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1 Research Program

In the past decade (2004-2015) we addressed the quest for the understanding of how quark confinement works, how it can be dissolved in a limited space-time domain, and what this means: i) for the paradigm of the laws of physics of present day; and, ii) for our understanding of cosmology.

The focus of our in laboratory matter formation work has been centered on the understanding of the less frequently produced hadronic particles (*e.g.* strange antibaryons, charmed and beauty hadrons, massive resonances, charmonium, B_c). We have developed a public analysis tool, SHARE (Statistical HAdronization with REsonances) which allows a precise model description of experimental particle yield and fluctuation data. We have developed a charm recombination model to allow for off-equilibrium rate of charmonium production. We have developed methods and techniques which allowed us to study the hadron resonance yield evolution by kinetic theory. We explored entropy, strangeness and charm as signature of QGP addressing the wide range of reaction energy for AGS, SPS, RHIC and LHC energy range. In analysis of experimental data, we obtained both statistical parameters as well as physical properties of the hadron source.

Addressing the quark-gluon phase (QGP) in laboratory we explore the physics governing the highly effective conversion of kinetic energy into abundant particle multiplicity. This is arguably the most remarkable feature of relativistic heavy ion (RHI) collisions. We devoted most of our effort to both phenomenological and theoretical understanding of this phenomenon which concerns the physics of ultra high acceleration. In our phenomenological analysis of experimental data we obtained the precise characterization of the QGP fireball at the time of hadronization. Our noteworthy results include the determination of universal conditions of fireball break-up into matter (hadronization), with universal pressure $P = 80 \pm 3$ MeV/fm^3. Hadronization conditions are obtained by computing the partial contributions of all hadron components in the final state, akin to the method used to compute flavor strangeness content of the fireball.

Matter in its present form was formed when our Universe emerged from the QGP era at about 20μs into its evolution. The mechanism of quark confinement is recognized today as governing the origin of mass and inertia, an important pillar motivating the entire field of RHI collision physics: mass in the Universe originates in the confinement of quarks with $\simeq 5\%$ Higgs-vacuum contribution. To explore this early Universe era in the laboratory, we study highly excited matter formed when in RHI collisions heavy nuclei crash into each other, and form compressed and energetically excited nuclear matter, resembling in its key features the stuff which filled the early Universe. In these experiments we further explore the physics of the vacuum structure of strongly interacting gauge theory, Quantum Chromodynamics (QCD) learning about possible origins of dark energy.

Among pivotal questions about the early Universe we have addressed are: **a)** How QGP transits to the hot hadronic universe, that is hadronization mode, matter-antimatter annihilation; and more generally **b)** The evolution path connecting QGP to the BBN phase of the Universe; **c)** Application of the chemical non-equilibrium methods developed in the study of hadronization of QGP to characterize the properties of the free-streaming neutrinos in the early universe; **d)** Demonstration that hadrons in the Universe remain in chemical equilibrium at all temperatures is among noteworthy achievements; **e)** The study of the transition from hadronic to the leptonic Universe, and how this affects free-streaming neutrino spectrum which affects physics of the BBN era of the universe, and how the BBN observables could be affected.

The following pages present listings of our primary writing on these questions. The abstracts are included in lieu of more detailed discussion of our research accomplishments in each of the publications. There are three lists:
2.1 Books and large reviews;
2.2 Refereed publications;
2.3 Conference reports tracked by Web of Science.

2 Publications

2.1 Books and large reviews

1. **By:** Rafelski, J (editor and author);
Title: Melting hadrons, boiling quarks: From Hagedorn Temperature to Ultra-Relativistic Heavy-Ion Collisions at CERN With a Tribute to Rolf Hagedorn;
Publisher Springer International Publishing, (2015); ISBN: 978-3-319-17544-7 (Print)
978-3-319-17545-4 (Online) `http://link.springer.com/book/10.1007/978-3-319-17545-4`
Description: This book shows how the study of multi-hadron production phenomena in the years after the founding of CERN culminated in Hagedorn's pioneering idea of limiting temperature, leading on to the discovery of the quark-gluon plasma – announced, in February 2000 at CERN. Following the foreword by Herwig Schopper – the Director General (1981-1988) of CERN at the key historical juncture – the first part is a tribute to Rolf Hagedorn (1919-2003) and includes contributions by contemporary friends and colleagues, and those who were most touched by Hagedorn: Tams Bir, Igor Dremin, Torleif Ericson, Marek Gadzicki, Mark Gorenstein, Hans Gutbrod, Maurice Jacob, Istvn Montvay, Berndt Mller, Grazyna Odyniec, Emanuele Quercigh, Krzysztof Redlich, Helmut Satz, Luigi Sertorio, Ludwik Turko, and Gabriele Veneziano. The second and third parts retrace 20 years of developments that after discovery of the Hagedorn temperature in 1964 led to its recognition as the melting point of hadrons into boiling quarks, and to the rise of the experimental relativistic heavy ion collision program. These parts contain previously unpublished material authored by Hagedorn and Rafelski: conference retrospectives, research notes, workshop reports, in some instances abbreviated to avoid duplication of material, and rounded off with the editor's explanatory notes.

2. **By:** Rafelski, J;
Title: Melting hadrons, boiling quarks
EUROPEAN PHYSICAL JOURNAL A **51** Article#: 114 `10.1140/epja/i2015-15114-0` (2015)
Abstract: In the context of the Hagedorn temperature half-centenary I describe our understanding of the hot phases of hadronic matter both below and above the Hagedorn temperature. The first part of the review addresses many frequently posed questions about properties of hadronic matter in different phases, phase transition and the exploration of quark-gluon plasma (QGP). The historical context of the discovery of QGP is shown and the role of strangeness and strange antibaryon signature of QGP illustrated. In the second part I discuss the corresponding theoretical ideas and show how experimental results can be used to describe the properties of QGP at hadronization. The material of this review is complemented by two early and unpublished reports containing the prediction of the different forms of hadron matter, and of the formation of QGP in relativistic heavy ion collisions, including the discussion of strangeness, and in particular strange antibaryon signature of QGP.

3. **By:** Rafelski, J; (one of many other contributors:)
Title: Heavy-ion collisions at the LHC-Last call for predictions
JOURNAL OF PHYSICS G-NUCLEAR AND PARTICLE PHYSICS **35** Article#: 054001 `10.1088/0954-3899/35/5/054001` (2008)
Abstract: This writeup is a compilation of the predictions for the forthcoming Heavy Ion Program at the Large Hadron Collider, as presented at the CERN Theory Institute 'Heavy Ion Collisions at the LHC - Last Call for Predictions', held from 14th May to 10th June 2007.

4. **By:** Barish, K; Huang, HZ; Kapusta, J; Odyniec, G; Rafelski, J; Whitten, CA (editors)
Title: Special issue: Proceedings of SQM 2006 - International Conference on Strangeness in Quark Matter (University of California Los Angeles, 26-31 March 2006)
JOURNAL OF PHYSICS G-NUCLEAR AND PARTICLE PHYSICS **32** (2006)
From the preface: The International Conference on Strangeness in Quark Matter (SQM) was held on 2631 March 2006 at the University of California Los Angeles campus. SQM2006 is the first conference

in the SQMseries where heavy quark physics in heavy-ion collisions has become as important a focus as strange quarks. In light of recent results from RHIC on the strong suppression and non-zero elliptic flow for non-photonic electrons from heavy quark decays, heavy quarks have become an increasingly important probe of QCD properties of dense matter created at RHIC.

5. **By:** Rafelski, J. (guest contributor); and many others,
Title: ALICE: Physics Performance Report, Volume II
JOURNAL OF PHYSICS G-NUCLEAR AND PARTICLE PHYSICS **32** pp. 1295-2040 (2006)
Abstract (abbreviated to the relevant part:) Since the comprehensive information on detector and physics performance was last published in the ALICE Technical Proposal in 1996, the detector, as well as simulation, reconstruction and analysis software have undergone significant development. The Physics Performance Report (PPR) provides an updated and comprehensive summary of the performance of the various ALICE subsystems, including updates to the Technical Design Reports, as appropriate. The present volume, Volume II, contains the majority of the information relevant to the physics performance in proton-proton, proton-nucleus, and nucleus-nucleus collisions. Following an introductory overview, Chapter 5 describes the combined detector performance and the event reconstruction procedures, based on detailed simulations of the individual subsystems. Chapter 6 describes the analysis and physics reach for a representative sample of physics observables, from global event characteristics to hard processes.

2.2 Refereed publications

REFEREED PAPERS TRACKED BY WEB OF SCIENCE

1. **By:** Rafelski, J; Birrell, J
Title: Dynamical emergence of the Universe into the false vacuum
JOURNAL OF COSMOLOGY AND ASTROPARTICLE PHYSICS **11** Article#: 035 `10.1088/1475-7516/2015/11/035` (2015)
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 $v =< h >$, 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 vacuua $v(1), v(2)$ can swap between being true and false. We evaluate the dynamical surface pressure on domain walls between low and high mass vaccua due to the presence of matter and show that the low mass state remains the preferred vacuum of the Universe.

2. **By:** Birrell, J; Rafelski, J
Title: Proposal for resonant detection of relic massive neutrinos
EUROPEAN PHYSICAL JOURNAL C **75** Article#: 91 `10.1140/epjc/s10052-015-3310-3` (2015)
Abstract: We present a novel method for detecting the relic neutrino background that takes advantage of structured quantum degeneracy to amplify the drag force from neutrinos scattering off a detector. Developing this idea, we present a characterization of the present day relic neutrino distribution in an arbitrary frame, including the influence of neutrino mass and neutrino reheating by e^+e^--annihilation. We present explicitly the neutrino velocity and de Broglie wavelength distributions for the case of an Earthbound observer. Considering that relic neutrinos could exhibit quantum liquid features at the present day temperature and density, we discuss the impact of neutrino fluid correlations on the possibility of resonant detection.

3. **By:** Birrell, J; Rafelski, J
Title: Quark-gluon plasma as the possible source of cosmological dark radiation
PHYSICS LETTERS B **741** pp. 77-81 `10.1016/j.physletb.2014.12.033` (2015)

Abstract: The effective number of neutrinos, $N_{\rm eff}$, 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 $N_{\rm eff}$ 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 a connection between $N_{\rm eff}$ and the QGP transformation for laboratory studies of QGP.

4. **By:** Birrell, J; Wilkening, J; Rafelski, J
Title: Boltzmann equation solver adapted to emergent chemical non-equilibrium
JOURNAL OF COMPUTATIONAL PHYSICS **281** pp. 896-916 10.1016/j.jcp.2014.10.056 (2015)
Abstract: We present a novel method to solve the spatially homogeneous and isotropic relativistic Boltzmann equation. We employ a basis set of orthogonal polynomials dynamically adapted to allow for emergence of chemical non-equilibrium. Two time dependent parameters characterize the set of orthogonal polynomials, the effective temperature $T(t)$ and phase space occupation factor $\gamma(t)$. In this first paper we address (effectively) massless fermions and derive dynamical equations for $T(t)$ and $\gamma(t)$ such that the zeroth order term of the basis alone captures the particle number density and energy density of each particle distribution. We validate our method and illustrate the reduced computational cost and the ability to easily represent final state chemical non-equilibrium by studying a model problem that is motivated by the physics of the neutrino freeze-out processes in the early Universe, where the essential physical characteristics include reheating from another disappearing particle component (e^+e^--annihilation).

5. **By:** Birrell, J; Yang, CT; Rafelski, J
Title: Relic neutrino freeze-out: Dependence on natural constants
NUCLEAR PHYSICS B **890** pp. 481-517 10.1016/j.nuclphysb.2014.11.020 (2015)
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 eta 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.

6. **By:** Petran, M; Letessier, J; Rafelski, J; Torrieri, G
Title: SHARE with CHARM
COMPUTER PHYSICS COMMUNICATIONS **185** pp. 2056-2079 10.1016/j.cpc.2014.02.026 (2014)
Abstract: SHARE with CHARM program (SHAREv3) implements the statistical hadronization model description of particle production in relativistic heavy-ion collisions. Given a set of statistical parameters, SHAREv3 program evaluates yields and therefore also ratios, and furthermore, statistical particle abundance fluctuations. The physical bulk properties of the particle source are evaluated based on all hadrons produced, including the fitted yields. The bulk properties can be prescribed as a fit input complementing and/or replacing the statistical parameters. The modifications and improvements in the SHARE suite of programs are oriented towards recent and forthcoming LHC hadron production results including charm hadrons. This SHAREv3 release incorporates all features seen previously in SHAREv1.x and v2.x and, beyond, we include a complete treatment of

charm hadrons and their decays, which further cascade and feed lighter hadron yields. This article is a complete and self-contained manual explaining and introducing both the conventional and the extended capabilities of SHARE with CHARM. We complement the particle list derived from the Particle Data Group tabulation (Beringer, 2012) composed of up, down, strange u, d, s quarks (including resonances) with hadrons containing charm $c, \bar{c}$ quarks. We provide a table of the charm hadron decays including partial widths. The branching ratios of each charm hadron decay add to unity, which is achieved by including some charm hadron decay channels based on theoretical consideration in the absence of direct experimental information. A very successful interpretation of all available LHC results has been already obtained using this program.

7. **By:** Birrell, J; Yang, CT; Chen, P; Rafelski, J
Title: Relic neutrinos: Physically consistent treatment of effective number of neutrinos and neutrino mass
PHYSICAL REVIEW D **89** Article#: 023008 `10.1103/PhysRevD.89.023008` (2014)
Abstract: We perform a model independent study of the neutrino momentum distribution at freeze-out, treating the freeze-out temperature as a free parameter. Our results imply that measurement of neutrino reheating, as characterized by the measurement of the effective number of neutrinos N_ν, amounts to the determination of the neutrino kinetic freeze-out temperature within the context of the standard model of particle physics where the number of neutrino flavors is fixed and no other massless (fractional) particles arise. At temperatures on the order of the neutrino mass, we show how cosmic background neutrino properties, i.e., energy density, pressure, and particle density, are modified in a physically consistent way as a function of neutrino mass and N_ν.

8. **By:** Labun, L; Rafelski, J
Title: Top anomalous magnetic moment and the two-photon decay of the Higgs boson
PHYSICAL REVIEW D **88** Article#: 071301 `10.1103/PhysRevD.88.071301` (2013)
Abstract: We compute the dependence of the Higgs to two-photon decay rate $\Gamma(h \to \gamma\gamma)$ on the top quark gyromagnetic factor $g(t)$ in the heavy top limit and evaluate the expected change for one-loop SM correction to $g(t)$. Our results are general and allow consideration of further modifications of $g(t)$, and we predict the resultant $Gamma(h \to \gamma\gamma)$.

9. **By:** Petran, M; Letessier, J; Petracek, V; Rafelski, J
Title: Hadron production and QGP hadronization in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$
PHYSICAL REVIEW C **88** Article#: 034907 `10.1103/PhysRevC.88.034907` (2013)
Abstract: We show that all central rapidity hadron yields measured in Pb-Pb collisions at root $s_{NN} = 2.76$ TeV are well described by the chemical nonequilibrium statistical hadronization model (SHM), where the chemically equilibrated quark-gluon plasma source breaks up directly into hadrons. SHM parameters are obtained as a function of centrality of colliding ions, and we compare CERN Large Hadron Collider (LHC) results with Brookhaven National Laboratory Relativistic Heavy Ion Collider (RHIC) results. We predict yields of unobserved hadrons and address antimatter production. The physical properties of the quark-gluon plasma fireball particle source show universality of hadronization conditions at LHC and RHIC.

10. **By:** Petran, M; Rafelski, J
Title: Universal hadronization condition in heavy ion collisions at $s_{NN} = 62\,\mathrm{GeV}$ and at $s_{NN} = 2.76\,\mathrm{TeV}$
PHYSICAL REVIEW C **88** Article#: 021901 `10.1103/PhysRevC.88.021901` (2013)
Abstract: We obtain a detailed description of all available hadron multiplicity yields in central Pb-Pb collisions at the CERN Large Hadron Collider (LHC) measured in the rapidity interval vertical$|y| <$ 0.5. We find that the hadronization of the fireball at the LHC occurs at nearly identical intensive physical bulk conditions for all centralities similar to those already seen at the Brookhaven National Laboratory Relativistic Heavy Ion Collider.

11. **By:** Rafelski, J; Labun, L; Birrell, J
Title: Compact Ultradense Matter Impactors
PHYSICAL REVIEW LETTERS **110** Article#: 111102 10.1103/PhysRevLett.110.111102 (2013)
Abstract: We study interactions of meteorlike compact ultradense objects (CUDO), having nuclear or greater density, with Earth and other rocky bodies in the Solar System as a possible source of information about novel forms of matter. We study the energy loss in CUDO puncture of the body and discuss differences between regular matter and CUDO impacts.

12. **By:** Labun, L; Rafelski, J
Title: Acceleration and vacuum temperature
PHYSICAL REVIEW D **86** Article#: 041701 10.1103/PhysRevD.86.041701 (2012)
Abstract: The quantum fluctuations of an "accelerated" vacuum state, that is, vacuum fluctuations in the presence of a constant electromagnetic field, can be described by the temperature T_M. Considering T_M for the gyromagnetic factor $g = 1$ we show that $T_M(g = 1) = T - U$, where $T - U$ is the Unruh temperature experienced by an accelerated observer. We conjecture that both particle production and nonlinear field effects inherent in the Unruh accelerated observer case are described by the case $g = 1$ QED of strong fields. We present rates of particle production for $g = 0, 1, 2$ and show that the case $g = 1$ is experimentally distinguishable from $g = 0, 2$. Therefore, either accelerated observers are distinguishable from accelerated vacuum or there is unexpected modification of the theoretical framework.

13. **By:** Kuznetsova, I; Rafelski, J
Title: Electron-positron plasma drop formed by ultra-intense laser pulses
PHYSICAL REVIEW D **85** Article#: 085014 10.1103/PhysRevD.85.085014 (2012)
Abstract: We study the initial properties and positron annihilation within a small electron-positron plasma drop formed by intense laser pulse energy. Such QED cascade generated plasma is, in general, far below the chemical (particle yield) equilibrium. We find that the available electrons and positrons equilibrate kinetically, yet despite relatively high particle density, the electron-positron annihilation is very slow, suggesting a rather long life span of the plasma drop.

14. **By:** Dietl, C; Labun, L; Rafelski, J
Title: Properties of gravitationally bound dark compact ultra dense objects
PHYSICS LETTERS B **709** pp. 123-127 10.1016/j.physletb.2012.02.015 (2012)
Abstract: We consider compact astrophysical objects formed from dark matter fermions of mass 250 GeV to 100 TeV or from massless fermions hidden by vacuum structure of similar energy scale. These objects have maximum stable masses of sub-planetary scale and radii of micron to centimeter scale. We describe the surface gravity and tidal forces near these compact ultra dense objects, as pertinent to signatures of their collisions with visible matter objects.

15. **By:** Miller, GA; Thomas, AW; Carroll, JD; Rafelski, J Thomas, Anthony G-4194-2012 0000-0003-0026-499X
Title: Toward a resolution of the proton size puzzle
PHYSICAL REVIEW A **84** Article#: 020101 10.1103/PhysRevA.84.020101 (2011)
Abstract: We show that off-mass-shell effects arising from the internal structure of the proton provide a new proton polarization mechanism in the Lamb shift, proportional to the lepton mass to the fourth power. This effect is capable of resolving the current puzzle regarding the difference in the proton radius extracted from muonic compared with electronic hydrogen experiments. These off-mass-shell effects could be probed in several other experiments. A significant ambiguity appearing in dispersion relation evaluations of the proton polarizability contribution to the Lamb shift is noted.

16. **By:** Labun, L; Rafelski, J
Title: Spectra of particles from laser-induced vacuum decay

PHYSICAL REVIEW D **84** Article#: 033003 10.1103/PhysRevD.84.033003 (2011)
Abstract: The spectrum of electrons and positrons originating from vacuum decay occurring in the collision of two noncollinear laser pulses is obtained. It displays high energy, highly collimated particle bunches traveling in a direction separate from the laser beams. This result provides an unmistakable signature of the vacuum-decay phenomenon and could suggest a new avenue for development of high energy electron and/or positron beams.

17. **By:** Carroll, JD; Thomas, AW; Rafelski, J; Miller, GA
Title: Nonperturbative relativistic calculation of the muonic hydrogen spectrum
PHYSICAL REVIEW A **84** Article#: 012506 10.1103/PhysRevA.84.012506 (2011)
Abstract: We investigate the muonic hydrogen $2P_{3/2}(F = 2) \to 2S_{1/2}(F = 1)$ transition through a precise, nonperturbative numerical solution of the Dirac equation including the finite-size Coulomb force and finite-size vacuum polarization. The results are compared with earlier perturbative calculations of (primarily) [E. Borie, Phys. Rev. A 71, 032508 (2005); E. Borie and G. A. Rinker, Rev. Mod. Phys. 54, 67 (1982); E. Borie, Z. Phys. A 275, 347 (1975) and A. P. Martynenko, Phys. Rev. A 71, 022506 (2005); A. Martynenko, Phys. At. Nucl. 71, 125 (2008), and K. Pachucki, Phys. Rev. A 53, 2092 (1996)] and experimental results recently presented by Pohl et al. [Nature (London) 466, 213 (2010)], in which this very comparison is interpreted as requiring a modification of the proton charge radius from that obtained in electron scattering and electronic hydrogen analyses. We find no significant discrepancy between the perturbative and nonperturbative calculations, and we present our results as confirmation of the perturbative methods.

18. **By:** Rafelski, J; Letessier, J
Title: Particle production in $s_{NN} = 2.76$ TeV heavy ion collisions
PHYSICAL REVIEW C **83** Article#: 054909 10.1103/PhysRevC.83.054909 (2011)
Abstract: We obtain within the statistical hadronization model (SHM) the hadron yields dh/dy in heavy ion reactions at root $s_{NN} = 2.76$ TeV. We discuss the dependence both on hadronization temperature T and on critical hadronization pressure P. We consider observables distinguishing the hadronization models and conditions.

19. **By:** Hadad, Y; Labun, L; Rafelski, J; Elkina, N; Klier, C; Ruhl, H
Title: Effects of radiation reaction in relativistic laser acceleration
PHYSICAL REVIEW D **82** Article#: 096012 10.1103/PhysRevD.82.096012 (2010)
Abstract: The goal of this paper is twofold: to explore the response of classical charges to electromagnetic force at the level of unity in natural units and to establish a criterion that determines physical parameters for which the related radiation-reaction effects are detectable. In pursuit of this goal, the Landau-Lifshitz equation is solved analytically for an arbitrary (transverse) electromagnetic pulse. A comparative study of the radiation emission of an electron in a linearly polarized pulse for the Landau-Lifshitz equation and for the Lorentz force equation reveals the radiation-reaction-dominated regime, in which radiation-reaction effects overcome the influence of the external fields. The case of a relativistic electron that is slowed down by a counterpropagating electromagnetic wave is studied in detail. We further show that when the electron experiences acceleration of order unity, the dynamics of the Lorentz force equation, the Landau-Lifshitz equation and the Lorentz-Abraham-Dirac equation all result in different radiation emission that could be distinguished in experiment. Finally, our analytic and numerical results are compared with those appearing in the literature.

20. **By:** Kuznetsova, I; Rafelski, J
Title: Unstable hadrons in hot hadron gas: In the laboratory and in the early Universe
PHYSICAL REVIEW C **82** Article#: 035203 10.1103/PhysRevC.82.035203 (2010)
Abstract: We study kinetic master equations for chemical reactions involving the formation and the natural decay of unstable particles in a thermal bath. We consider the decay channel of one into two

particles and the inverse process, fusion of two thermal particles into one. We present the master equations for the evolution of the density of the unstable particles in the early Universe. We obtain the thermal invariant reaction rate using as an input the free space (vacuum) decay time and show the medium quantum effects on $\pi + \pi \leftrightarrow \rho$ reaction relaxation time. As another laboratory example we describe the $K + K \leftrightarrow \phi$ process in thermal hadronic gas in heavy-ion collisions. A particularly interesting application of our formalism is the $\pi^0 \leftrightarrow \gamma + \gamma$ process in the early Universe. We also explore the physics of $\pi^{\pm}$ and $\mu^{\pm}$ freeze-out in the Universe.

21. **By:** Petran, M; Rafelski, J
Title: Multistrange particle production and the statistical hadronization model
PHYSICAL REVIEW C **82** Article#: 011901 `10.1103/PhysRevC.82.011901` (2010)
Abstract: We consider the chemical freeze-out of $\Xi, \bar{\Xi}$, and ϕ multistrange hadrons within a statistical hadronization model inspired approach. We study particle yields across a wide range of reaction energy and centrality from NA49 at the Super Proton Synchrotron (SPS) and the Solenoidal Tracker at RHIC (STAR) experiments. We constrain the physical conditions present in the fireball source of strange hadrons and anticipate results expected at the Large Hadron Collider (LHC).

22. **By:** Labun, L; Rafelski, J
Title: QED energy-momentum trace as a force in astrophysics
PHYSICS LETTERS B **687** pp. 133-138 `10.1016/j.physletb.2010.02.083` (2010)
Abstract: We study the properties of the trace $\mathcal{T}$ of the QED energy-momentum tensor in the presence of quasi-constant external electromagnetic fields. We exhibit the origin of $\mathcal{T}$ in the quantum nonlinearity of the electromagnetic theory. We obtain the quantum vacuum fluctuation-induced interaction of a particle with the field of a strongly magnetized compact stellar object.

23. **By:** Labun, L; Rafelski, J
Title: Dark energy simulacrum in nonlinear electrodynamics
PHYSICAL REVIEW D **81** Article#: 065026 `10.1103/PhysRevD.81.065026` (2010)
Abstract: Quasiconstant external fields in nonlinear electromagnetism generate a global contribution proportional to g(mu nu) in the energy-momentum tensor, thus a simulacrum of dark energy. To provide a thorough understanding of the origin and strength of its effects, we undertake a complete theoretical and numerical study of the energy-momentum tensor $T^{\mu\nu}$ for nonlinear electromagnetism. The Euler-Heisenberg nonlinearity due to quantum fluctuations of spinor and scalar matter fields is considered and contrasted with the properties of classical nonlinear Born-Infeld electromagnetism. We address modifications of charged particle kinematics by strong background fields.

24. **By:** Kuznetsova, I; Habs, D; Rafelski, J
Title: Thermal reaction processes in a relativistic QED plasma drop
PHYSICAL REVIEW D **81** Article#: 053007 `10.1103/PhysRevD.81.053007` (2010)
Abstract: The equilibrium size and temperature limits of thermally and chemically equilibrated $e^+e^-\gamma$ plasma drops are investigated at a given energy content. For a plasma to be equilibrated it must be opaque to electron and photon interactions. The opaqueness condition is determined by comparing plasma size with the mean free electron and photon paths. We calculate those paths using thermal Lorentz-invariant reaction rates for pair production and electron (positron) and photon scattering. The range of the corresponding plasma temperature and size is evaluated numerically. Considering the energy and size we find that the opaque and equilibrated plasma drop may be experimentally attainable.

25. **By:** Zayakin, AV; Rafelski, J
Title: Confinement property in SU(3) gauge theory
PHYSICAL REVIEW D **80** Article#: 034024 `10.1103/PhysRevD.80.034024` (2009)
Abstract: We study the confinement property of the pure SU(3) gauge theory, combining in this

effort the nonperturbative gluon and ghost propagators obtained as solutions of Dyson-Schwinger equations with solutions of an integral ladder diagram summation type equation for the Wilson loop. We obtain the string potential and effective UV coupling.

26. **By:** Labun, L; Rafelski, J
Title: Vacuum-decay time in strong external fields
PHYSICAL REVIEW D **79** Article#: 057901 `10.1103/PhysRevD.79.057901` (2009)
Abstract: We consider dynamics of vacuum decay and particle production in the context of short pulse laser experiments. We identify and evaluate the invariant "materialization time," τ, the time scale for the conversion of an electromagnetic field energy into particles and compare to the laser related time scales.

27. **By:** Kuznetsova, I; Rafelski, J
Title: Resonance production in heavy ion collisions: Suppression of $\Lambda(1520)$ and enhancement of $\Sigma(1385)$
PHYSICAL REVIEW C **79** Article#: 014903 `10.1103/PhysRevC.79.014903` (2009)
Abstract: We investigate the yield of $\Lambda(1520)$ resonance in heavy ion collisions within the framework of a kinetic master equation without the assumption of chemical equilibrium. We show that reactions such as $\Lambda(1520) + \pi \leftrightarrow \Sigma*$ can favor $\Sigma*$ production, thereby decreasing the $\Lambda(1520)$ yield. Within the same approach we thus find a yield enhancement for $\Sigma(1385)$ and a yield suppression for $\Lambda(1520)$.

28. **By:** Kuznetsova, I; Rafelski, J
Title: Enhanced production of Delta and Sigma (1385) resonances
PHYSICS LETTERS B **668** pp. 105-110 `10.1016/j.physletb.2008.08.018` (2008)
Abstract: Yields of $\Delta(1230)$, $\Sigma(1385)$ resonances produced in heavy ion collisions are studied within the framework of a kinetic master equation. The time evolution is driven by the process $\Delta \leftrightarrow N\pi$, $\Sigma(1385) \leftrightarrow \Lambda\pi$. We obtain resonance yield both below and above chemical equilibrium, depending on initial hadronization condition and separation of kinetic and chemical freeze-out.

29. **By:** Kuznetsova, I; Habs, D; Rafelski, J
Title: Pion and muon production in $e^+e^-\gamma$ plasma
PHYSICAL REVIEW D **78** Article#: 014027 `10.1103/PhysRevD.78.014027` (2008)
Abstract: We study production and equilibration of pions and muons in relativistic electron-positron-photon plasma at a temperature of $T < m_\mu, m_\pi$. We argue that the observation of pions and muons can be a diagnostic tool in the study of the initial properties of such a plasma formed by means of strong laser fields. Conversely, properties of muons and pions in a thermal environment become accessible to precise experimental study.

30. **By:** Letessier, J; Rafelski, J
Title: Hadron production and phase changes in relativistic heavy-ion collisions
EUROPEAN PHYSICAL JOURNAL A **35** pp. 221-242 `10.1140/epja/i2007-10546-7` (2008)
Abstract: We study soft hadron production in relativistic heavy-ion collisions in a wide range of reaction energy, $4.8 < \sqrt{s_{NN}} < 200$ GeV, and make predictions about yields of particles using the statistical hadronization model. In fits to experimental data, we obtain both the statistical parameters as well as physical properties of the hadron source. We identify the properties of the fireball at the critical energy threshold, $6.26 < \sqrt{s_{NN}} < 7.61$ GeV, marking for higher energies the hadronization of an entropy-rich phase. In terms of the chemical composition, one sees a phase which at low energy is chemically under-saturated, and which turns into a chemically over-saturated state persisting up to the maximum accessible energy. Assuming that there is no change in physical mechanisms in the energy range $15 > \sqrt{s_{NN}} \geq 200$ GeV, we use continuity of particle yields and statistical parameters to predict the hadron production at $\sqrt{s_{NN}} = 62.4$ GeV, and obtain total yields of hadrons at root $\sqrt{s_{NN}} = 130$ GeV. We consider, in depth, the pattern we uncover within the hadronization condition,

and discuss possible mechanisms associated with the identified rapid change in system properties at root $\sqrt{s_{NN}}_{\rm cr}$. We propose that the chemically over-saturated 2 + 1 flavor hadron matter system undergoes a 1st-order phase transition.

31. **By:** Pin-Zhen, B; Rafelski, J
Title: Delta(33)-medium mass modification and pion spectra
EUROPEAN PHYSICAL JOURNAL A **32** pp. 267-272 10.1140/epja/i2007-10386-5 (2007)
Abstract: We study the $\pi^{\pm}$ spectra obtained in 2, 4, 6 and 8 A GeV Au - Au collisions within the thermal model. We find that the main features of the data can be well described after we include the pions from the decay of the Delta -resonance with medium mass modification.

32. **By:** Kuznetsova, I; Rafelski, J
Title: Heavy flavor hadrons in statistical hadronization of strangeness-rich QGP
EUROPEAN PHYSICAL JOURNAL C **51** pp. 113-133 10.1140/epjc/s10052-007-0268-9 (2007)
Abstract: We study b and c quark hadronization from QGP. We obtain the yields of charm and bottom flavored hadrons within the statistical hadronization model. The important novel feature of this study is that we take into account the high strangeness and entropy content of QGP, conserving the strangeness and entropy yields at hadronization.

33. **By:** Torrieri, G; Rafelski, J
Title: Hadron resonances and phase threshold in heavy ion collisions
PHYSICAL REVIEW C **75** Article#: 024902 10.1103/PhysRevC.75.024902 (2007)
Abstract: We show that a measurement of the reaction energy (root s) dependence of relative hadron resonance yields in heavy ion collisions can be used to study the phase structure of the dense strongly interacting matter created in these collisions and investigate the origin of the trends observed in the excitation functions of certain soft hadronic observables. We show that the presence of chemical nonequilibrium in light quark abundance imparts a characteristic signature on the energy dependence of resonance yields that differs considerably from what is expected in the equilibrium picture.

34. **By:** Letessier, J; Rafelski, J
Title: Strangeness chemical equilibration in a quark-gluon plasma
PHYSICAL REVIEW C **75** Article#: 014905 10.1103/PhysRevC.75.014905 (2007)
Abstract: We study, in the dynamically evolving quark-gluon plasma (QGP) fireball formed in relativistic heavy ion collisions at the BNL Relativistic Heavy Ion Collider (RHIC) and CERN Large Hadron Collider (LHC), the growth of strangeness yield toward and beyond the chemical equilibrium. We account for the contribution of the direct strangeness production and evaluate the thermal-QCD strangeness production mechanisms. The specific yield of strangeness per entropy, s/S, is the primary target variable. We explore the effect of collision impact parameter, i.e., fireball size, on kinetic strangeness chemical equilibration in QGP. Insights gained in studying the RHIC data with regard to the dynamics of the fireball are applied to the study of strangeness production at the LHC. We use these results and consider the strange hadron relative particle yields at RHIC and LHC in a systematic fashion. We consider both the dependence on s/S and the direct dependence on the participant number.

35. **By:** Torrieri, G; Jeon, S; Letessier, J; Rafelski, J Torrieri, Giorgio H-1776-2014 0000-0002-0611-766X
Title: SHAREv2: fluctuations and a comprehensive treatment of decay feed-down
COMPUTER PHYSICS COMMUNICATIONS **175** pp. 635-649 10.1016/j.cpc.2006.07.010 (2006)
Abstract: This the user's manual for SHARE version 2. SHARE [G. Torrieri, S. Steinke, W. Broniowski, W. Florkowski, J. Letessier, J. Rafelski, Comput. Phys. Comm. 167 (2005) 229] (Statistical Hadronization with Resonances) is a collection of programs designed for the statistical analysis of particle production in relativistic heavy-ion collisions. While the structure of the program remains similar to v1x, v2 provides several new features such as evaluation of statistical fluctuations of particle

yields, and a greater versatility, in particular regarding decay feed-down and input/output structure. This article describes all the new features, with emphasis on statistical fluctuations.

36. **By:** Torrieri, G; Jeon, S; Rafelski, J
Title: Particle yield fluctuations and chemical nonequilibrium in Au-Au collisions at root(NN)-N-S=100 GeV
PHYSICAL REVIEW C **74** Article#: 024901 `10.1103/PhysRevC.74.024901` (2006)
Abstract: We study charge fluctuations within the statistical hadronization model. Considering both the particle yield ratios and the charge fluctuations we show that it is possible to differentiate between chemical equilibrium and non-equilibrium freeze-out conditions. As an example of the procedure we show quantitatively how the relative yield ratio Lambda/K- together with the normalized net charge fluctuation constrain the chemical conditions at freeze-out. We also discuss the influence of the limited detector acceptance on fluctuation measurements, and show how this can be accounted for within a quantitative analysis.

37. **By:** Bialas, A; Rafelski, J
Title: Balance of baryon number in the quark coalescence model
PHYSICS LETTERS B **633** pp. 488-491 `10.1016/j.physletb.2005.11.084` (2006)
Abstract: The charge and baryon balance functions are studied in the coalescence hadronization mechanism of quark-gluon plasma. Assuming that in the plasma phase the $q\bar{q}$ pairs form uncorrelated clusters whose decay is also uncorrelated, one can understand the observed small width of the charge balance function in the Gaussian approximation. The coalescence model predicts even smaller width of the baryon-antibaryon balance function. (c) 2005 Elsevier B.V. All rights reserved.

38. **By:** Rafelski, J; Letessier, J
Title: Soft hadron ratios at the LHC
EUROPEAN PHYSICAL JOURNAL C **45** pp. 61-72 `10.1140/epjc/s2005-02414-7` (2006)
Abstract: High precision soft hadron abundance data produced in relativistic nuclear collisions at LHC at $\sqrt{s_{NN}} = 5500$ GeV will become available beginning in 2007/8. We explore, within the statistical hadronization model, how these results can help us understand the properties of the deconfined quark-gluon phase at its breakup. We make assumptions about the physical properties of the fireball and obtain particle production predictions. Then, we develop a strategy to measure parameters of interest, such as strangeness occupancy $\gamma(s)$, chemical potentials μ_B and μ_S.

39. **By:** Letessier, J; Rafelski, J
Title: Centrality dependence of strangeness and (anti)hyperon production at root N-S N=200GeV
PHYSICAL REVIEW C **73** Article#: 014902 `10.1103/PhysRevC.73.014902` (2006)
Abstract: We evaluate strangeness produced in Au-Au interactions at root $\sqrt{s_{NN}} = 200$ GeV, as a function of reaction participant number A, and obtain the relative strange quark content at hadronization. Strange baryon and antibaryon rapidity density yields are studied relative to, and as function of, participant number and produced hadron yields.

40. **By:** Letessier, J.; Rafelski, J.
Title: Centrality dependence of strangeness and (anti)hyperon production at radics NN=200 GeV
Physical Review C (Nuclear Physics) **73** pp. 14902-1-4 `10.1103/PhysRevC.73.014902` (2006)
Abstract: We evaluate strangeness produced in Au-Au interactions at $\sqrt{s_{NN}} = 200$ GeV, as a function of reaction participant number A, and obtain the relative strange quark content at hadronization. Strange baryon and antibaryon rapidity density yields are studied relative to, and as function of, participant number and produced hadron yields.

41. **By:** Rafelski, J; Letessier, J; Torrieri, G Torrieri, Giorgio H-1776-2014 0000-0002-0611-766X
Title: Centrality dependence of bulk fireball properties in root s(NN)=200 GeVAu-Au collisions

PHYSICAL REVIEW C **72** Article#: 024905 10.1103/PhysRevC.72.024905 (2005)
Abstract: We explore the centrality dependence of the properties of the dense hadronic matter created in $\sqrt{s_{NN}} = 200$ GeV Au-Au collisions at the Relativistic Heavy Ion Collider. Using the statistical hadronization model, we fit particle yields known for 11 centrality bins. We present the resulting model parameters, rapidity yields of physical quantities, and the physical properties of bulk matter at hadronization as function of centrality. We discuss the production of strangeness and entropy.

42. **By:** Torrieri, G; Steinke, S; Broniowski, W; Florkowski, W; Letessier, J; Rafelski, J Torrieri, Giorgio H-1776-2014 0000-0002-0611-766X
Title: SHARE: Statistical hadronization with resonances
COMPUTER PHYSICS COMMUNICATIONS **167** pp. 229-251 10.1016/j.cpc.2005.01.004 (2005)
Abstract: SHARE is a collection of programs designed for the statistical analysis of particle production in relativistic heavy-ion collisions. With the physical input of intensive statistical parameters, it generates the ratios of particle abundances. The program includes cascade decays of all confirmed resonances from the Particle Data Tables. The complete treatment of these resonances has been known to be a crucial factor behind the success of the statistical approach. An optional feature implemented is the Breit-Wigner distribution for strong resonances. An interface for fitting the parameters of the model to the experimental data is provided.

2.3 Conference reports tracked by Web of Science

REPRINTED CONFERENCE REPORTS TRACKED BY WEB OF SCIENCE

1. **By:** Rafelski, J
Title: Strangeness and phase changes in hot hadronic matter-1983 (REPRINTED)
EUROPEAN PHYSICAL J. A **51** Article#: 116 10.1140/epja/i2015-15116-x (2015)
Abstract: Two phases of hot hadronic matter are described with emphasis put on their distinction. Here the role of strange particles as a characteristic observable of the quark-gluon plasma phase is particularly explored.

2. **By:** Rafelski, J
Title: Extreme states of nuclear matter-1980 (REPRINTED)
EUROPEAN PHYSICAL J. A **51** Article#: 115 10.1140/epja/i2015-15115-y (2015)
Abstract: The theory of hot nuclear fireballs consisting of all possible finite-size hadronic constituents in chemical and thermal equilibrium is presented. As a complement of this hadronic gas phase characterized by maximal temperature and energy density, the quark bag description of the hadronic fireball is considered. Preliminary calculations of temperatures and mean transverse momenta of particles emitted in high multiplicity relativistic nuclear collisions together with some considerations on the observability of quark matter are offered.

CONFERENCE REPORTS TRACKED BY WEB OF SCIENCE

3. **By:** Rafelski, J; Petran, M
Title: QCD phase transition studied by means of hadron production
PHYSICS OF PARTICLES AND NUCLEI **46** pp. 748-755 10.1134/S1063779615050238 (2015)
Abstract: We address the hadronization process of a QGP fireball formed in relativistic heavy-ion collisions in the entire range of past and present heavy ion collision reaction energies. A precise method of analysis of hadron multiplicities has evolved into the "SHARE with CHARM" statistical hadronization model. Using this tool we describe successfully-over many orders of magnitude-the yield of all hadrons produced in the full range of reaction energies and centralities; exceptions are peripheral and more central collisions at low energies. The properties of the fireball final state can be understood by considering all primary hadronic particles. The dense hadron fireball created at SPS, RHIC, and

LHC shows the final state differentiated solely by: i) volume changes; and ii) strangeness, (charm) flavor content. A universal hadronization pressure $P = 80 \pm 3$ MeV/fm^3 is found. The strangeness content of a large fireball as compared to entropy shows the presence of quark-gluon plasma degrees of freedom near the chemical QGP equilibrium. The 'Universal Hadronization' condition common to SPS, RHIC, and LHC agrees with the proposed direct QGP fireball evaporation into free-streaming hadrons. Looking forward we discuss qualitatively how heavy flavor production contributes to energy stopping in the central rapidity region as function of reaction energy: the cases of LHC at full energy and future super-LHC.

4. **By:** Hegelich, BM; Mourou, G; Rafelski, J
Title: Probing the quantum vacuum with ultra intense laser pulses
EUROPEAN PHYSICAL J.-SPECIAL TOPICS **223** pp. 1093-1104 10.1140/epjst/e2014-02160-8 (2014)
Abstract: This article presents 1) The theoretical background of strong field physics along with vacuum structure and stability; 2) The instrumental developments in the area of pulsed lasers and considers the physics case for the construction of ultra-intense laser facilities; and 3) The applied and fundamental uses of ultra-intense lasers.

5. **By:** Rafelski, J; Petran, M
Title: Universal QGP Hadronization Conditions at RHIC and LHC
WIGNER 111 - COLOURFUL & DEEP SCIENTIFIC SYMPOSIUM
EPJ Web of Conferences **78** Article#: 06004 10.1051/epjconf/20147806004 (2014)
Abstract: We address the principles governing QGP hadronization and particle production in relativistic heavy-ion collisions. We argue that chemical non-equilibrium is required and show that once this condition is assumed a very good description of hadron production in collider RHIC and LHC heavy ion experiments follows. We present results of our analysis as a function of centrality. Comparing most extreme experimental conditions we show that only the reaction volume and degree of strangeness phase space saturation change. We determine the universal QGP fireball hadronization conditions.
Conference Title: Wigner 111 - Colourful & Deep Scientific Symposium Conference Date: NOV 11-13, 2013 Conference Location: Hungarian Acad Sci, Budapest, HUNGARY

6. **By:** Petran, M ; Letessier, J; Petracek, V; Rafelski, J
Title: Interpretation of strange hadron production at LHC
14TH INT. CONFERENCE ON STRANGENESS IN QUARK MATTER (SQM2013)
Journal of Physics Conf. Ser. **509** Article#: 012018 10.1088/1742-6596/509/1/012018 (2014)
Abstract: We extend the SHM analysis of hadron production results showing here consistency with the increased experimental data set, stability of the fit with regard to inclusion of finite resonance widths and 2-star hyperon resonances. We present new results on strangeness yield as a function of centrality and present their interpretation in terms of QGP inspired model of strangeness abundance in the hadronizing fireball.
Conference Title: 14th International Conference on Strangeness in Quark Matter (SQM) Conference Date: JUL 22-27, 2013 Conference Location: Univ Birmingham, Birmingham, ENGLAND

7. **By:** Petran, M; Letessier, J; Petracek, V; Rafelski, J
Title: Charm decay as a source of multistrange hadrons
14TH INT. CONFERENCE ON STRANGENESS IN QUARK MATTER (SQM2013)
Journal of Physics Conf. Ser. **509** Article#: 012063 10.1088/1742-6596/509/1/012063 (2014)
Abstract: We describe a newly formulated approach to account for charm production and decay in Statistical Hadronization approach. Considering Pb-Pb collisions at $\sqrt{S_{NN}} = 2.76$ TeV at LHC we show that charm hadron decays can be a significant contributor to the multistrange hadron

abundance. We discuss the magnitude of expected effects as a function of charm yield.
Conference Title: 14th International Conference on Strangeness in Quark Matter (SQM) Conference Date: JUL 22-27, 2013 Conference Location: Univ Birmingham, Birmingham, ENGLAND

8. **By:** Rafelski, J; Birrell, J
Title: Traveling Through the Universe: Back in Time to the Quark-Gluon Plasma Era
14TH INT. CONFERENCE ON STRANGENESS IN QUARK MATTER (SQM2013)
Journal of Physics Conf. Ser. **509** Article#: 012014 `10.1088/1742-6596/509/1/012014` (2014)
Abstract: We survey the early history of the discovery of quark gluon plasma and the early history of the Universe, beginning with the present day and reaching deep into QGP and almost beyond. We introduce cosmological Universe dynamics and connect the different Universe epochs with one another. We describe some of the many remaining open questions that emerge.
Conference Title: 14th International Conference on Strangeness in Quark Matter (SQM) Conference Date: JUL 22-27, 2013 Conference Location: Univ Birmingham, Birmingham, ENGLAND

9. **By:** Birrell, J; Yang, CT; Chen, PS; Rafelski, J
Title: FUGACITY AND REHEATING OF PRIMORDIAL NEUTRINOS
MODERN PHYSICS LETTERS A **28** Article#: 1350188 `10.1142/S0217732313501885` (2013)
Abstract: We clarify in a quantitative way the impact that distinct chemical T_c and kinetic T_k freeze-out temperatures have on the reduction of the neutrino fugacity γ_ν below equilibrium, i.e. $\gamma_\nu < 1$, and the increase of the neutrino temperature T_ν via partial reheating. We establish the connection between γ_ν and T_k via the modified reheating relation $T_\nu(\gamma_\nu)/T_\gamma$, where T_γ is the temperature of the background radiation. Our results demonstrate that one must introduce the chemical nonequilibrium parameter, i.e. the fugacity, $gamma_\nu$, as an additional standard cosmological model parameter in the evaluation of CMB fluctuations as its: value allows measurement of T_k.

10. **By:** Rafelski, J; Labun, L
Title: CRITICAL ACCELERATION AND QUANTUM VACUUM
MODERN PHYSICS LETTERS A **28** Article#: 1340014 `10.1142/S0217732313400142` (2013)
Abstract: Little is known about the physics frontier of strong acceleration; both classical and quantum physics need further development in order to be able to address this newly at accessible area of physics. In this lecture we discuss what strong acceleration means, possible experiments using electron-laser collisions, and data available from ultra-relativistic heavy ion collisions. We review the foundations of the current understanding of charged particle dynamics in presence of critical forces and discuss the radiation reaction inconsistency in electromagnetic theory and the apparent relation with quantum physics and strong :field particle production phenomena. The role of the quantum vacuum as an inertial reference frame is emphasized, as well as the absence of such a 'Machian' reference frame in the conventional classical limit of quantum field theory.
Conference Title: 1st Leung Center for Cosmology and Particle Astrophysics (LeCosPA) Symposium - Towards Ultimate Understanding of the Universe Conference Date: FEB 06-09, 2012 Conference Location: Natl Taiwan Univ, Taipei,
REPRINTED IN:
TOWARDS ULTIMATE UNDERSTANDING OF THE UNIVERSE, PS. Chen, ed. pp. 141-152 (2013)
Conference Title: 1st LeCosPA Symposium on Towards Ultimate Understanding of the Universe Conference Date: FEB 06-09, 2012 Conference Location: Natl Taiwan Univ, Taipei, TAIWAN

11. **By:** Rafelski, J
Title: Connecting QGP-Heavy Ion Physics to the Early Universe
Nuclear Phys, B-Proc. Supplements **243** pp. 155-162 `10.1016/j.nuclphysbps.2013.09.017` (2013)
Abstract: We discuss properties and evolution of quark-gluon plasma in the early Universe and compare to laboratory heavy ion experiments. We describe how matter and antimatter emerged from a

primordial soup of quarks and gluons. We focus our discussion on similarities and differences between the early Universe and the laboratory experiments.
Conference Title: 4th International Conference on Particle and Fundamental Physics in Space Conference Date: NOV 05-07, 2012 Conference Location: CERN, Geneva, SWITZERLAND

12. **By:** Labun, L; Rafelski, J
Title: TEMPERATURE OF ELECTRON FLUCTUATIONS IN AN ACCELERATED VACUUM
MODERN PHYSICS LETTERS A **28** Article#: 1340015 10.1142/S0217732313400154 (2013)
Abstract: The electron vacuum fluctuations measured by $\langle\psi\bar{\psi}\rangle$ do not vanish in an externally applied electric field. For an exactly constant field, that is for presence of a constant accelerating force, we show that $\langle\psi\bar{\psi}\rangle$ has a Boson-like structure with spectral state density $\tanh^{-1}(E/m)$ and temperature T_M. Considering the vacuum fluctuations of 'classical' gyromagnetic ratio 1 particles we find Fermi-like structure with the same spectral state density at a smaller temperature which corresponds to the Unruh temperature of an accelerated observer.
Conference Title: 1st Leung Center for Cosmology and Particle Astrophysics (LeCosPA) Symposium - Towards Ultimate Understanding of the Universe Conference Date: FEB 06-09, 2012 Conference Location: Natl Taiwan Univ, Taipei
REPRINTED IN:
TOWARDS ULTIMATE UNDERSTANDING OF THE UNIVERSE eed. P. Chen, pp. 153-158 (2013)

13. **By:** Labun, L; Rafelski, J
Title: NONLINEAR ELECTROMAGNETIC FORCES IN ASTROPHYSICS
ACTA PHYSICA POLONICA B **43** pp. 2237-2250 10.5506/APhysPolB.43.2237 (2012)
Abstract: Electromagnetism becomes a nonlinear theory having (effective) photon-photon interactions due at least to electron-positron fluctuations in the vacuum. We discuss the consequences of the nonlinearity for the force felt by a charge probe particle, and compare the impact of Euler-Kockel QED effective nonlinearity to the possibility of Born-Infeld-type nonlinearity.
DOI:10.5506/APhysPolB.43.2237
Conference Title: 52nd Conference on Astroparticle Physics in the LHC Era of Cracow-School-of-Theoretical-Physics Conference Date: MAY 19-27, 2012 Conference Location: Zakopane, Poland

14. **By:** Rafelski, J; Dietl, C; Labun, L
Title: COMPACT ULTRADENSE OBJECTS IN THE SOLAR SYSTEM
ACTA PHYSICA POLONICA B **43** pp. 2251-2259 10.5506/APhysPolB.43.2251 (2012)
Abstract: We describe properties and gravitational interactions of meteor-mass and greater compact ultra dense objects with nuclear density or greater (CUDOs). We discuss possible enclosure of CUDOs in comets and the stability of these objects on impact with the Earth and Sun showing that the hypothesis of a CUDO core helps resolve issues challenging the understanding of a few selected cometary impacts.
Conference Title: 52nd Conference on Astroparticle Physics in the LHC Era of Cracow-School-of-Theoretical-Physics
Conference Date: MAY 19-27, 2012 Conference Location: Zakopane, Poland

15. **By:** Fromerth, MJ; Kuznetsova, I; Labun, L; Letessier, J; Rafelski, J
Title: FROM QUARK-GLUON UNIVERSE TO NEUTRINO DECOUPLING: 200 ¡ T ¡ 2 MeV
ACTA PHYSICA POLONICA B **43** pp. 2261-2283 10.5506/APhysPolB.43.2261 (2012)
Abstract: The properties of the quark and hadron Universe are explored. Kinetic theory considerations are presented proving that hadron abundances after phase transformation from quarks to hadrons remain intact till abundances of hadrons become irrelevant. The hadronization process and the evolution of hadron yields are described in detail.

Conference Title: 52nd Conference on Astroparticle Physics in the LHC Era of Cracow-School-of-Theoretical-Physics
Conference Date: MAY 19-27, 2012 Conference Location: Zakopane, Poland

16. **By:** Miller, GA; Thomas, A; Carroll, JD; Rafelski, J
Title: What's New with the Neutron and Proton
FEW-BODY SYSTEMS **52** pp. 357-366 10.1007/s00601-011-0288-8 (2012)
Abstract: The existence and importance of the proton radius puzzle, observed via a Lamb shift measurement in muonic atoms, is discussed. Possible resolutions of the puzzle are discussed. Then the broader question of the meaning of the proton radius is addressed and examples of correctly defined charge densities are presented.
Conference Title: LIGHTCONE Conference (LC) Conference Date: MAY 23-27, 2011 Conference Location: So Methodist Univ, Dallas, TX

17. **By:** Rafelski, J
Title: STRANGENESS AND QUARK-GLUON PLASMA
ACTA PHYSICA POLONICA B **43** pp. 829-842 10.5506/APhysPolB.43.829 (2012)
Abstract: I review the foundational motivations which led us to the ultra relativistic heavy ion collision research at SPS, RHIC and now LHC: the quantum vacuum structure; the deconfined nature of the quark-gluon plasma (QGP) phase filling the Universe for the first 30μs after the Big Bang; the origin of mass of stable matter; and the origin of flavor. The special roles of strangeness enhancement and strange antibaryon signature are highlighted. It is shown how hadron production can be used to determine the properties of QGP and how the threshold energy for QGP formation is determined.
Conference Title: Conference on Strangeness in Quark Matter Conference Date: SEP 18-24, 2011 Conference Location: Krakow, Poland

18. **By:** Petran, M; Letessier, J; Petracek, V; Rafelski, J
Title: STRANGENESS PRODUCTION IN Au-Au COLLISIONS AT root s(NN)=62.4 GeV
STRANGENESS IN QUARK MATTER 2011
Acta Physica Polonica B Proceedings Supplement **5** pp. 255-260 10.5506/APhysPolBSupp.5.255 (2012)
Abstract: We obtain strangeness production as function of centrality in a statistical hadronization model analysis of all experimental hadron production data in Au-Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV. Our analysis describes successfully the yield of strange and multi-strange hadrons recently published. We explore condition of hadronization as a function of centrality and find universality for the case of chemical non-equilibrium in the hadron phase space corresponding to quark-gluon plasma (QGP) in chemical equilibrium.
Conference Title: Conference on Strangeness in Quark Matter Conference Date: SEP 18-24, 2011 Conference Location: Krakow, Poland

19. **By:** Labun, L; Rafelski, J
Title: PLANETARY IMPACTS BY CLUSTERED QUARK MATTER STRANGELETS
STRANGENESS IN QUARK MATTER 2011
Acta Physica Polonica B Proceedings Supplement **5** pp. 381-386 10.5506/APhysPolBSupp.5.381 (2012)
Abstract: We propose a model of clustered u-d-s quark matter that leads to stable bulk strange quark matter. We discuss qualitatively consequences of impacts by sub-planetary mass strangelets on rocky solar system bodies.
Conference Title: Conference on Strangeness in Quark Matter Conference Date: SEP 18-24, 2011 Conference Location: Krakow, Poland

20. **By:** Miller, GA; Thomas, AW; Carroll, JD; Rafelski, J Thomas, Anthony 0000-0003-0026-499X
Title: Resolution of the Proton Radius Puzzle via Off-shell Form Factors
19TH PARTICLES AND NUCLEI INT. CONFERENCE (PANIC11)
AIP Conference Proceedings **1441** pp. 150-152 10.1063/1.3700496 (2012)
Abstract: We show that off-mass-shell effects arising from the internal structure of the proton provide a new proton polarization mechanism in the Lamb shift, proportional to the lepton mass to the fourth power. This effect is capable of resolving the current puzzle regarding the difference in the proton radius extracted from muonic compared with electronic hydrogen experiments. These off-mass-shell effects could be probed in several other experiments. A significant ambiguity appearing in dispersion relation evaluations of the proton polarizability contribution to the Lamb shift is noted.
Conference Title: 19th Particles and Nuclei International Conference (PANIC) Conference Date: JUL 24-29, 2011 Conference Location: Massachusetts Inst Technol, Cambridge, MA

21. **By:** Carroll, JD; Thomas, AW; Rafelski, J; Miller, GA
Title: The Radius of the Proton: Size Does Matter
T(R)OPICAL QCD 2010
AIP Conference Proceedings **1354** 10.1063/1.3587581 (2011)
Abstract: The measurement by Pohl et al. [1] of the $2S_{1/2}(F = 1) \rightarrow 2P_{3/2}(F = 2)$ transition in muonic hydrogen and the subsequent analysis has led to a conclusion that the rms charge radius of the proton differs from the accepted (CODATA [2]) value by approximately 4%, leading to a 4.9σ discrepancy. We investigate the muonic hydrogen spectrum relevant to this transition using bound-state QED with Dirac wave-functions and comment on the extent to which the perturbation-theory analysis which leads to the above conclusion can be confirmed.
Conference Title: Workshop on T(R)OPICAL QCD II Conference Date: SEP 26-OCT 01, 2010 Conference Location: Cairns, AUSTRALIA

22. **By:** Carroll, J.D.; Thomas, A.W.; Rafelski, J.; Miller, G.A.
Title: The Radius of the Proton: Size Does Matter
AIP Conference Proceedings **1354** pp. 25-31 10.1063/1.3599780 (2011)
Abstract: The measurement by Pohl et al. of the $2S_{1/2}(F = 1) \rightarrow 2P_{3/2}(F = 2)$ transition in muonic hydrogen and the subsequent analysis has led to a conclusion that the rms charge radius of the proton differs from the accepted (CODATA) value by approximately 4%, leading to a 4.9σ discrepancy. We investigate the muonic hydrogen spectrum relevant to this transition using bound-state QED with Dirac wave-functions and comment on the extent to which the perturbation-theory analysis which leads to the above conclusion can be confirmed.
Conference Title: T(r)opical qcd ii Workshop Conference Date: 26 Sept.-1 Oct. 2010 Conference Location: Cairns, QLD, Australia

23. **By:** Labun, L; Rafelski, J
Title: STRONG FIELD PHYSICS: PROBING CRITICAL ACCELERATION AND INERTIA WITH LASER PULSES AND QUARK-GLUON PLASMA
ACTA PHYSICA POLONICA B **41** pp. 2763-2783 (DEC 2010)
Abstract: Understanding physics in domains of critical (quantum unstable) fields requires investigating the classical and quantum particle dynamics at the critical acceleration, $du/d\tau \rightarrow 1$ [natural units]. This regime of physics remains today experimentally practically untested. Particle and laser pulse collision experiments reaching critical acceleration are becoming feasible. Ultra-relativistic heavy ion collisions breach the critical domain but are complicated by the presence of much other physics. The infamous problem of radiation reaction and the challenging environment of quantum vacuum instability arising in the high field domain signal the need for a thorough redress of the present theoretical framework.
Conference Title: Conference on the Particle Physics at the Dawn of the LHC Conference Date: JUN

09-19, 2010 Conference Location: L Cracow Sch Theoretical Phys, Zakopane, Poland

24. **By:** Petran, M; Letessier, J; Petracek, V; Rafelski, J
Title: STATISTICAL HADRONIZATION OF MULTISTRANGE PARTICLES
ACTA PHYSICA POLONICA B **41** pp. 2785-2797 (DEC 2010)
Abstract: We study multistrange hadrons produced in NA49 and STAR experiments at center of mass energies varying from $\sqrt{s_{NN}} = 7.61$ GeV to 200 GeV. We show that the yields of $\Xi, \bar{\Xi}$ and ϕ can help to constrain the physical conditions present in the hot dense fireball source of these multistrange hadrons created in heavy ion collision. We address the question of chemical equilibrium of individual quark flavors before and after hadronization and offer a few predictions for LHC.
Conference Title: Conference on the Particle Physics at the Dawn of the LHC Conference Date: JUN 09-19, 2010 Conference Location: L Cracow Sch Theoretical Phys, Zakopane, Poland

25. **By:** Labun, L; Rafelski, J
Title: VACUUM STRUCTURE AND DARK ENERGY
INT. J. OF MODERN PHYSICS D **19** pp. 2299-2304 10.1142/S0218271810018384 (2010)
Abstract: We consider that the universe is trapped in an excited vacuum state and the resulting excitation energy provides the observed dark energy. We explore the conditions under which this situation can arise from physics already known. Considering the example of how macroscopic quantum electrodynamic fields alter the vacuum structure, we find that the energy scale 1 meV – 1 eV is particularly interesting. We discuss how dark energy of this form is accessible to laboratory experiments.

26. **By:** Rafelski, J; Labun, L; Hadad, Y (Hadad, Yaron)
Title: Horizons of Strong Field Physics
LIGHT AT EXTREME INTENSITIES
AIP Conference Proceedings **1228** pp. 39-53 10.1063/1.3426079 (2010)
Abstract: Discussing the limitations on the validity of classical electrodynamics, we show that present day laser pulse technology applied to head-on-collisions with relativistic electrons generates fields strong enough to permit experimentation at the limits of validity of the Lorentz force, and the development of experimental tests of Mach's principle. We also discuss more distant opportunities for exploring the nature of laws of physics and the vacuum structure. We then conclude that the predictions of quantum electrodynamics in the presence of critical fields are not completely satisfactory and argue that the study of Laser materialization into particle pairs opens a new domain of quantum electrodynamics.
Conference Title: 1st International Conference on Light at Extreme Intensities (LEI 2009) Conference Date: OCT 16-21, 2009 Conference Location: Brasov, ROMANIA

27. **By:** Rafelski, J; Letessier, J
Title: Critical hadronization pressure
J. OF PHYSICS G-Nucle. Phys. **36** Article#: 064017 10.1088/0954-3899/36/6/064017 (2009)
Abstract: We discuss the bulk properties of QGP produced at the RHIC obtained at time of hadronization. We argue that hadronization of a quark-gluon plasma occurs at a critical pressure near to 82 MeV fm^{-3}, obtained for the SPS energy range.
Conference Title: 12th International Conference on Strangeness in Quark Matter Conference Date: OCT 05-10, 2008 Conference Location: Tsinghua Univ, Beijing, PEOPLES R CHINA

28. **By:** Kuznetsova, I (Kuznetsova, Inca); Letessier, J; Rafelski, J
Title: RESONANCES DO NOT EQUILIBRATE
ACTA PHYSICA POLONICA B **40** pp. 1013-1024 (2009)
Abstract: We discuss, in qualitative and quantitative fashion, the yields of hadron resonances. We show that these yields, in general, are not in chemical equilibrium. We evaluate the non-equilibrium abundances in a dynamic model implementing the $1 + 2 \leftrightarrow 3$ resonance formation reactions. Due

to the strength of these reactions, we show the $\Sigma(1385)$ enhancement, and the $\Lambda(1520)$ suppression explicitly.
Conference Title: 4th Workshop on Particle Correlations and Femtoscopy Conference Date: 2008 Conference Location: Polish Acad Arts & Sci, Cracow, Poland

29. **By:** Kuznetsova, I; Rafelski, J
Title: Non-equilibrium heavy-flavored hadron yields from chemical equilibrium strangeness-rich QGP
J. OF PHYSICS G-Nucle. Phys. **35** Article#: 044043 10.1088/0954-3899/35/4/044043 (2008)
Abstract: The yields of heavy-flavored hadrons emitted from strangeness-rich QGP are evaluated within the chemical non-equilibrium statistical hadronization model, conserving strangeness, charm and entropy yields at hadronization.
Conference Title: International Conference on Strangeness in Quark Matter Conference Date: JUN 24-29, 2007 Conference Location: Levoca, SLOVAKIA

30. **By:** Rafelski, J; Letessier, J
Title: Strangeness enhancement at LHC
J. OF PHYSICS G-Nucle. Phys. **35** Article#: 044042 10.1088/0954-3899/35/4/044042 (2008)
Abstract: We study production of strangeness in the hot QGP fireball under conditions achieved at LHC, and use these results to obtain soft (strange) hadron multiplicities. We compare the chemical equilibrium and non-equilibrium conditions and identify characteristic experimental observables.
Conference Title: International Conference on Strangeness in Quark Matter Conference Date: JUN 24-29, 2007 Conference Location: Levoca, SLOVAKIA

31. **By:** Rafelski, J; Kuznetsova, I; Letessier, J
Title: Strangeness at the threshold of phase change
J. OF PHYSICS G-Nucle. Phys. **35** Article#: 044011 10.1088/0954-3899/35/4/044011 (2008)
Abstract: We explore entropy and strangeness as the signature of quark-gluon plasma (QGP) for the top AGS and the energy scan at SPS. We find that the hadronization dynamics changes between 20 and 30 A GeV projectile energy. The high-energy results are consistent with the QGP.
Conference Title: International Conference on Strangeness in Quark Matter Conference Date: JUN 24-29, 2007 Conference Location: Levoca, SLOVAKIA

32. **By:** Rafelski, J
Title: Strangeness enhancement - Challenges and successes
EUROPEAN PHYSICAL J.-SPECIAL TOPICS **155** pp. 139-166 10.1140/epjst/e2008-00598-9 (2008)
Abstract: Highly effective conversion of kinetic energy into abundant particle multiplicity is the remarkable feature discovered in high energy heavy ion collisions. This short and pedagogic review addresses topical issues related to the understanding of this phenomenon, originating in the creation of the deconfined quark-gluon plasma phase. I consider in depth the apparently simple, yet sometimes misunderstood, intricate issues: a) statistical hadro-chemistry, chemical parameters, b) strange flavor chemical equilibration in quark-gluon plasma, and c) particle yields and sudden hadronization, in the historic perspective of work and competition with my friend Jozsef Zimanyi.

33. **By:** Thews, R.L.
Title: Quarkonium Production via Recombination
Nuclear Phys, A **783** pp 301-308 (2007)
Abstract: The contrast between model predictions for the transverse momentum spectra of J/Ψ observed in Au-Au collisions at RHIC is extended to include effects of nuclear absorption. We find that the difference between initial production and recombination is enhanced in the most central collisions. Models utilizing a combination of these sources may eventually be able to place constraints on their relative magnitudes.

34. **By:** Rafelski, J
Title: Quarks in the Universe
INT. J. OF MODERN PHYSICS E-Nuclear Phys, **16** pp. 813-828 10.1142/S0218301307006307 (2007)
Abstract: Matter in its present form was formed when our Universe emerged from the quark-gluon phase (QGP) at about 30mus into its evolution. To explore this early period in the laboratory, we study highly excited matter formed in relativistic heavy ion collision experiments: heavy nuclei crash into each other, and form compressed and energetically excited nuclear matter, resembling in its key features the stuff which filled the early Universe. In these experiments we further explore the physics of the vacuum structure of strongly interacting gauge theory, Quantum Chromodynamics (QCD). The common beginning for both, heavy ion collisions, and vacuum structure investigations, is the physics of the quantum electrodynamic (QED) vacuum in the presence of the supercritical external field that is formed when two highly charged heavy ions are brought together near to the Coulomb barrier in a considerably lower reaction energy collision.
Conference Title: International Symposium on Heavy Ion Physics Conference Date: APR, 2006 Conference Location: Frankfurt, GERMANY

35. **By:** Rafelski, J ; Letessier, J
Title: Status of strangeness-flavor signature of QGP
ACTA PHYSICA POLONICA B **37** pp. 3315-3341 (2006)
Abstract: Is the new state of matter formed in relativistic heavy ion collisions the deconfined quark-gluon plasma? We survey the status of several strange hadron observables and discuss how these measurements help understand the dense hadronic matter.
Conference Title: 46th Cracow School of Theoretical Physics Conference Date: MAY 27-JUN 05, 2006 Conference Location: Zakopane, Poland

36. **By:** Kuznetsova, I; Rafelski, J
Title: Charmed hadrons from strangeness-rich QGP
J. OF PHYSICS G-Nucle. Phys. **32** pp. S499-S504 10.1088/0954-3899/32/12/S64 (2006)
Abstract: The yields of charmed hadrons emitted by strangeness-rich QGP are evaluated within the chemical non-equilibrium statistical hadronization model, conserving strangeness, charm and entropy yields at hadronization.
Conference Title: International Conference on Strangeness in Quark matter Conference Date: MAR 26-31, 2006 Conference Location: Univ Calif Los Angeles, Los Angeles, CA

37. **By:** Steinke, S (Steinke, Steven); Rafelski, J
Title: Quantum collective QCD string dynamics
J. OF PHYSICS G-Nucle. Phys. **32** pp. S455-S460 10.1088/0954-3899/32/12/S55 (2006)
Abstract: The string breaking model of particle production is extended in order to help explain the transverse momentum distribution in elementary collisions. Inspired by an idea of Bialas, we treat the string using a collective coordinate approach. This leads to a chromo-electric field strength which fluctuates, and in turn implies that quarks are produced according to a thermal distribution.
Conference Title: International Conference on Strangeness in Quark matter Conference Date: MAR 26-31, 2006 Conference Location: Univ Calif Los Angeles, Los Angeles, CA

38. **By:** Rafelski, J; Letessier, J
Title: Strangeness and thresholds of phase changes in relativistic heavy ion collisions
Nuclear Phys, B-Proc. Supplements **161** pp. 200-209 10.1016/j.nuclphysbps.2006.08.049 (2006)
Abstract: We discuss how the dynamics of the evolving hot fireball of quark-gluon matter impacts phase transition between the deconfined and confined state of matter. The rapid expansion of the fireball of deconfined matter created in heavy ion collisions facilitates formation of an over-saturated

strange quark phase space. The related excess abundance of strangeness is compensating the suppression of this semi-heavy quark yield by its quark mass. In addition, the dynamical expansion of colored quanta pushes against the vacuum structure, with a resulting supercooling of the transition temperature. We address the status of the search for the phase boundary as function of reaction energy and collision centrality and show evidence for a change in reaction mechanism at sufficiently low energies. The phase diagram derived from the study of hadron production conditions shows two boundaries, one corresponding to the expected transition between confined and deconfined matter, with a downward temperature shift, and the other a high quark density hadronization which appears to involve heavy effective quarks, at relatively large temperatures.
Conference Title: 8th Workshop on Light-Cone QCD and Nonperturbative Hadron Physics Conference Date: 2005 Conference Location: Cairns, AUSTRALIA

39. **By:** Rafelski, J; Letessier, J
Title: Hadronization of expanding QGP
EUROPEAN PHYSICAL J. A **29** pp. 107-111 `10.1140/epja/i2005-10307-8` (2006)
Abstract: We discuss how the dynamics of an exploding hot fireball of quark-gluon matter impacts the actual phase transition conditions between the deconfined and confined state of matter. We survey the chemical conditions prevailing at hadronization.
Conference Title: 18th International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions Conference Date: AUG 04-09, 2005 Conference Location: Budapest, HUNGARY

40. **By:** Rafelski, J; Letessier, J
Title: Strangeness and the discovery of Quark-Gluon plasma
5TH INT. CONFERENCE ON PHYSICS AND ASTROPHYSICS OF QUARK GLUON PLASMA
Journal of Physics Conf. Ser. **50** pp. 176-191 `10.1088/1742-6596/50/1/021` (2006)
Abstract: Strangeness flavor yield s and the entropy yield S are the observables of the deconfined quark-gluon state of matter which can be studied in the entire available experimental energy range at AGS, SPS, RHIC, and, in near future, at the LHC energy range. We present here a comprehensive analysis of strange, soft hadron production as function of energy and reaction volume. We discuss the physical properties of the final state and argue how evidence about the primordial QGP emerges.
Conference Title: 5th International Conference on Physics and Astrophysics of Quark Gluon Plasma Conference Date: FEB 08-12, 2005 Conference Location: Saha Inst Nucl Phys, Salt Lake City, UT

41. **By:** Torrieri, G; Jeon, SY; Rafelski, J Torrieri, Giorgio H-1776-2014 0000-0002-0611-766X Sumbera, Michal O-7497-2014 0000-0002-0639-7323
Title: Particle multiplicities and fluctuations in 200 GeVAu-Au collisions
MULTIPARTICLE DYNAMICS
AIP Conference Proceedings **828** pp. 55-61 (2006)
Abstract: We use the statistical hadronization model (SHM) to describe hadron multiplicity yields and fluctuations. We consider 200 GeV Au-Au collisions, and show that both event averaged yields of stable particles and resonances, and event-by-event fluctuation of the K17r ratio can be described within the SHM using the same set of thermal parameters, provided that the phase space occupancy parameter value is significantly above chemical equilibrium, and the freeze-out temperature is similar to 140 MeV. We present predictions that allow to test the consistency of our results.
Conference Title: 35th International Symposium on Multiparticle Dynamics/Workshop on Particle Correlations and Femtoscopy Conference Date: AUG 09-17, 2005 Conference Location: Kromeriz, Czech Republik

42. **By:** Torrieri, G; Jeon, S; Rafelski, J
Title: A statistical model analysis of yields and fluctuations in 200 GeV Au-Au collisions
NUKLEONIKA **51** pp. S99-S103 Supplement: 3 (2006)

Abstract: We show that the simultaneous measurement of yields and fluctuations is capable of falsifying and constraining the statistical hadronization model. We show how such a measurement can test for chemical non-equilibrium, and distinguish between a high temperature chemically equilibrated freeze-out from a supercooled freeze-out with an over-saturated phase space. We perform a fit, and show that both yields and fluctuations measured at RHIC 200 GeV can be accounted for within the second scenario, with both the light and strange quark phase space saturated significantly above detailed balance. We point to the simultaneous fit of the K/π fluctuation and the $K*/K-$ ratio as evidence that the effect of hadronic re-interactions after freeze-out is small.
Conference Title: Conference on Relativistic Heavy-Ion Physics Conference Date: 2005 Conference Location: Budapest, HUNGARY

43. **By:** Huang, H.Z.; Rafelski, J.
Title: Hadronization and quark probes of deconfinement at RHIC
AIP Conference Proceedings **756** pp. 210-27 (2005)
Abstract: We discuss experimental features of identified particle production from nucleus-nucleus collisions. These features reflect hadronization from a deconfined partonic matter whose particle formation scheme is distinctly different from fragmentation phenomenology in elementary collisions. Multi-parton dynamics, such as quark coalescences or recombinations, appear to be essential to explain the experimental measurements at the intermediate transverse momentum of 2-5 GeV/c. Constituent quarks seem to be the dominant degrees of freedom at hadronization. Heavy quark production should help quantify deconfined matter properties.
Conference Title: 6th Conference on Quark Confinement and the Hadron Spectrum Conference Date: 21-25 Sept. 2004 Conference Location: Villasimius, Italy

44. **By:** Torrieri, G; Rafelski, J
Title: Multiplicities and bulk thermodynamic quantities at root S(NN)=130 GeV with SHARE
FOCUS ON MULTIPLICITY: INT. WORKSHOP ON PARTICLE MULTIPLICITY IN RELATIVISTIC HEAVY ION COLLISIONS
Journal of Physics Conf. Ser. **5** pp. 246-254 `10.1088/1742-6596/5/1/023` (2005)
Abstract: We introduce the Statistical Hadronization with Resonances (SHARE) suite of programs and perform a study of particle multiplicities as well as bulk thermodynamic quantities for the RHIC Au-Au reactions at,root(s)NN = 130 GeV. We also show that the statistical hadronization model, with parameters fitted to match pion, proton and hyperon ratios, in turn correctly and consistently reproduces rapidity particle multiplicity.
Conference Title: International Workshop on Particle Multiplicity in Relativistic Heavy Ion Collisions Conference Date: JUN 17-19, 2004 Conference Location: Bari, Italy

45. **By:** Huang, HZ; Rafelski, J
Title: Hadronization and quark probes of deconfinement at RHIC
QUARK CONFINEMENT AND THE HADRON SPECTRUM VI
AIP Conference Proceedings **756** pp. 210-227 (2005)
Abstract: (1) We discuss experimental features of identified particle production from nucleus-nucleus collisions. These features reflect hadronization from a deconfined partonic matter whose particle formation scheme is distinctly different from fragmentation phenomenology in elementary collisions. Multi-parton dynamics, such as quark coalescences or recombinations. appear to be essential to explain the experimental measurements at the intermediate transverse momentum of 2-5 GeV/c. Constituent quarks seem to be the dominant degrees of freedom at hadronization. Heavy quark production should help quantify deconfined matter properties.
Conference Title: 6th Conference on Quark Confinement and the Hadron Spectrum Conference Date: SEP 21-25, 2004 Conference Location: Villasimius, Italy

46. **By:** Torrieri, G; Letessier, J; Rafelski, J; Steinke, S Torrieri, Giorgio H-1776-2014 0000-0002-0611-766X
Title: Statistical hadronization with resonances
ACTA PHYSICA POLONICA B **35** pp. 2911-2927 (2004)
Abstract: We introduce the equilibrium and non-equilibrium statistical hadronization picture of particle production in ultra-relativistic heavy ion collisions. We describe the related physical reaction scenarios, and show how these can lead to quark pair yield non-equilibrium. Using the SHARE1.2 program suite we quantitatively model particle yields and ratios for RHIC-130 run. We study how experimental particle ratios can differentiate between model scenarios, and discuss in depth the importance of hadronic resonances in understanding of hadron production processes.
Conference Title: 44th Cracow School of Theoretical Physics Conference Date: MAY 28-JUN 06, 2004 Conference Location: Zakopane, Poland

47. **By:** Rafelski, J.; Letessier, J.
Title: Strangeness excitation function in heavy ion collisions
AIP Conference Proceedings **739** pp. 216-23 (2004)
Abstract: We study as function of energy strangeness created in relativistic heavy ion collisions. We consider statistical hadronization with chemical freeze-out in both equilibrium and nonequilibrium. We present strangeness per baryon and per entropy in the energy range of SPS and RHIC. A baryon density independent evaluation of the kaon to pion ratio is presented.
Conference Title: 9th Hadron Physics and 7th Relativistic Aspects of Nuclear Physics (HADRON-RANP 2004): A Joint Meeting on QCD and QGP; Conference Location: Rio de Janeiro, Brazil

48. **By:** Sherman, T; Rafelski, J
Title: Generalization of Boltzmann equilibration dynamics
DECOHERENCE AND ENTROPY IN COMPLEX SYSTEMS
LECTURE NOTES IN PHYSICS **633** pp. 377-384 (2004)
Abstract: We propose a novel approach in the study of transport phenomena in dense systems or systems with long range interactions where multiple particle interactions must be taken into consideration. Within Boltzmann's kinetic formalism, we study the influence of other interacting particles in terms of a random distortion of energy and momentum conservation occurring when multi-particle interactions are considered as binary collisions. Energy and momentum conservation still holds exactly but not in each model binary collision. We show how this new system differs from the Boltzmann system and we note that our approach naturally explains the emergence of Tsallis-like equilibrium statistics in physically relevant systems in terms of the long since neglected physics of interacting and dense systems.
Conference Title: 1st International Workshop on Decoherence, Information, Complexity and Entropy Conference Location: Piombino, Italy

49. **By:** Rafelski, J; Letessier, J
Title: Strangeness excitation function in heavy ion collisions
IX HADRON PHYSICS AND VII RELATIVISTIC ASPECTS OF Nuclear Phys,
AIP CONFERENCE PROCEEDINGS **739** pp. 216-223 (2004)
Abstract: We study as function of energy strangeness created in relativistic heavy ion collisions. We consider statistical hadronization with chemical freeze-out in both equilibrium and nonequilibrium. We present strangeness per baryon and per entropy in the energy range of SPS and RHIC. A baryon density independent evaluation of the kaon to pion ratio is presented.
Conference Title: Joint Meeting on 9th Hadron Physics/7th Relativistic Aspects of Nuclear Physics Conference Date: MAR 28-APR 03, 2004 Conference Location: Rio de Janeiro, BRAZIL