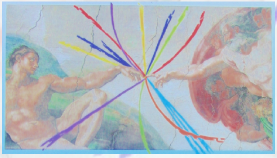
The next round of RHI collision discoveries awaits you

The forthcoming AA collisions at the LHC promise to advance our understanding of Flavor, Strong Fields, Confinement, and Hadron Mass. For flavor we recognize QGP at LHC as the only physics system that has in one space-time spot all quark types present. I will look at observables suitable to explore dynamical differences among the heavy c, b, t quarks in the deconfined domain filled with u, d, s thermal plasma. I will explain how a near-missed peripheral collision creates EM fields that rip the vacuum and offer a path to seek the origin of vacuum meta stability that the SM parameters predict. In the already explored Confinement and Hadron mass domains we will seek quantitative understanding of vacuum condensates, and the mass spectrum, learning how to adapt the lattice results to the highly dynamical AA collision environment.



Jan Rafelski, Wroclaw, January 6, 2018

Happy, Healthy and Prosperous New Year 2018!

And a special happy '60th to my friend Wojtek Broniowski

dedicating my first picture of 2018

Souvenir: working with students on SHARE in Tucson January 14, 2004

1964/65 discovery of [50+ years ago]:

- Quarks, Higgs → Standard Model of Particle Physics
- Hagedorn Temperature & Statistical Bootstrap Model
- Cosming Microwave Radiation → Big-Bang Cosmology

15 years later [soon 40 years ago]

These new ideas merged into new framework of Quark-gluon plasma, a new state of matter that preceded the matter in history of the Universe and can be recreated in relativistic heavy ion collisions.

Topics today:

1. QGP discovery
2. My interests such as strangeness
3. A few words on creating Matter = Hadronization
4. Grand Challenges: e.g. flavor, Æther and the quantum vacuum, Strong-Field Physics = Acceleration Frontier

What is special with RHI collisons & Quark Gluon Plasma?

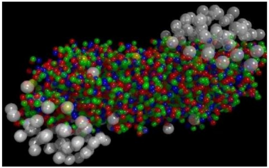
1. RECREATE THE EARLY UNIVERSE IN LABORATORY
   Recreate and understand the high energy density conditions prevailing in the Universe when matter formed from elementary degrees of freedom (quarks, gluons) at about 20 μs after the Big-Bang.
2. PROBING OVER A 'LARGE' DISTANCE THE (DE)CONFINING QUANTUM VACUUM STRUCTURE
   The quantum vacuum, the present day relativisitic æther, determines prevailing form of matter and laws of nature.
3. STUDY OF THE ORIGIN OF MATTER & OF MASS
   Matter and antimatter created when QGP 'hadronizes'. Mass of matter originates in the confining vacuum structure
4. PROBE ORIGIN OF FLAVOR
   Normal matter made of first flavor family $(d, u, e, [\nu_e])$. Strangeness-rich quark-gluon plasma the sole laboratory environment filled 'to the rim' with 2nd family matter $(s, c, [\mu, \nu_\mu]))$. and considerable abundance of b and even t.
5. PROBE STRONGEST FORCES IN THE UNIVERSE
   For a short time the relativistic approach and seperation of large charges $Ze \leftrightarrow Ze$ generates EM fields 1000's time stronger than those in Magnetars; strongfields=strong force=strong acceleration =acceleration frontier

CERN-Feb 2000 and BNL-April 2005 announce QGP

CERN press office

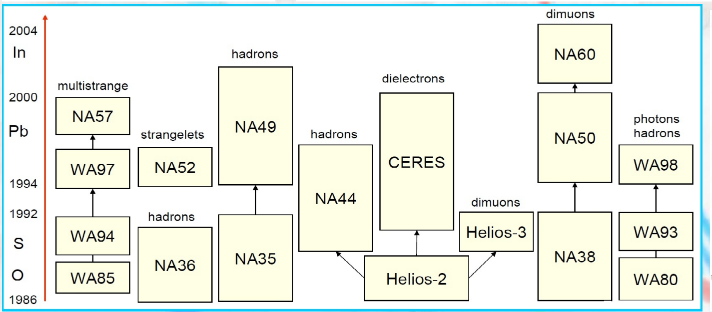
New State of Matter created at CERN

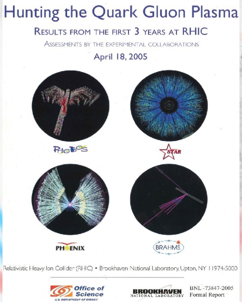
10 Feb 2000



At the April 2005 meeting of the American Physical Society, held in Tampa, Florida a press conference took place on Monday, April 18, 9:00 local time. The public announcement of this event was made April 4, 2005:

EVIDENCE FOR A NEW TYPE OF NUCLEAR MATTER At the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab (BNL), two beams of gold atoms are smashed together, the goal being to recreate the conditions thought to have prevailed in the universe only a few microseconds after the big bang, so that novel forms of nuclear matter can be studied. At this press conference, RHIC scientists will sum up all they have learned from several years of observing the worlds most energetic collisions of atomic nuclei. The four experimental groups operating at RHIC will present a consolidated, surprising, exciting new interpretation of their data. Speakers will include: Dennis Kovar, Associate Director, Office of Nuclear Physics, U.S. Department of Energy's Office of Science; Sam Aronson, Associate Laboratory Director for High Energy and Nuclear Physics, Brookhaven National Laboratory. Also on hand to discuss RHIC results and implications will be: Praveen Chaudhari, Director, Brookhaven National Laboratory; representatives of the four experimental collaborations at the Relativistic Heavy Ion Collider; and several theoretical physicists.





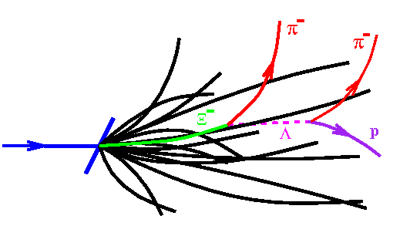
A: There are many strange particles allowing to study different physics questions $(q = u, d)$:

$$K(q\bar{s}), \quad \overline{K}(\bar{q}s), \quad K^*(890), \quad \Lambda(qqs), \quad \overline{\Lambda}(\bar{q}\bar{q}\bar{s}), \quad \Lambda(1520)$$

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

B: Production rates hence statistical significance is high

C: Strange hadrons are subject to a self analyzing decay within a few cm from the point of production (more detail in⇓ the (2000) book)



Hadrons and Quark–Gluon Plasma

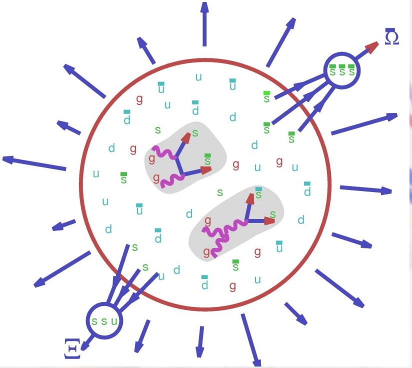
Series: Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology (No. 18)

Jean Letessier
Université de Paris VII (Denis Diderot)

Johann Rafelski
University of Arizona

Hardback (ISBN-13: 9780521385367 | ISBN-10: 0521385369) Also available in Paperback | Adobe eBook

Theory: two-step strange hadron formation



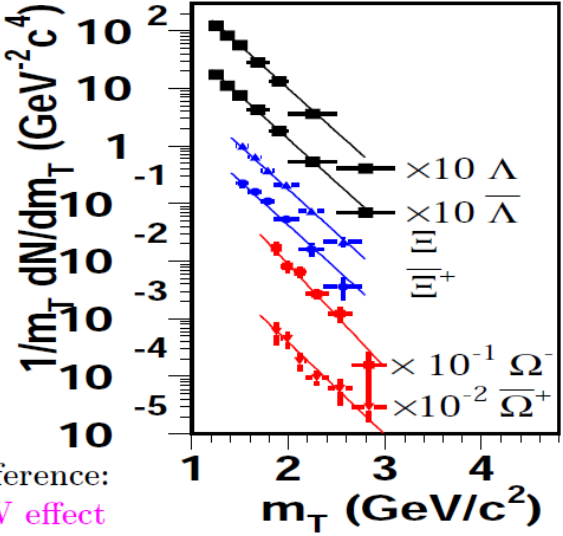
1. $GG \to s\bar{s}$ (<u>thermal</u> gluons collide)
   $GG \to c\bar{c}$ (<u>initial</u> parton collision)
   gluon dominated reactions
2. hadronization of pre-formed
   $s, \bar{s}, c, \bar{c}, b, \bar{b}$ quarks

Evaporation-recombination formation of complex rarely produced (multi)exotic flavor (anti)particles from QGP is signature of quark mobility thus of deconfinement. Enhancement of flavored (strange, charm,. . .) antibaryons progressing with 'exotic' flavor content. J. Rafelski, *Formation and Observables of the Quark-Gluon Plasma* Phys.Rept. **88** (1982) p331; P. Koch, B. Muller, and J. Rafelski; *Strangeness in Relativistic Heavy Ion Collisions*, Phys.Rept. **142** (1986) p167

Predicted: matter-antimatter symmetry: Sudden hadronization of QGP

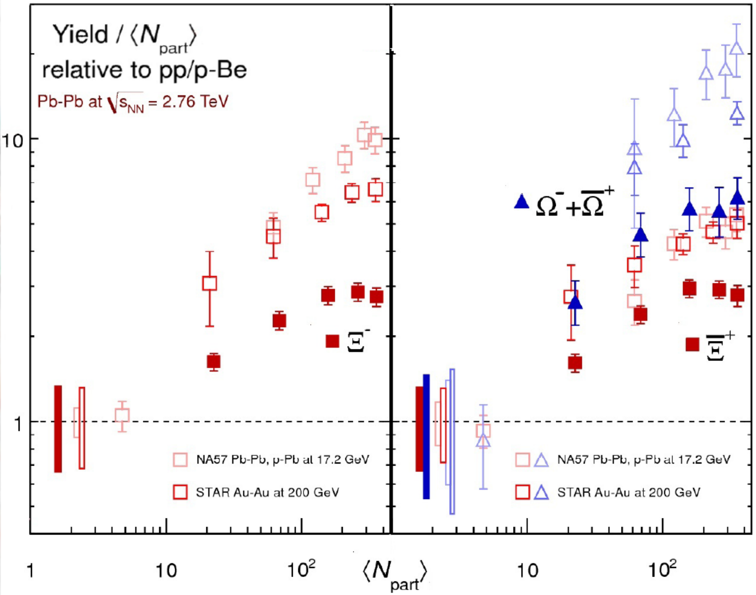
WA97	$T_\perp^{\rm Pb}$ [MeV]
T^{K^0}	230 ± 2
T^{Λ}	289 ± 3
$T^{\overline{\Lambda}}$	287 ± 4
T^{Ξ}	286 ± 9
$T^{\overline{\Xi}}$	284 ± 17
$T^{\Omega+\overline{\Omega}}$	251 ± 19

Λ within 1% of $\overline{\Lambda}$

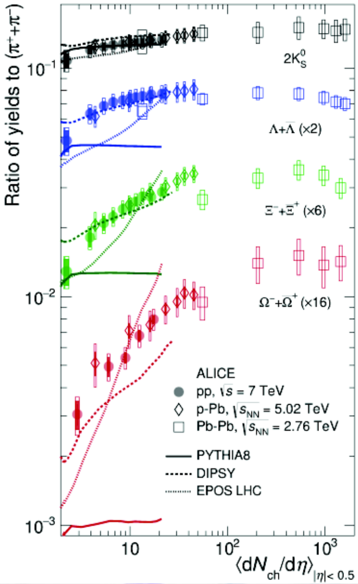


Kaon – hyperon difference:
EXPLOSIVE FLOW effect

Predicted: Strange antibaryons enhanced=largest medium effect



Since: Enhancement smoothly rising with entropy of fireball



Nature Physics 2017; doi:10.1038/nphys4111 ALICE

Significant enhancement of strangeness with multiplicity in high multiplicity pp events

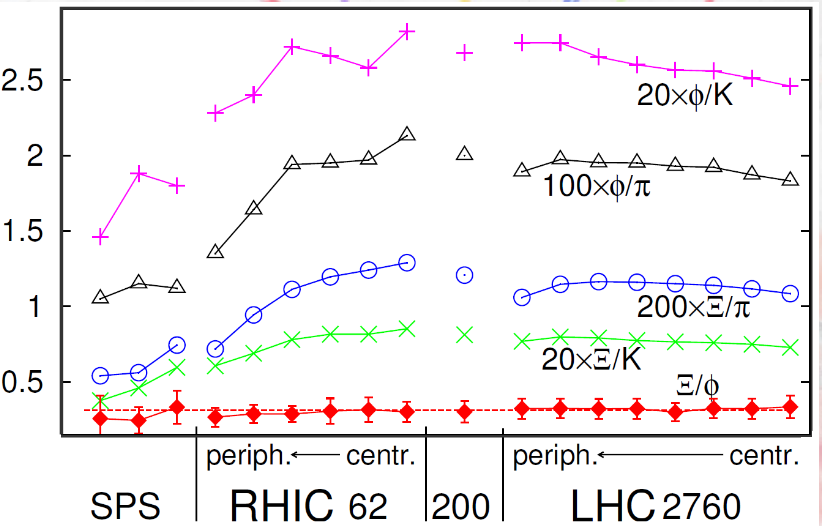
pp behavior resamble p-Pb : both in term of value of the ratio and shape

No evident dependence on cms energy: strangeness production apparently driven by final state rather than collision system or energy

At high mult. pp ratio reaches values similar to the one in Pb-Pb (when ratio saturates)

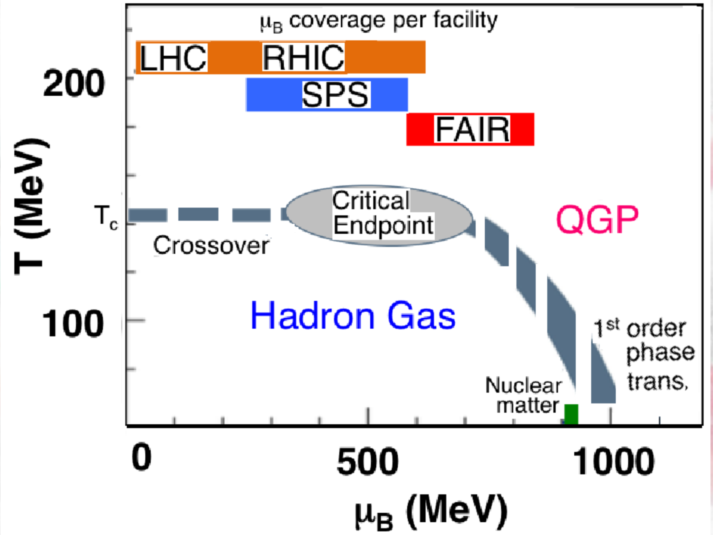
Models fail to riproduce data. Only DIPSY gives a qualitative description.

Several non-QGP models excluded by $\Xi(ssq)/\phi(s\bar{s})$ constant!



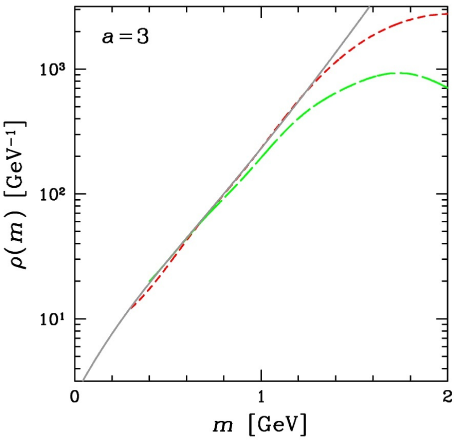
M. Petran, J. Rafelski, *Multistrange Particle Production and the Statistical Hadronization Model* Phys.Rev. C **82** (2010) 011901

Current interest I: Explore QGP phase diagram



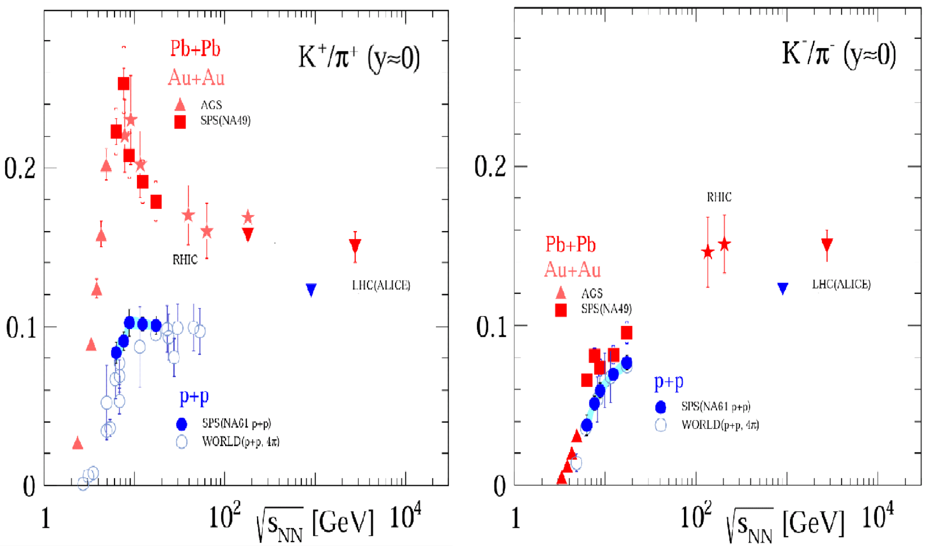
See e.g. Hagedorn Model of Critical Behavior: Comparison of Lattice and SBM Calculations **Ludwik Turko** Hagedorn Blue book pp 81-86 and arXiv:1502.03647

Current interest II: Explore Hagedorn exponential hadron mass spectrum



Slope for prescribed pre-exponential shape is the Hagedorn Temperature: this is a way to determine critical properties of deconfinement phase change. See e.g. The Legacy of Rolf Hagedorn: Statistical Bootstrap and Ultimate Temperature **Krzysztof Redlich**, and Helmut Satz Hagedorn Blue book pp 49-68 and arXiv:1501.07523

Current interest III: Strangeness excitation: All accessible energies SPS, RHIC, LHC



Wroclaw Context: Quark core $\Leftrightarrow$ mass of neutron stars

Nuclear Theory arXiv.org > nucl-th > arXiv:1503.04832

Quark matter in high-mass neutron stars?

R. Lastowiecki, D. Blaschke, T. Fischer, T. Klahn *(Submitted on 16 Mar 2015)*

The recent measurements of the masses of the pulsars PSR J1614-2230 and PSR J0348-0432 provide independent proof for the existence of neutron stars with masses in range of 2 $M_\odot$. This fact has significant implications for the physics of high density matter and it challenges the hypothesis that the cores of NS can be composed of deconfined quark matter. In this contribution we study a description of quark matter based on the Nambu--Jona-Lasinio effective model and construct the equation of state for matter in beta equilibrium. This equation of state together with the hadronic Dirac-Brueckner-Hartree-Fock equation of state is used here to describe neutron star and hybrid star configurations. We show that compact stars masses of 2 $M_\odot$ are compatible with the possible existence of deconfined quark matter in their core.

Comments: 6 pages, 2 figures

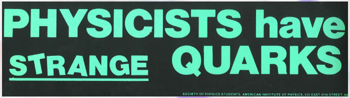
Subjects: **Nuclear Theory (nucl-th)**; High Energy Astrophysical Phenomena (astro-ph.HE); High Energy Physics - Phenomenology (hep-ph)

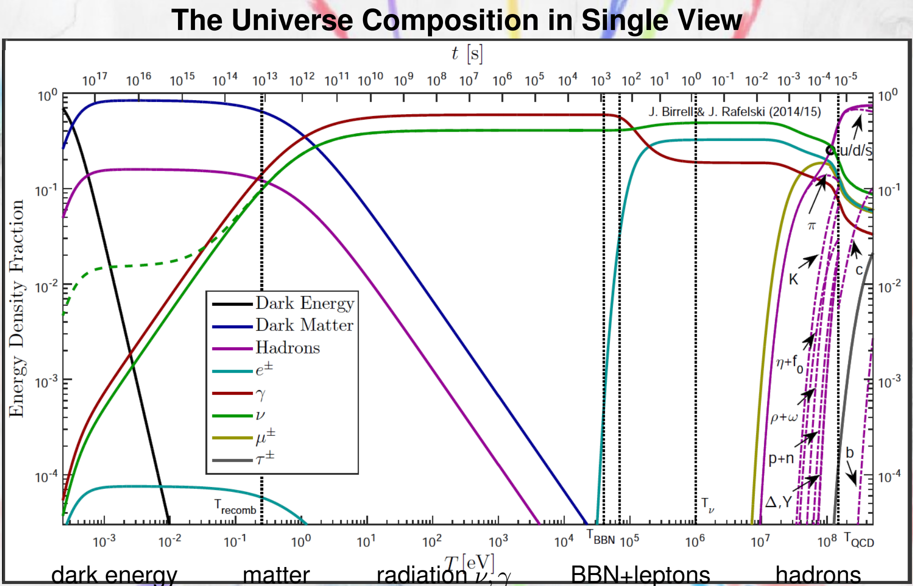
Journal reference: Phys. Part. Nucl. 46 (2015) 843-845

DOI: 10.1134/S1063779615050159

Cite as: **arXiv:1503.04832 [nucl-th]**

My current interest I:
Cooking heavy quarks → heavy antibaryons & exotic heavy flavored hadron

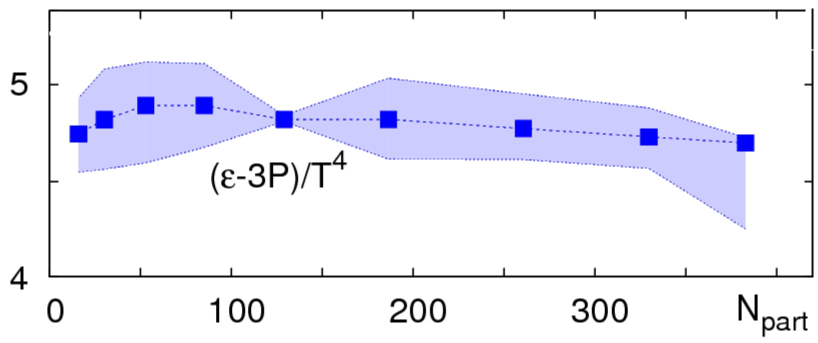




Different dominance eras: Temperature grows to right

Statistical Hadronization (flavor) riddles info on SHM follows

- Phase space alone describes particle production. Quark-hadron strong interaction practically invisible.
- Why do the massive c, b(?) seen in hadrons flow along?
- Can weekly bound light nuclei be produced at $T = 150$ MeV?→ Krzysztof
- Why universal hadronization condition tracks trace anomaly?



STATISTICAL HADRONIZATION MODEL (SHM)

Very strong interactions: equal hadron production strength irrespective of produced hadron type particle yields depending only on the available phase space

- Fermi: Micro-canonical phase space
  sharp energy and sharp number of particles
  E. Fermi, Prog.Theor.Phys. 5 (1950) 570: HOWEVER
  Experiments report event-average rapidity particle abundances, model should describe an average event
- Canonical phase space: sharp number of particles
  ensemble average energy $E \to T$ temperature
  T could be, but needs not to be, a kinetic process temperature
- Grand-canonical – ensemble average energy and number of particles:
  $N \to \mu \Leftrightarrow \Upsilon = e^{(\mu/T)}$

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

Thermal equilibrium particle yields

TO DESCRIBE PRODUCED HADRON YIELDS

- Average per collision yield of hadron i is calculated from integral of the distribution over phase space

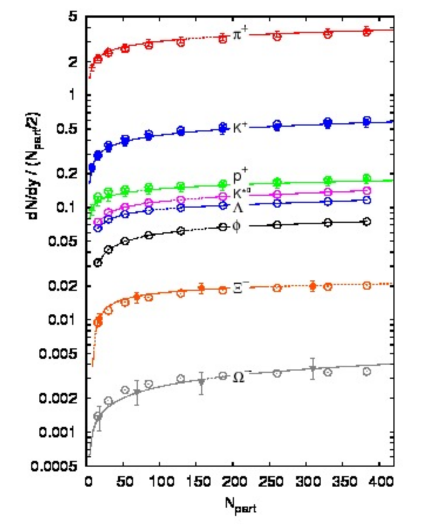
$$\langle N_i \rangle \rightarrow \frac{dN_i}{dy} = g_i \frac{dV}{dy} \int \frac{\mathrm{d}^3 p}{(2\pi)^3} n_i; \quad n_i(\varepsilon_i; T, \Upsilon_i) = \frac{1}{\Upsilon_i{}^{-1} e^{\varepsilon_i/T} \pm 1}$$

$$= \frac{g_i T^3}{2\pi^2} \frac{dV}{dy} \sum_{n=1}^{\infty} \frac{(\pm 1)^{n-1} (\Upsilon_i)^n}{n^3} \left(\frac{n m_i}{T}\right)^2 K_2\left(\frac{n m_i}{T}\right)$$

• Hadron mass	PDG Tables
• Degeneracy (spin), $g_i = (2J + 1)$	PDG Tables
• Overall normalization	outcome of SHM fit
• Hadronization temperature	outcome of SHM fit
• Fugacity Υ_i for each hadron	outcome of SHM fit

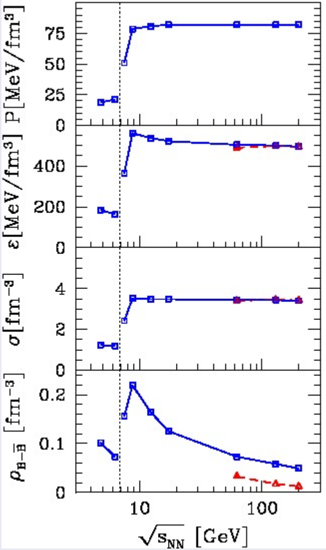
SHM Analysis (Chemical Nonequilibrium – SHARE)

Particle Yield Example:LHC



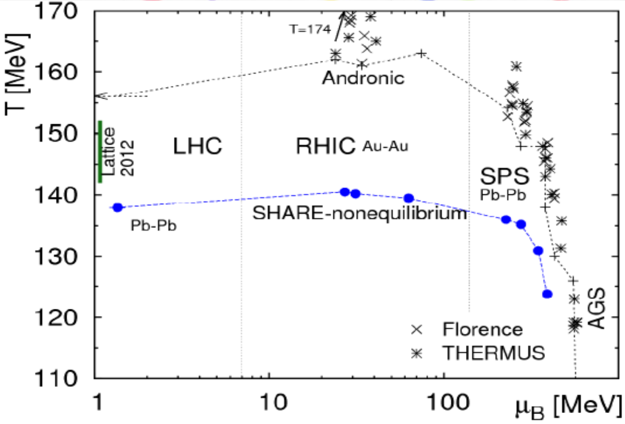
M. Petran, J.Letessier, V. Petracek, J. Rafelski Phys.Rev. C **88** (2013) no.3, 034907

Bulk poperties from SHM yields



J. Letessier, J. Rafelski, Eur.Phys.J. A **35** (2008) 221-242

SHARE consistent with lattice QCD



Chemical freeze-out MUST be below lattice results. For direct free-streaming hadron emission from QGP, T-SHM is the QGP source temperature, there cannot be full chemical equilibrium.

SPS, RHIC, LHC comparison

- SHARE based determination of hadronization condition reveals near perfect Universality of properties across the entire reaction energy domain and L-QCD consistency
- There are no discernible differences in strange antibaryon signature of QGP, at all energies where data exist there is clear evidence for the same new state of matter.
- At least up to $\sqrt{s_{\rm NN}} < 20$ GeV (where particle ID'd data in 4π exists), and probably at much higher energies as well, there is no sign of the McLerran-Bjorken transparency – we see a pileup of energy at central rapidity. Where we can evaluate: Baryon number deposition varies strongly as function of collision energy. WHY?

Grand Challenge I: Origin of 10^{-9} baryon asymmetry

- RHI to search for truly new physics: Are we sure that
  a) baryon number is conserved?
  b) energy balances out?
  'dark' radiation is compatible with Early Universe
- Why seeking 10^{-9} baryon asymmetry at EW phase transition $T_{\rm EW} = 1000 T_{\rm had}$? Everybody knows things do not add-up; this demands of our community to look at the hadronizing Universe.
- We have all that is needed in hadronization in early Universe at $T \simeq 150$ where (oscillating) neutrinos coupled to hadrons, heavy flavor c, b in abundance assuring sufficient matter over antimatter asymmetry, large nonequilibrium assured by need to annihilate 20% of total energy content put into antimatter.BUT we need baryon non-conserving processes!

Grand Challenge II: Darkness radiation

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

Show more

doi:10.1016/j.physletb.2014.12.033

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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

Grand Challenge III: The Æther

Relativistically Invariant Aether 1920: Albert Einstein at first rejected æther as unobservable when formulating special relativity, but eventually changed his initial position, re-introducing what is referred to as the 'relativistically invariant' æther. In a letter to H.A. Lorentz of November 15, 1919, see page 2 in *Einstein and the Æther*, L. Kostro, Apeiron, Montreal (2000). Einstein writes:
It would have been more correct if I had limited myself, in my earlier publications, to emphasizing only the non-existence of an æther velocity, instead of arguing the total non-existence of the æther, for I can see that with the word æther we say nothing else than that space has to be viewed as a carrier of physical qualities.

In a lecture published in Berlin by Julius Springer, in May 1920, presentation at Reichs-Universität zu Leiden, addressing H. Lorentz delayed till 27 October 1920 by visa problems, also in Einstein collected works:

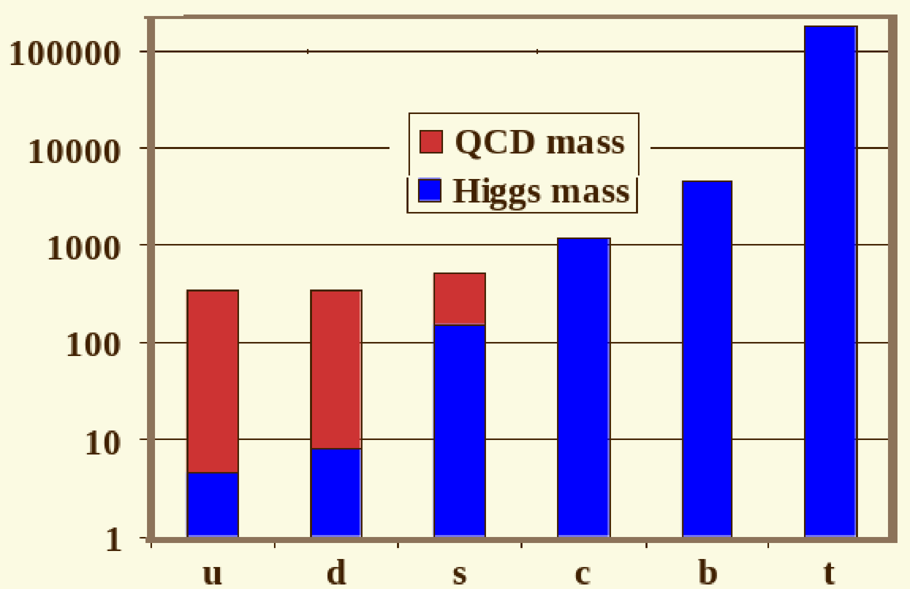
In conclusion:
...space is endowed with physical qualities; in this sense, therefore, there exists an æther. According to the general theory of relativity space without æther is unthinkable; for in such space there not only would be no propagation of light, but also no possibility of existence for standards of space and time (measuring-rods and clocks), nor therefore any space-time intervals in the physical sense. But this æther may not be thought of as endowed with the quality characteristic of ponderable media, as (NOT) consisting of parts which may be tracked through time. The idea of motion may not be applied to it.

From Æther to QGP – Quantum Vacuum

Development of quantum physics leads to the recognition that vacuum fluctuations define laws of physics (Weinberg's effective theory picture). All this is nonperturbative property of the vacuum.

- The 'quantum æther' is polarizable: Coulomb law is modified; E.A.Uehling, 1935
- New interactions (anomalies) such as light-light scattering arise considering the electron, positron vacuum zero-point energy; Euler, Kockel, Heisenberg (1930-36);
- Casimir notices that the photon vacuum zero point energy also induces a new force, referred today as Casimir force 1949
- Non-fundamental vacuum symmetry breaking particles possible: Goldstone Bosons '60-s
- 'Fundamental electro-weak theory is effective - model of EW interactions, 'current' masses as VEV Weinberg-Salam '70-s
- Color confinement and high-T deconfinement Quark-Gluon Plasma '80-s

Grand Challenge IV: Quark mass, Matter mass



Critical Acceleration

An electron in presence of the critical 'Schwinger' (Vacuum Instability) field strength of magnitude:

$$E_s = \frac{m_e^2 c^3}{e\hbar} = 1.323 \times 10^{18} V/m$$

is subject to critical natural unit =1 acceleration:

$$a_c = \frac{m_e c^3}{\hbar} \to 2.331 \times 10^{29} \mathrm{m/s}^2$$

Truly dimensionless unit acceleration arises when we introduce specific acceleration

$$\aleph = \frac{a_c}{mc^2} = \frac{c}{\hbar}$$

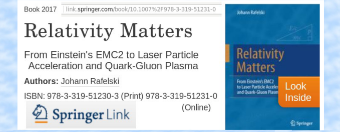
Specific unit acceleration arises in Newton gravity at Planck length distance: $\aleph_G \equiv G/L_p^2 = c/\hbar$ at $L_p = \sqrt{\hbar G/c}$.

In the presence of sufficiently strong electric field E_s by virtue of the equivalence principle, electrons are subject to Planck 'critical' force.

Summary: Fantastic progress in 100 years

- Particle accelerators barely started 100 years ago, particle production study begins in earnest 75 years ago; leading us to understand origin of mass of matter, the early Universe, the Æther = quantum vacuum.
- Much 'naive' and 'profound ' mystery remains: Why colliding hadrons make lots of entropy – what else is in quantum vacuum? What is baryon number and why matter is stable? Why three flavors? . . .

Big riddles will not be solved by trying the same thing with more, or different symmetry (current particle physics philosophy). In my view the new physics we are looking for is associated with 'FORCES' and the biggest hammer is a relativistic heavy ion, aside



of some laser stuff, see Text pdf available for free if your library subscribes to Springer Phy