Time Evolution of the Hot Hagedorn Universe

Results obtained in collaboration with
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The University of Arizona

1965: Penzias and Wilson discover Alpher-Gamov 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 and certain aspects of the subject are attracting more attention from physicists. Growing emphasis on physics has been stimulated by discovery of the universal black-body radiation and by growing realization that the 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 eras to its present state of comparative darkness and emptiness.

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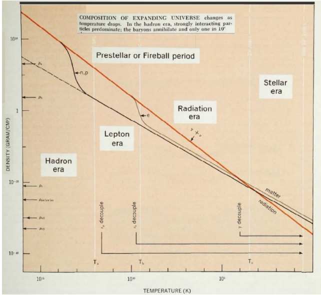

SBM the only model providing initial singular condition 1967 many regard SBM as the Hot Big-Bang theory

Actes de la Société Helvétique des Sciences Naturelles.
Partie scientifique et administrative 148 (1968) 51
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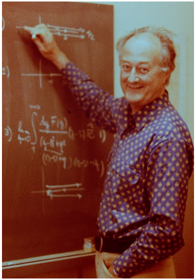
Siedende Urmaterie

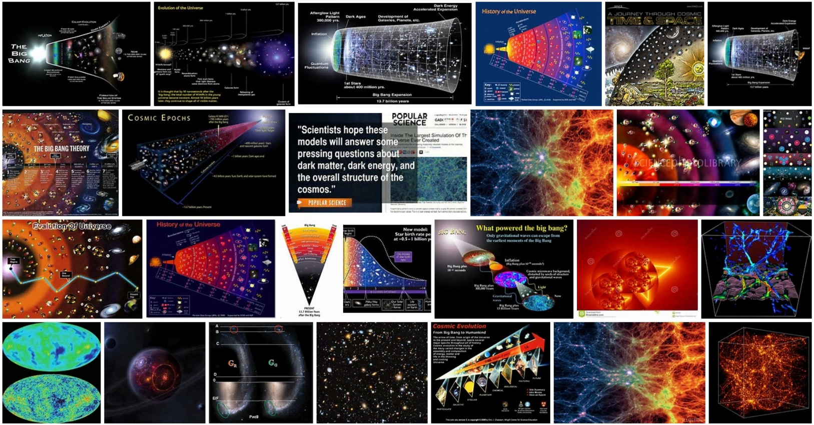
R. Hagedorn, CERN (Genève)

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.

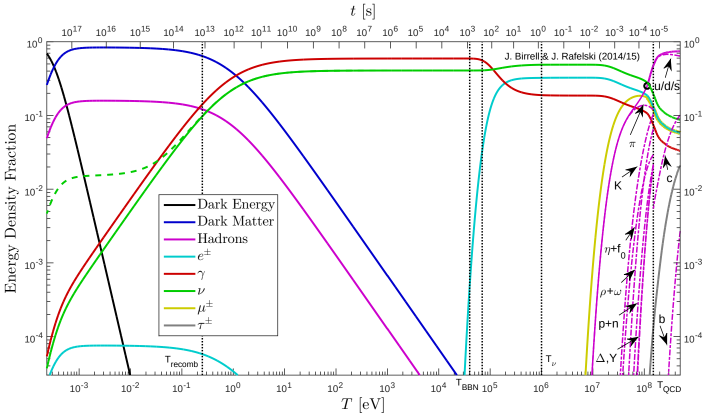


Boiling Primordial Matter *Even though no one was present when the Universe was born, our current understanding of atomic, nuclear and elementary particle physics, constrained by the assumption that the Laws of Nature are unchanging, allows us to construct models with ever better and more accurate descriptions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

Forward to the Universe 2015



The time evolution of the energy density composition



Input into the image

- FRW Cosmology
- Disappearing Particles:
  Degrees of Freedom and Reheating – tracking T_γ
- Connecting the Eras
  - From the beginning to QGP – remarks
  - And matter free-streams, latest when:
  - QGP turns into disappearing hadrons, invisible radiation,. . .
  - Onset of neutrino free-streaming
  - Big-Bang nucleosynthesis and disappearance of matter
  - Emergence of free streaming dark matter, baryons follow
  - Photon Free-streaming – Composition Cross-Point
  - Dark Energy Emerges – vacuum energy
- Open questions abound

Overview: the Friedmann–Lemaitre–Robertson–Walker (FRW) cosmology assumes

- Homogeneous
- Isotropic

Einstein Universe

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2(\theta)d\phi^2)\right].$$

Flat ($k=0$) metric is favored [1] in the ΛCDM analysis. $a(t)$ determines the distance between objects at rest in the Universe frame (comoving). Skipping $g^{\mu\nu} \to R^{\mu\nu}$

[1] *Planck Collaboration, Astron. Astrophys.* **571**, *A16 (2014) [arXiv:1303.5076] and arXiv:1502.01589 [astro-ph.CO].*

Einstein's Equations, where $R = g_{\mu\nu}R^{\mu\nu}$:

$$G^{\mu\nu} = R^{\mu\nu} - \left(\frac{R}{2} + \Lambda\right) g^{\mu\nu} = 8\pi G_N T^{\mu\nu}, \quad T^{\mu}_{\nu} = \mathrm{diag}(\rho, -P, -P, -P),$$

We absorb the vacuum energy (Einstein Λ-term) into the energy ρ and pressure P

$$\rho \to \rho + \rho_\Lambda, \qquad P \to P + P_\Lambda$$

which contain other components in the Universe including CDM: cold dark matter. The ΛCDM speaks thus of Dark Energy, or equivalently, non-vanishing vacuum energy density

$$\rho_\Lambda \equiv \Lambda/(8\pi G_N) = 25.6\ \mathrm{meV}^4, \qquad P_\Lambda = -\rho_\Lambda$$

The pressure P_Λ has a) opposite sign from all matter contributions and b) $\rho_\Lambda/P_\Lambda = -1$.

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 $8\pi G_N/3 \rightarrow$ we find for the deceleration parameter:

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

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 $\rho = \rho(T(t))$ also $\dot{T}$ fixed.

The contents of the Universe:

- Matter coupled to photons: thermal matter = ideal Bose-Fermi gases
- Free-streaming matter: today
  - dark matter: since at or before QGP hadronization
  - neutrinos: since T =few MeV
  - photons: since $T = 0.25 eV$
  - hypothetical darkness: quasi-massless particles, like neutrinos but due to earlier decoupling small impact on Universe dynamics
- dark energy = vacuum energy

Degrees of Freedom

The effective number of entropy degrees of freedom, g_*^S, defined by

$$S = \frac{2\pi^2}{45} g_*^S T_\gamma^3 a^3 .$$

For ideal Fermi and Bose gases

$$g_*^S = \sum_{i=\text{bosons}} g_i \left(\frac{T_i}{T_\gamma}\right)^3 f_i^- + \frac{7}{8} \sum_{i=\text{fermions}} g_i \left(\frac{T_i}{T_\gamma}\right)^3 f_i^+ .$$

g_i are the degeneracies, $f_i^\pm$ are functions varying valued between 0 and 1 that turn off the various species as the temperature drops below their mass.

Degrees of Freedom

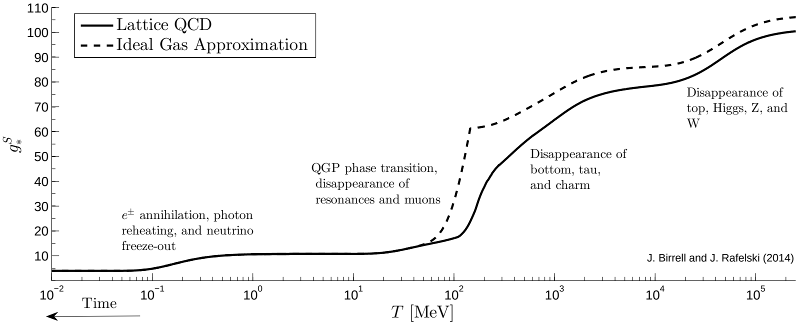


Figure: Ideal gas approximation is not valid during QGP phase transition and equation of state from lattice QCD must be used [1]. At and above 300 MeV non-rigorous matching [2] with perturbation calculations may impact result.

[1] *S. Borsanyi, Nucl. Phys. A904-905, 270c (2013)*
[2] *Mike Strickland (private communication of results and review of thermal SM).*

Conservation of Entropy and Reheating

Once (example) Darkness decouples from SM particles at a photon temperature of $T_{d,s}$, a difference in its temperature from that of photons will build up during subsequent reheating periods. Conservation of entropy leads to a temperature ratio at $T_\gamma < T_{d,s}$ of

$$R_s \equiv T_s/T_\gamma = \left(\frac{g_*^S(T_\gamma)}{g_*^S(T_{d,s})}\right)^{1/3} .$$

This can be used to determine the present day reheating ratio as a function of decoupling temperature throughout the Universe history.

Reheating and Particle Disappearance History

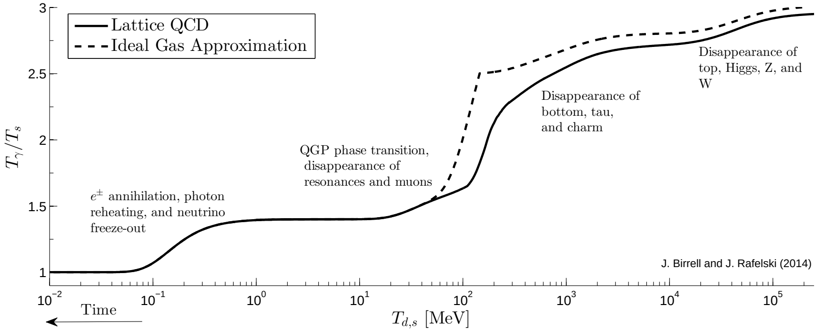


Figure: The reheating ratio reflects the disappearance of degrees of freedom from the Universe. At and above 300 MeV non-rigorous matching with perturbative calculations may impact result. These results are for adaiabatic evolution of the Universe.

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

$$\rho = \frac{g_\nu}{2\pi^2}\int_0^\infty \frac{\left(m_\nu^2 + p^2\right)^{1/2} p^2 dp}{\Upsilon_\nu^{-1} e^{\sqrt{p^2/T_\nu^2 + m_\nu^2/T_k^2}} + 1}, \quad P = \frac{g_\nu}{6\pi^2}\int_0^\infty \frac{\left(m_\nu^2 + p^2\right)^{-1/2} p^4 dp}{\Upsilon_\nu^{-1} e^{\sqrt{p^2/T_\nu^2 + m_\nu^2/T_k^2}} + 1},$$

$$n = \frac{g_\nu}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\Upsilon_\nu^{-1} e^{\sqrt{p^2/T_\nu^2 + m_\nu^2/T_k^2}} + 1}.$$

These differ from the corresponding expressions for an equilibrium distribution by the replacement $m \rightarrow mT_\nu(t)/T_k$ *only* in the exponential. Only for massless photons free-streaming = thermal distributions.

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).*

Identifying Eras by Deceleration Parameter q

$$q \equiv -\frac{\ddot{a}a}{\dot{a}^2}.$$

Using Einsteins equations exact expression in terms of matter content

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

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

Hadron and QGP Era

- QGP era down to phase transition at $T \approx 150$MeV. Energy density dominated by photons, neutrinos, $e^{\pm}$, $\mu^{\pm}$ along with u,d,s.
- $2+1$-flavor lattice QCD equation of state must be used $[1]$.
- u,d,s lattice energy density is matched by ideal gas of hadrons to sub percent-level at $T = 115$MeV.
- Hadrons included: pions, kaons, eta, rho, omega, nucleons, delta, Y
- without all resonances hadron pressure is discontinuous at 10% level. Causes hard to notice discontinuity in q (slops match).

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

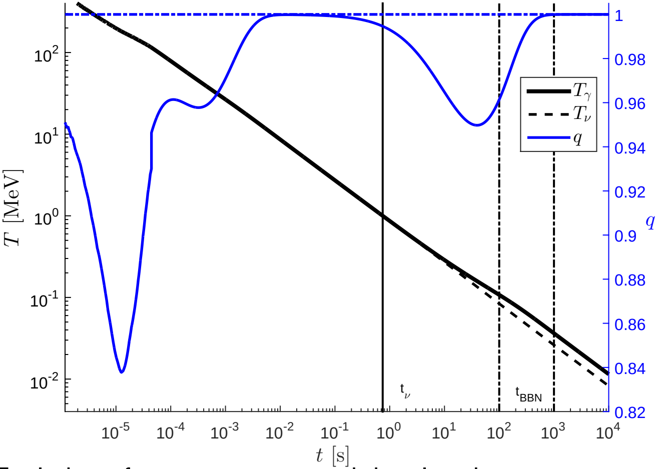


Figure: Evolution of temperature T and deceleration parameter q from QGP era until near BBN.

Relic Neutrino Background:

At a temperature of 5 MeV the Universe consisted up to 10^{-9} of plasma made of $e^{\pm}$-pairs, photons, and neutrinos. At around 1 MeV neutrinos stop interacting or freeze-out and free stream through the universe. Today they comprise the relic neutrino background (CNB).

Direct measurement:
Relic neutrinos have not been directly measured.

Indirect measurement:
Impact on speed of Universe expansion can be seen in the CMB. This constrains: i) neutrino mass, ii) reheating of neutrinos by $e^{\pm}$-pair annihilation, and iii) the number of additional invisible relativistic degrees of freedom.

Reheating Ratio and δN_ν

If a particle species with g_s degrees of freedom (normalized to bosons) decouples from SM particles at a photon temperature of $T_{d,s}$ then the impact on the value of N_ν at a photon temperature of T_γ is

$$\delta N_\nu = \frac{4g_s}{7R_\nu^4}\left(\frac{g_*^S(T_\gamma)}{g_*^S(T_{d,s})}\right)^{4/3}. \tag{1}$$

In particular, after $e^\pm$ annihilation the SM particles remaining are photons and SM neutrinos, the latter with temperature $R_\nu T_\gamma$, and so $g_*^S(T_\gamma) = 2 + 7/8 \times 6 \times 4/11$ and

$$\delta N_\nu \approx g_s\left(\frac{7.06}{g_*^S(T_{d,s})}\right)^{4/3}. \tag{2}$$

If Understanding of Neutrino Freeze-out Accurate

The computed best value is $N_\nu = 3.046$ (some flow of $e^{\pm}$-pair entropy into ν) [1]. Only drastic changes in neutrino properties and/or physical laws can change this value noticeably [2].

- δN_ν probes 'Darkness' particle content in the Universe: new relativistic particles in the early Universe modify N_ν, see e.g. [3].
- δN_ν limits variation of fundamental constants in early Universe [4]

[1] *G. Mangano et. al., Nucl. Phys. B* **729**, *221 (2005)*
[2] *J. Birrell, C. T. Yang and JR, Nucl. Phys. B* **890**, *481 (2014) [1406.1759 [nucl-th]]*
[3] *Steven Weinberg Phys. Rev. Lett.* **110**, *241301 (2013)*
[4] *J. Birrell, C-T Yang, J. Rafelski Nucl.Phys. B* **890** *481-517 (2014)*

How understanding the Universe enters laboratory experiments: Example

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Quark–gluon plasma as the possible source of cosmological dark radiation

Jeremiah Birrell, Johann Rafelski

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Abstract

The effective number of neutrinos, N_{eff}, obtained from CMB fluctuations accounts for all effectively massless degrees of freedom present in the Universe, including but not limited to the three known neutrinos. Using a lattice-QCD derived QGP equation of state, we constrain the observed range of N_{eff} in terms of the freeze-out of unknown degrees of freedom near to quark–gluon hadronization. We explore limits on the coupling of these particles, applying methods of kinetic theory, and discuss the implications of

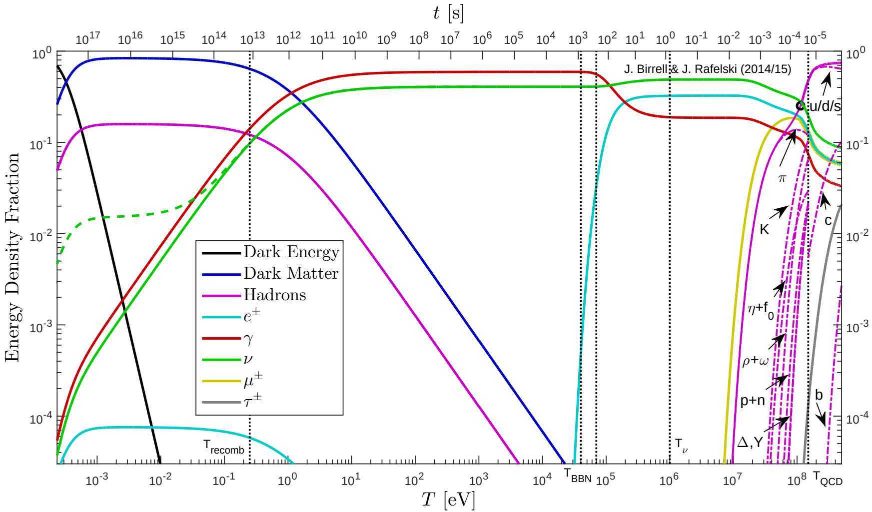
- We showed quantitatively how freeze-out of a reasonable number of Bose or fermi DoF at T_c during the QGP phase transition in the Universe leads to δN_ν in the range compatible with Planck.
- The existence of such Dark QCD related particles should lead to observable effects in heavy ion collisions: search for missing energy in connection to dynamics of hadronization near to phase boundary as function of $\sqrt{s}$ with energy imbalance increasing with A.

Radiation Dominated Era

- Neutrinos freeze-out at $T \approx 1$MeV.
- A small deviation from radiation dominated during $e^{\pm}$ annihilation.
- Energy density dominated by neutrinos, photons down through BBN ($T = 40 - 70$keV) until $T = O(1\text{eV})$

Dark energy and Matter Dominated Eras

- Present day on left of plot: 69% dark energy, 26% dark matter, 5% baryons, $< 1\%$ photons and neutrinos.
- Solid neutrino line shows massless neutrinos. Dashed line shows 1 massless and 2×0.1 eV neutrinos (Neutrino mass choice is just for illustration. Other values are possible)
- First vertical line on the left shows recombination at $T \approx 0.25$eV.



t [s]
T [eV]
Energy Density Fraction
J. Birrell & J. Rafelski (2014/15)
Dark Energy
Dark Matter
Hadrons
$e^{\pm}$
γ
ν
$\mu^{\pm}$
$\tau^{\pm}$
T_{recomb}
T_{BBN}
T_{ν}
T_{QCD}
u/d/s
π
K
c
η+f_0
$\rho+\omega$
p+n
Δ,Y
b

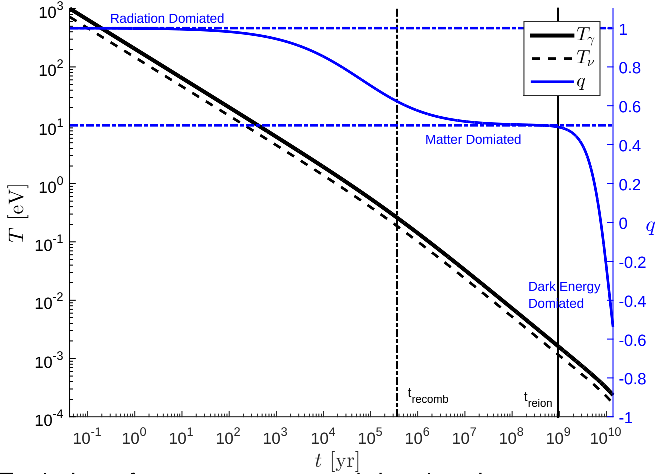


Figure: Evolution of temperature T and deceleration parameter q from soon after BBN to the present day

In Conclusion

- We connected the hot melted quark Universe, to the boiling hadron Universe, on to lepton Universe, and the ensuing matter emergence, and dark energy emergence.
- Limits on effects due to modifications of natural constants and any new radiance from the deconfined Universe were set.
- CMB fluctuations (PLANCK, WMAP data) have been for the first time connected to the QGP work in the laboratory.

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