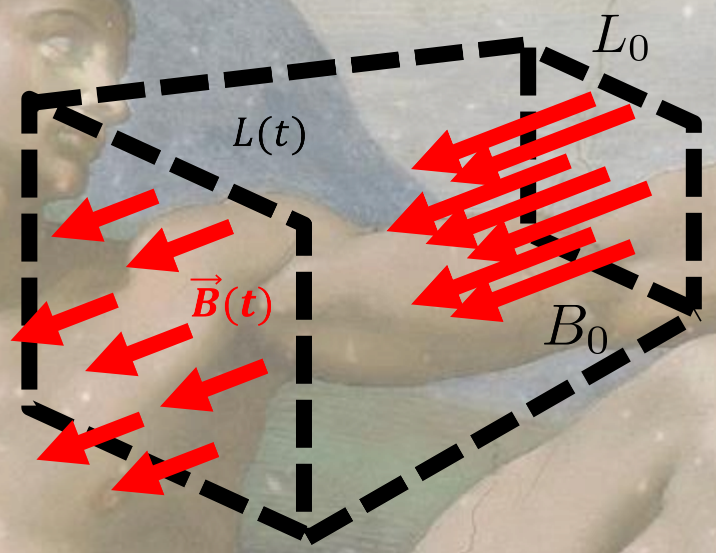
Example: How magnetism is function of temperature

Magnetic flux is conserved over a comoving surface

$$L(t)^2 = L_0^2 a(t)^2 / a(t_0)^2$$

The magnetic field then dilutes over time as

$$B(t)^2 = B_0^2\, a(t_0)^2 / a(t)^2$$



Magnetic flux:

$$\Phi_B = B(t) L^2(t) = B_0 L_0^2$$

Constant relic magnetic scale

The temperature also decreases over cosmic expansion as

$$T(t) = T_0 a(t_0)/a(t)$$

Magnetic fields present in cosmic voids would be "uncontaminated" primordial relics.

This lets us define a conserved cosmic "magnetic scale" for charged particles.

$$b_0 \equiv eB(t)/T(t)^2 = eB_0/T_0^2 = \text{const}$$

In natural units:

$$\hbar = c = k_B = 1$$

Contemporary B-fields

$$10^{-12}\text{T} > B_0 > 10^{-20}\text{T}$$

Upper: Faraday rotation of radio AGN
Lower: Spectra of "blazar" AGN

Contemporary temperature

$$T_0 = 2.7\,\text{K} = 2.3 \times 10^{-4}\,\text{eV}$$

As determined from the Cosmic Microwave Background (CMB)

$$10^{-3} > b_0 > 10^{-11}$$

Thus b_0 controls the strength of the magnetization of the primordial electron-positron plasma.

Note: B-field decreases with decreasing temperature.

The upper and lower bounds on inter-galactic magnetic fields (IGMF) coherent over Mpc scales is shown.

Magnetization of e^-e^+-plasma in Boltzmann limit

The partition function of nonrelativistic electron-positron plasma with a uniform magnetic field pointing along the z-axis

$$\ln \mathcal{Z}_{e^+e^-} = \frac{T^3 V}{2\pi^2}\left[2\cosh\left(\frac{\mu_e}{T}\right)\right]\sum_{i=\pm}\left\{x_i^2 K_2(x_i) + \frac{b_0}{2} x_i K_1(x_i) + \frac{b_0^2}{12} K_0(x_i)\right\}$$

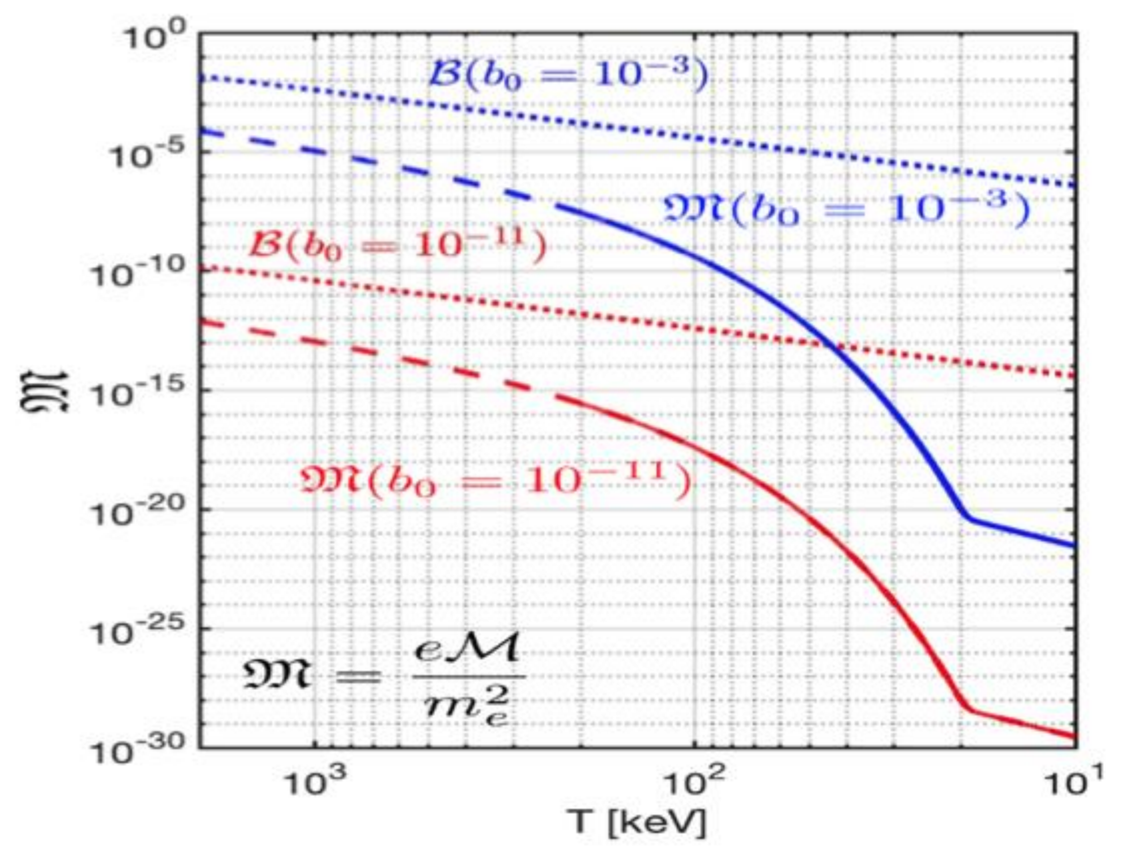
$$x_i = \tilde{m}_i / T \qquad \tilde{m}_\pm^2 = m_e^2 + eB\left(1 \mp \frac{g}{2}\right)$$

First approximation:

$$\frac{\eta_s}{T} \ll 1$$

J.Rafelski, J.Birrell, A.Steinmetz and C.T.Yang, ``A short survey of matter-antimatter evolution in the primordial universe,'' Universe 9, 309 (2023)

We can explore the electron-positron magnetization process in plasma via the partition function.



Magnetization

$$\mathcal{M} = \left(\frac{T}{V}\frac{\partial \ln \mathcal{Z}_{e^+e^-}}{\partial B}\right)$$

- The e^-e^+-plasma has paramagnetic properties when subjected to an external field
- The magnetization never exceeds the external field under the parameters considered.
- The research of nonzero spin chemical potential is continue by Andrew Steinmetz's Phd thesis and paper. **A. Steinmetz, C.T. Yang and J. Rafelski,``Matter-antimatter origin of cosmic magnetism,''[arXiv:2308.14818 [hep-ph]], Phys. Rev.D 108, 12, 123522(2023)**

Highlights

- The universe's evolution contains distinct eras of different particles forming the plasma.
- Standard particle model plasma predict to contain long lasting chemical nonequilibrium.
- Antibaryons disappear at 38.2 MeV; long lasting strangeness and muons to 4.2 MeV.
- Progressive decoupling and free streaming neutrino at a few MeV.
- Positron disappear at 20.3 keV, electron-positron plasma as a source of magnetization in study.
- **→ Lecture by Chris Grayson for strong & weak ee screening in BBN 86-50 keV.**