# QGP in the Universe and in the Laboratory

Results obtained in collaboration with

Jeremiah Birrell, Michael Fromerth, Inga Kuznetsowa, Michal Petran

Former Students at The University of Arizona

# What is special with Quark Gluon Plasma?

1. RECREATE THE EARLY UNIVERSE IN LABORATORY:
   The topic of this talk
2. PROBING OVER A LARGE DISTANCE THE CONFINING VACUUM STRUCTURE
3. STUDY OF THE ORIGIN OF MASS OF MATTER
4. OPPORTUNITY TO PROBE ORIGIN OF FLAVOR?
   Normal matter made of first flavor family $(u, d, e, [\nu_e])$.
   Strangeness-rich quark-gluon plasma the sole laboratory environment filled with 2nd family matter $(s, c)$.

## 50 years ago 1964/65: Beginning of a new scientific epoch

- Quarks, Higgs $\rightarrow$ Standard Model of Particle Physics
- CMB discovered
- Hagedorn Temperature, Statistical Bootstrap
  $\rightarrow$ QGP: A new elementary state of matter
- Superheavy elements and critical external fields:
  $\rightarrow$ local changes of the vacuum Another day

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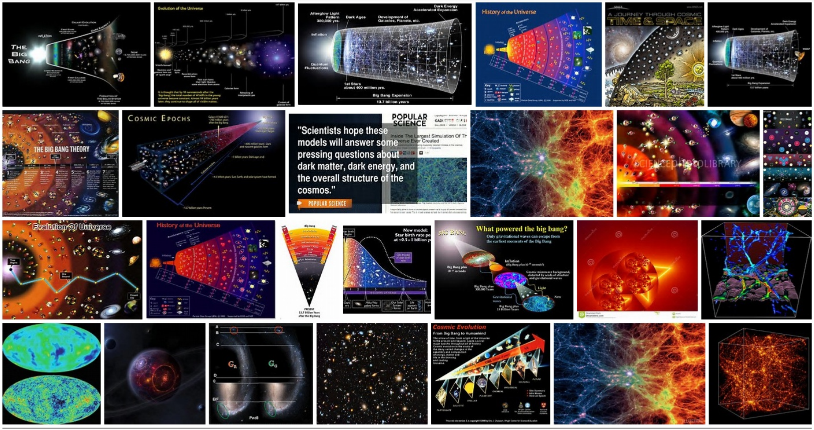
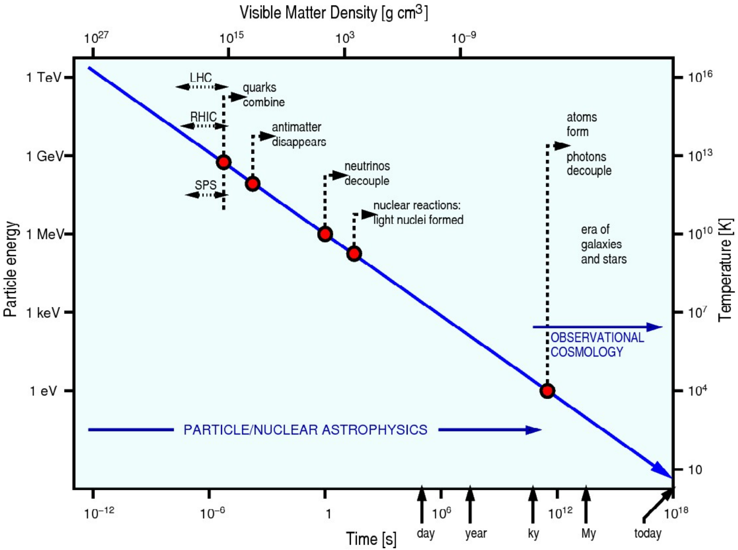
**Topics today:**

1. Introduction to QGP in Universe and Laboratory
2. Discovery of QGP
3. Quark-gluon plasma in the Universe
4. Particles in the evolving Universe
5. New Ideas? Darkness

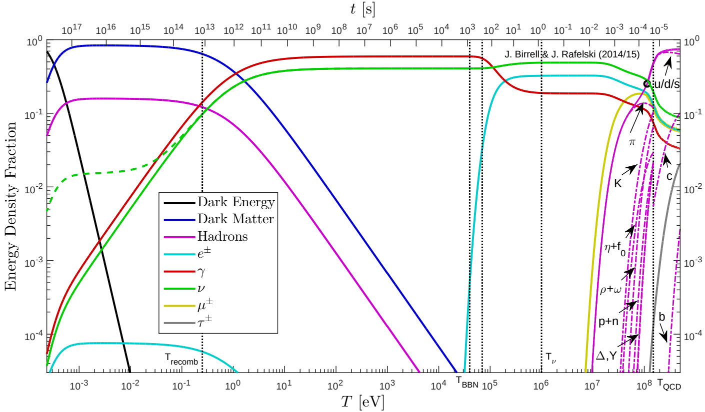
# The Universe 2015



# Experiments Probe the Universe



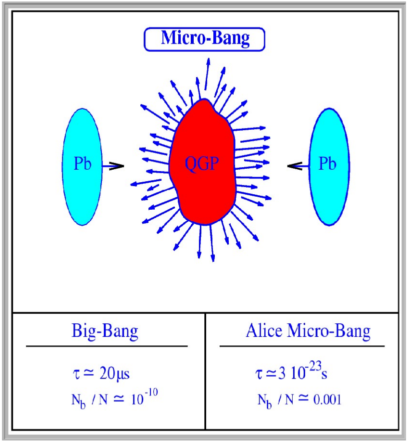
# The Universe Composition Changes




dark energy matter radiation $\nu, \gamma$ leptons hadrons

$\Longrightarrow$ Different dominance eras

# Connection to Relativistic Heavy Ion Collisions




- 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

# Boiling quarks

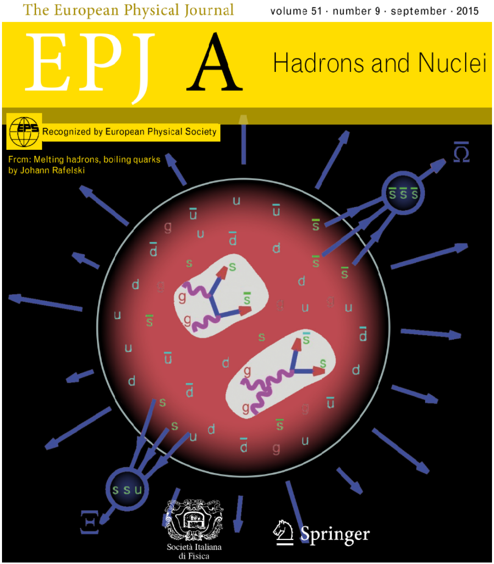
THE ROOTS:

- Cold quark matter in diverse formats from day 1: 1965 $\longrightarrow$
- Hot interacting QCD quark-gluon plasma: 1979 $\longrightarrow$
- Formation of QGP in relativistic nuclear (heavy ion collisions) 1979 $\longrightarrow$
- Experimental signatures: Strange antibaryons 1980 $\longrightarrow$
- Materialization of QGP: 1982 $\longrightarrow$
  Statistical Hadronization Model (SHM)

Key student and collaborator: Peter Koch

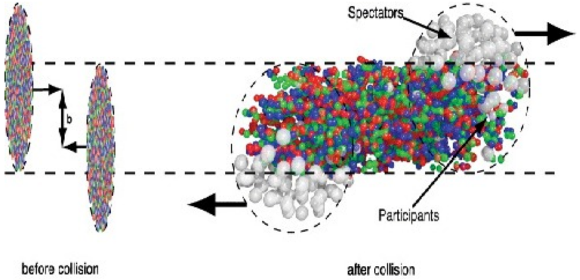
# Cooking strange quarks $\rightarrow$ strange antibaryons

APS sticker from period

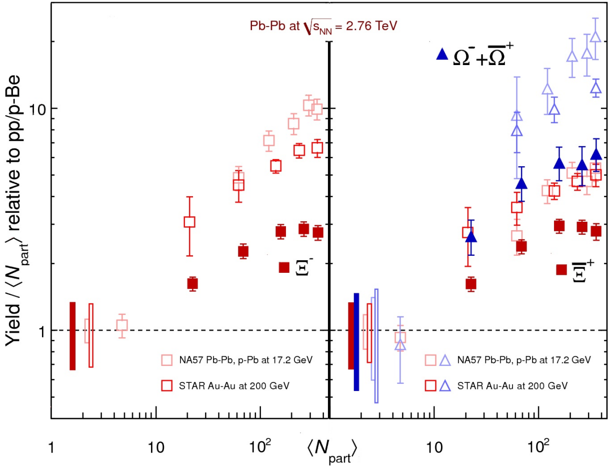
# PARTICLE YIELDS: INTEGRATED SPECTRA

Particle yields allow exploration of the source bulk properties in the co-moving frame – collective matter flow dynamics integrated out. This avoids the dynamical mess:




Our interest in the bulk thermal properties of the source evaluated independent from complex transverse dynamics is the reason to analyze integrated spectra.

# Prediction: 1980-86 confirmed by experimental results

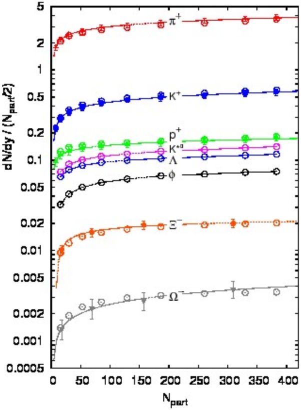


# Statistical Hadronization Model Interpretation (SHM)

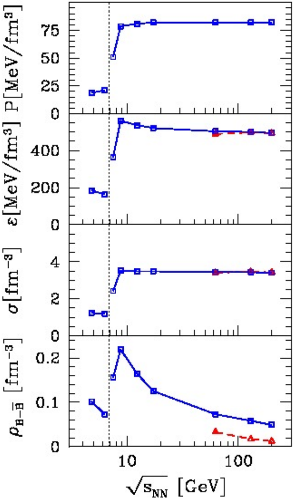
equal hadron production strength

yield depending on available phase space

**Example data from LHC⇓**



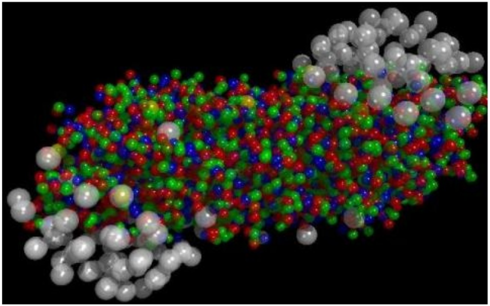

**Bulk properties⇓**



# CERN press office

## New State of Matter created at CERN

10 Feb 2000



At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

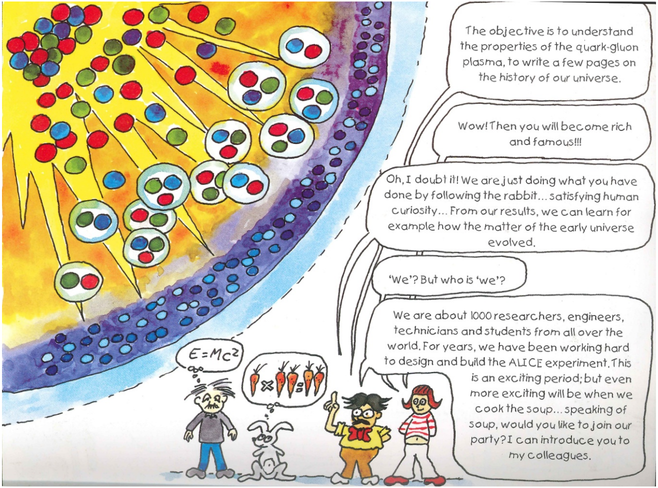
**Preeminent signature: Strange antibaryon enhancement**

press.web.cern.ch/press-releases/2000/02/new-state-matter-created-cern

# 9AM, 18 April 2005; US – RHIC announces QGP Press conference APS Spring Meeting


**Preeminent property: non-viscous flow**

# LHC-Alice: Exploration of QGP



# Universe: QGP and Hadrons in full Equilibrium

The key doorway reaction too 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 $\pi^0$ 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 $\pi^0$ remains always in chemical equilibrium All charged leptons always in chemical equilibrium – with photons

Neutrinos freeze-out (like photons later) at $T = \mathcal{O}$MeV

# Particle Content and Chemical Potentials

Chemical potentials control particle/antiparticle abundances:

$$f_{p/a} = \frac{1}{e^{\beta(\varepsilon \mp \mu)} \pm 1}, \qquad \varepsilon = \sqrt{p^2 + m^2}$$

• Quark side: $d \leftrightarrow s \leftrightarrow b_{\text{ottom}}$ oscillation means $\mu_d = \mu_s = \mu_{\text{bottom}}$ and similarly $\mu_{\nu_e} = \mu_{\nu_\mu} = \mu_{\nu_\tau}$. WI reaction e.g. $d \to u + e^- + \bar{\nu}_e$ imply $\mu_d - \mu_u = \Delta\mu_l$ with

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

• Hadron side: Quark chemical potentials control valence quarks and can be used in the hadron phase, e.g. $\Sigma^0$ (*uds*) has chemical potential $\mu_{\Sigma^0} = \mu_u + \mu_d + \mu_s$. The baryochemical potential $\mu_B$ is:

$$\mu_B = \frac{1}{2}(\mu_p + \mu_n) = \frac{3}{2}(\mu_d + \mu_u) = 3\mu_d - \frac{3}{2}\Delta\mu_l$$

# Three Constraints

The chemistry of particle reaction and equilibration in the Universe has three chemical potentials 'free' i.e. not only baryochemical potential $\mu_B$. We need three physics constraints Michael J. Fromerth , JR e-Print: astro-ph/0211346:

i. Charge neutrality eliminates Coulomb energy

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

$Q_i$ and $n_i$ charge and number density of species $i$.

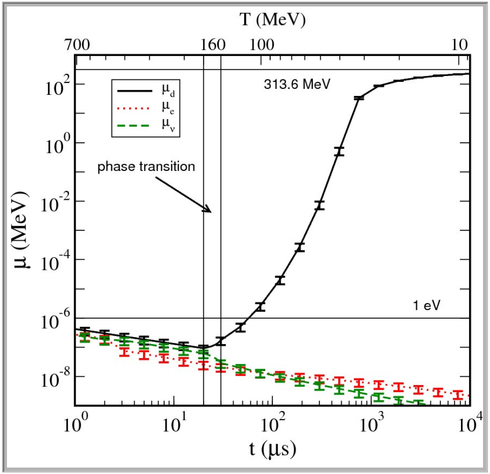
ii. Net lepton number equals net baryon number However, possible neutrino-antineutrino asymmetry can hide an imbalance

iii. Prescribed value of entropy-per-baryon

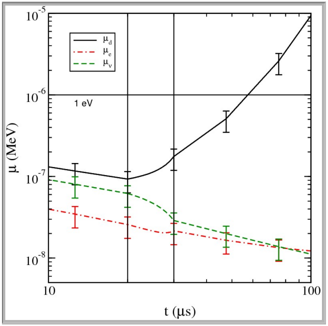
$$\frac{\sigma}{n_B} \equiv \frac{\sum_i \sigma_i(\mu_i, T)}{\sum_i B_i \, n_i(\mu_i, T)} = 3.2 \ldots 4.5 \times 10^{10}$$

Today best est. $S/B = 3.5 \times 10^{10}$, results shown for $4.5 \times 10^{10}$

# Chemical Potential in the Universe

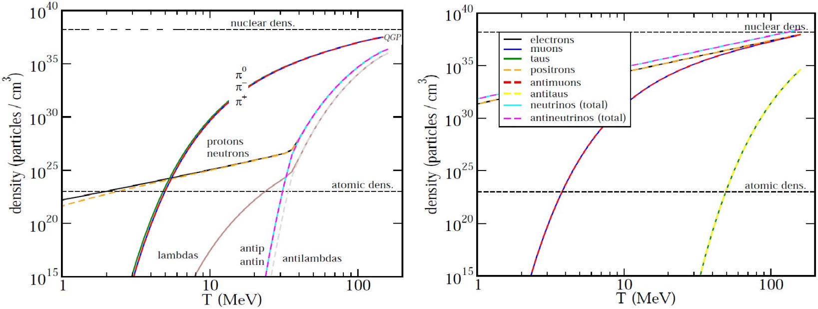



Minimum:
$\mu_B = 0.33^{+0.11}_{-0.08}$eV




$\Longrightarrow$ $\mu_B$ defines remainder of matter after annihilation

# Particle Composition after QGP Hadronization




$\Longrightarrow$ Antimatter annihilates to below matter abundance before $T = 30$ MeV, universe dominated by photons, neutrinos, leptons for $T < 30$ MeV Next: distribution normalized to unity

## Particles in the Universe=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 varying functions valued between $0$ and $1$ that turn off the various species as the temperature drops below their mass.

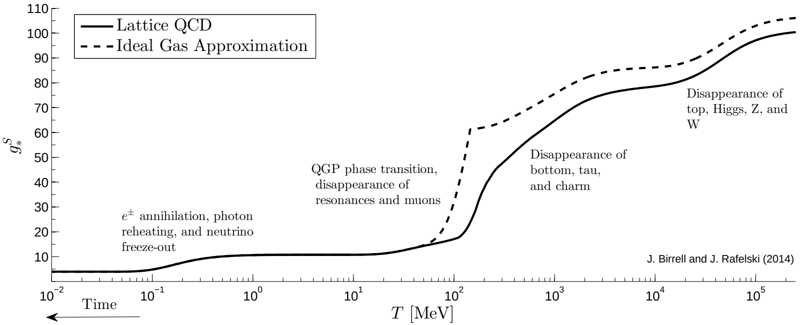
Speed of Universe expansion controlled by degrees of freedom thus $g$ is an observable

# Distinct Composition Eras

Composition of the Universe changes as function of $T$:

- From Higgs freezing to freezing of QGP
- QGP hadronization
- Antimatter annihilation
- Last leptons disappear just when
- Onset of neutrino free-streaming and begin of
- Big-Bang nucleosynthesis within a remnant lepton plasma
- Emergence of free streaming dark matter
- Photon Free-streaming – Composition Cross-Point
- Dark Energy Emerges – vacuum energy

# Count of Degrees of Freedom




Distinct Composition Eras visible. In PDG ideal gas approximation (dashed) is not valid in QGP domain, 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

# Reheating History

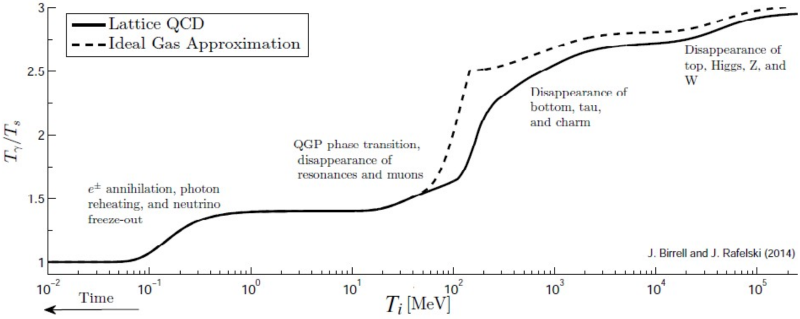



Figure: The reheating ratio reflects the disappearance of degrees of freedom from the Universe as function of $T_i$. These results are for adiabatic evolution of the Universe. Primordial dark matter colder by factor 3. Particles decouple at QGP hadronization colder by factor 2.

## Connecting time to temperature

### Friedmann–Lemaitre–Robertson–Walker (FRW) cosmology

- Einstein Universe:

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

  where $T^{\mu}_{\nu} = \mathrm{diag}(\rho, -P, -P, -P)$, $R = g_{\mu\nu}R^{\mu\nu}$, and

- • Homogeneous and • Isotropic metric

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

  $a(t)$ determines the distance between objects comoving in the Universe frame. Skipping $g^{\mu\nu} \to R^{\mu\nu}$
  Flat ($k = 0$) metric favored in the $\Lambda$CDM analysis, see e.g. Planck Collaboration, Astron. Astrophys. **571**, A16 (2014) [arXiv:1303.5076] and arXiv:1502.01589 [astro-ph.CO]].

We absorb the vacuum energy (Einstein $\Lambda$-term) into the energy $\rho$ 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; this is $\Lambda$CDM model.

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

The pressure $P_\Lambda$ has a) opposite sign from all matter contributions and b) $\rho_\Lambda/P_\Lambda = -1$. The independent measurement of $\rho$ and $P$ or, equivalently, expansion speed (next slide) allows to disentangle matter from dark energy

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:

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

In flat $k = 0$ Universe: $\rho$ 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.

# The contents of the Universe today and yesterday:

1. Photons and all matter coupled to photons:
   thermal matter = ideal Bose-Fermi gases
2. Free-streaming matter (particles that have ‘frozen’ out):
   - dark matter:from before QGP hadronization
   - darkness: at QGP hadronization
   - neutrinos: since $T =$ a few MeV
   - photons: since $T = 0.25$eV
3. Dark energy = vacuum energy

darkness: quasi-massless particles, like neutrinos but due to earlier decoupling small impact on Universe dynamics; includes recent speculations on dark photons for dark matter

Free-streaming matter contributions: 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 $m \to mT(t)/T_k$ *only* in the exponential. Only for massless photons free-streaming = thermal distributions (absence of mass-energy scale).

*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 exact expression in terms of energy, pressure content

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

- Radiation dominated universe: $P = \rho/3 \implies q = 1$.
- Matter dominated universe: $P \ll \rho \implies q = 1/2$.
- Dark energy ($\Lambda$) dominated universe: $P = -\rho \implies q = -1$.
  Accelerating Universe TODAY(!):
  This implies that our Universe has a finite energy density, just like bag constant but $10^{43}$ smaller: $\mathcal{B}_U = 25.6\text{meV}^4$

# Do we live in false vacuum?

- "We conclude that there are no credible mechanisms for catastrophic scenarios (with heavy ion collisions at RHIC)" Jaffe, R.L., Busza, W., Sandweiss, J., and Wilczek, F, 2000, Rev. Mod. Phys. 72, 1125-1140
- Yet we probably do live in false vacuum

PREPARED FOR SUBMISSION TO JCAP

## Dynamical Emergence of the Universe into the False Vacuum

arXiv:1510.05001v2 [astro-ph.CO] 19 Nov 2015

**Johann Rafelski and Jeremiah Birrell**

Department of Physics, University of Arizona, Tucson, Arizona, 85721, USA

**Abstract.** We study how the hot Universe evolves and acquires the prevailing vacuum state, demonstrating that in specific conditions which are believed to apply, the Universe becomes frozen into the state with the smallest value of Higgs vacuum field $v = \langle h \rangle$, even if this is not the state of lowest energy. This supports the false vacuum dark energy $\Lambda$-model. Under several likely hypotheses we determine the temperature in the evolution of the Universe at which two vacua $v_1, v_2$ can swap between being true and false. We evaluate the dynamical surface pressure on domain walls between low and high mass vacua due to the presence of matter and show that the low mass state remains the preferred vacuum of the Universe.

### 1 Introduction

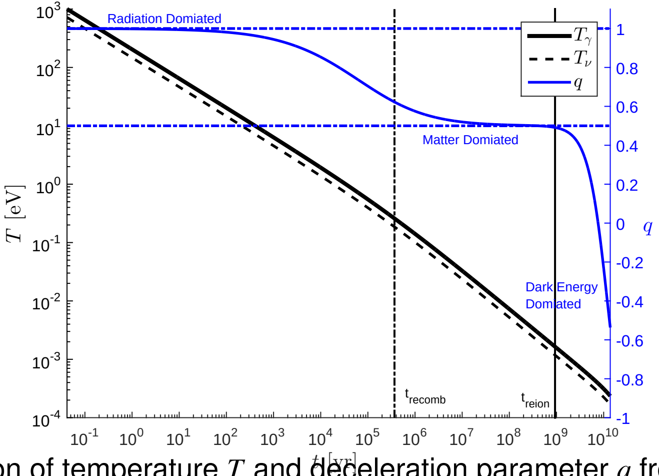
This work presents relatively simple arguments for why the cosmological evolution selects the vacuum with smallest Higgs VEV $v = \langle h \rangle$ which, in general, could be and likely is the 'false' vacuum. Our argument relies on the Standard Model (SM) *minimal coupling:* $m \to gh$, or similar generalizations in 'beyond' SM (BSM), so that the vacuum with the smallest Higgs VEV also has the smallest particle masses. In anticipation of the model with multiple vacua, we call the vacuum state with lowest free energy at temperature $T$ 'the true vacuum' and all others 'the false vacua'. Note that this is a temperature dependent statement: we live today in the false vacuum which as we will show was once the true vacuum.

In the presence of pairs of particles and antiparticles at high temperature the vacuum state with smallest $v$ is energetically preferred, even if it has a large vacuum energy. This is so because smaller $v$ implies smaller particle masses and hence less energy, and free energy, in the particle distributions. By the time the Universe cools sufficiently for the larger vacuum energy to dominate the smaller particle free energies, the probability of swap to the large mass true vacuum is vanishingly small in general.

Therefore, the Higgs minimum with the lowest value of the Higgs field $v$, and thus *not necessarily* the lowest value of the effective potential $W(v) = \langle V(h) \rangle$, emerges as the prevalent vacuum in our Universe. The difference, $\rho_\Lambda = \Delta W$, between the prevalent vacuum state today and the true minimum is a natural candidate to explain the observed dark energy density,

$$\rho_\Lambda = 25.6\ \mathrm{meV}^4. \tag{1.1}$$

# Today and recent evolution




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

# Long ago: 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 used
- 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
- Pressure between QGP/Hadrons is discontinuous at up to $10\%$ level. Causes hard to notice discontinuity in $q$ (slopes match). Need more detailed hadron and quark-quark interactions input

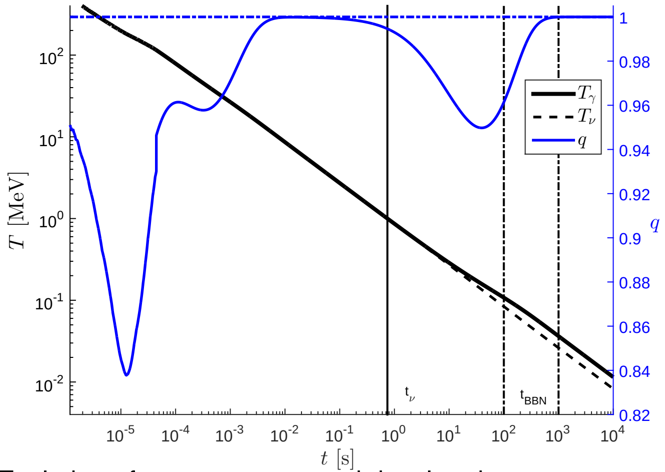



Figure: Evolution of temperature $T$ and deceleration parameter $q$ from QGP era until near BBN.

# Are there additional dark degrees of freedom

Darkness Candidates

a) ‘True’ Goldstone bosons related to symmetry breaking in reorganization of QCD vacuum structure. My favorite candidate, theoretical details need work.

b) Super-WI neutrino partners. Connection to deconfinement not straightforward.

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Massive $m > \mathcal{O}$(eV) sterile $\nu$ not within ‘Darkness’ context. Mass must emerge after CMB decouples, $m < 0.25$ eV. Allowing higher ‘sterile mass’ requires full reevaluation of many steps in the analysis including key elements we do not control (PLANCK CMB fluctuations).

## How understanding the Universe enters laboratory experiments: Example

ELSEVIER

Physics Letters B

Volume 741, 4 February 2015, Pages 77–81

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

Jeremiah Birrell, Johann Rafelski

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doi:10.1016/j.physletb.2014.12.033

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Abstract

The effective number of neutrinos, $N_{\mathrm{eff}}$, 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 $N_{\mathrm{eff}}$ 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

# Activation of QCD Scale Interactions

QGP activation: Missing Energy in RHI Collisions

- Breakup: Counting degrees of freedom and presuming Darkness equilibration before hadronization, approximately $12 \pm 8\%$ of all entropy content of the QGP is in Darkness.
- Continuous emission: Darkness stops interacting at the QGP surface – escapes freely during the entire lifespan of the QGP. This Dark-radiation loss proportionally largest for long-lived QGP $\rightarrow$ Does energy in/out balance in large $AA$ collision systems beyond threshold of QGP formation?
- Experiment: A systematic exploration of the energy balance as function of $\sqrt{s}$ and $A$ at energies near to QGP formation threshold: = NA61 experiment..

# Summary

- 50 years ago particle production in $pp$ reactions prompted introduction of Hagedorn Temperature $T_{\rm H}$; soon after recognized as the critical temperature at which matter surrounding us dissolves into its different fundamental phase of quarks and gluons – QGP.
- Laboratory work confirms QGP and leads the way to an understanding of the properties of the Universe below the age of $18\mu$s.
- A first possible link between observational cosmology and hadronization stage of the Quark Universe: Released Darkness could be a new component pushing the Universe apart.
- Laboratory effort: a search for missing energy in connection to dynamics of hadronization near to phase boundary as function of $\sqrt{s}$ with energy imbalance increasing with $A$.

## In Conclusion – and outlook

- 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.
- We studied/set limits on effects due to modifications of natural constants, and on any new radiance from the deconfined Universe
- CMB fluctuations (PLANCK, WMAP data) have been connected to the QGP work in the laboratory.