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Theory Summary - International Conference on Matter at Extreme Conditions: Then and Now

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This is a summary of theory presentations at the "International conference on matter at extreme conditions: then and now" which was held at Bose Institute, Kolkata in January, 2014.

Key Words : Quark-Gluon Plasma; QCD Phase Diagram; Fluctuations; Dense Astrophysical Objects

Introduction

The conference covered essentially all topics of current interest in the area of strong interactions at extreme conditions, that is at high energies and high baryon densities. There were presentations on the experimental side, covering recent experimental results from various ongoing relativistic heavy-ion collision experiments, e.g. RHIC at BNL, and LHC at CERN. There were also presentations on the upcoming FAIR facility at Darmstadt. Here we provide a summary of the theory presentations at the conference. Theory presentations covered a very wide range of topics, starting with a comprehensive overview by Blaizot. Fig. 1 from Blaizot's talk summarizes the term *Then and Now* in the title of this conference, illustrating the long journey from AGS to LHC. The evidence for QGP has been mounting, with RHIC and LHC data virtually leaving no doubt that QGP has been created in the collisions of nuclei at ultra-relativistic energies at these facilities. Fig. 2 is the summary of the important stages of the nucleus-nucleus collision leading to the transient stage of QGP formation and its subsequent hadronization.

There were talks at the meeting covering various probes of this transient stage of quark-gluon plasma (QGP), on flow and hydrodynamics, heavy quark dynamics, properties of quarkonium, correlations and fluctuations, etc. Several talks provided updates on perturbative QCD calculations of various quantities of interest, such as parton distributions at small-x, photon production at finite baryon density, etc. Lattice QCD

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was discussed in several talks where recent developments on equation of state, and QCD phase diagram were discussed. Latest updates on the calculations of hadronic spectrum from lattice QCD were provided. Various aspects of QCD transitions were discussed, e.g. UA(1) symmetry breaking effects at high temperatures. There were several talks on nuclear astrophysics, with detailed discussions of compact star cores with exotic QCD phases at high baryon density some of which may be probed in various experiments, see Fig. 3 (from Senger's talk).

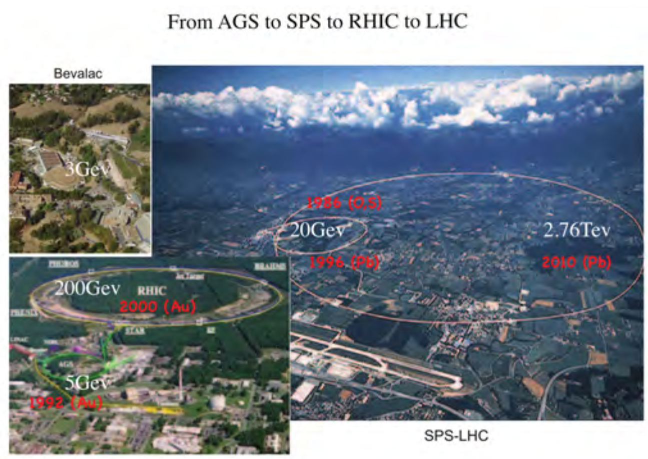

Fig. 1: Long journey in search for QGP: from AGS to LHC

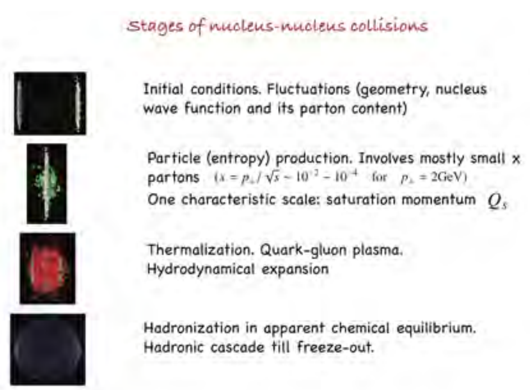

Fig. 2: Important stages in nucleus-nucleus collisions leading to formation of QGP and its subsequent hadronization

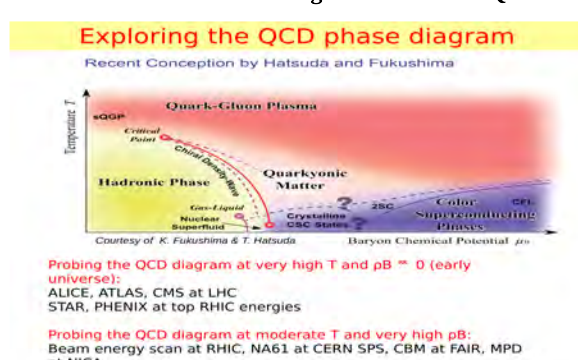

Fig. 3: QCD phase diagram

Flow and Hydrodynamics

Since the discovery of large elliptic flow at RHIC, the strongly coupled nature of QGP produced has been firmly established. Relativistic hydrodynamics calculations with proper account of viscosity have confronted data on elliptic flow and have convincingly shown that QGP has very low viscosity to entropy ratio, close to the AdS/CFT bound. Fig. 4 shows the constraint on η/S from data.

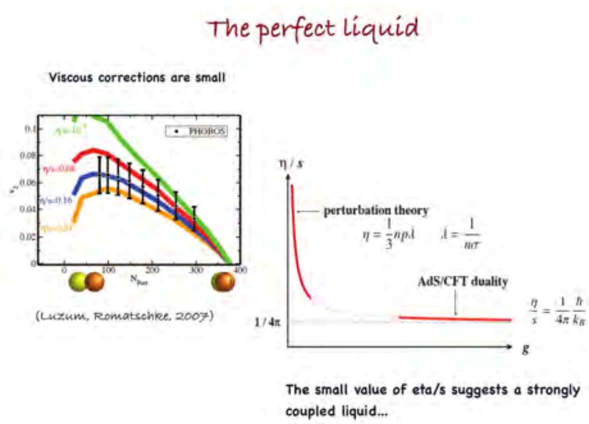

Fig. 4: Constraints on η/s from data on elliptic flow

As discussed by Blaizot, the strongly coupled character of the quark-gluon plasma (implied by the low viscosity) does not seem related in any obvious way to a large value of the coupling constant. The cooperation of many degrees of freedom, or strong classical fields may lead to such non-perturbative features. Important thing to recognize is that the quark-gluon plasma produced in these experiments is a multiscale system which appears to be neither weakly nor strongly coupled.

Importance of initial state fluctuations in nucleus-nucleus collisions for flow measurements has been recognized for some time, starting from its effects on the determination of the event plane for and its resultant effects on elliptic flow measurements, see Fig. 5. Recent discussions of flow fluctuations have reached a different level with the possibility that the evolution of these fluctuations may lead to a power spectrum similar to that for the cosmic microwave background radiation.

In confronting detailed flow data from experiments, hydrodynamics calculations have to be well controlled (Ollitrault, 2008). Jaisawal discussed relativistic third-order viscous hydrodynamics from kinetic theory. Expression for the viscous corrections to the distribution function were derived. The results are in better agreement with transport calculation compared to the Israel-Stewart theory. Mitra discussed medium effects on the transport coefficients of a pion gas by evaluating $\pi\pi$ scattering amplitude from effective field theory using ρ meson exchange. Shear and bulk viscosity coefficients along with thermal conductivity were evaluated with a temperature dependent chemical potential. It was seen that the temperature dependence of η with and without medium effects showed noticeable difference.

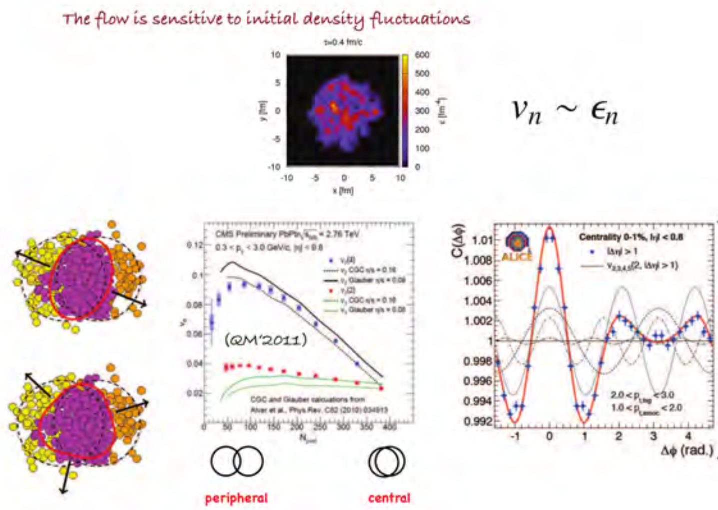

Fig. 5: Importance of initial fluctuations in determination of the event plane and hence the elliptic flow

Quarkonium

Suppression of J/ψ (and Upsilon) has been one of the most important signals for QGP formation (Kluberg and Satz, 2009). Produced during very early stages of collision, as the heavy quarkonium propagates through deconfined QGP medium, Debye screening leads to melting of the state depending on the QGP temperature. Indeed, anomalous suppression of J/ψ was observed at SPS. However, this trend did not continue at higher energies, see Fig. 6. Lack of expected suppression is understood in terms of regeneration resulting from large initial multiplicity of heavy quark. This makes it complicated to reach any systematic conclusions about J/ψ melting in the QGP phase. Nonetheless, the general picture holds true that a hot and dense QGP medium will lead to suppression of quarkonium states and this suppression will be stronger for the excited quarkonium states.

This pattern is clearly visible in the bottomonium states in Fig. 7 where higher states of Upsilon are seen to be strongly suppressed in Pb-Pb collisions. Upsilon states are expected to provide a cleaner signal for QGP due to absence of b-hadron feed down as well as less expected recombination compared to the the charm quark. A summary of sequential suppression of quarkonium states is seen in Fig. 8 (from Shukla's talk).

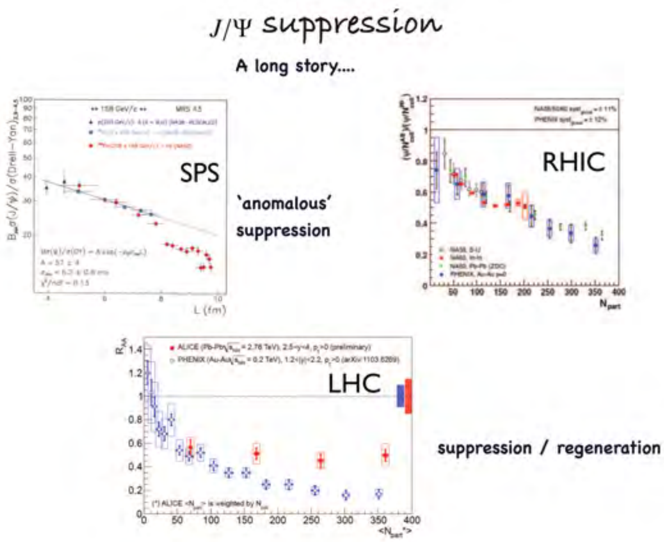

Fig. 6: Anomalous suppression of J/ψ at SPS, regeneration at higher energy

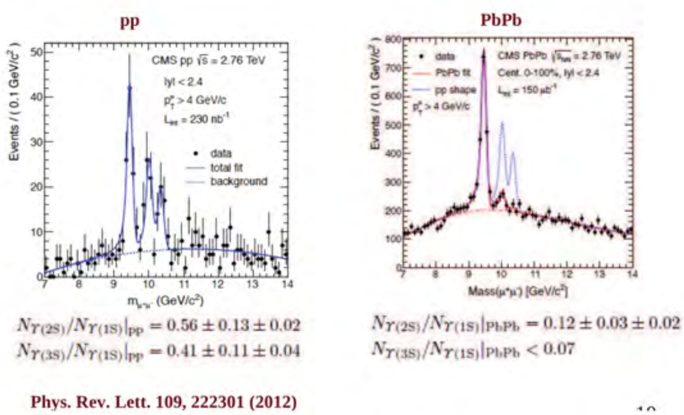

Fig. 7: Suppression of excited states of upsilon in Pb-Pb collisions

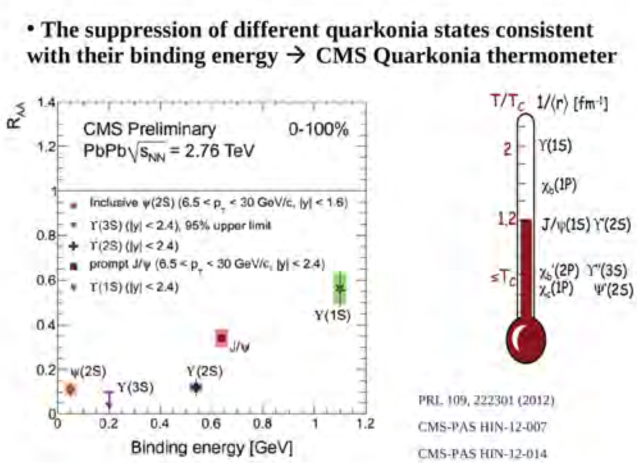

Fig. 8: Sequential suppression of quarkonium states

Thakur discussed dissociation of quarkonium in a complex potential with the imaginary part of the potential providing a contribution to the width of quarkonium bound states which determines their dissociation temperatures. It was argued that anisotropic description is necessary for the descriptions of QGP due to differences between longitudinal and transverse dynamics with the partonic distribution becoming anisotropic. It was shown that quarkonium binding becomes stronger and increases with the increase of anisotropy and the Debye mass decreases in the anisotropic medium.

Heavy Quark Dynamics

There were several talks discussing calculations of energy loss of heavy quarks in the QGP medium. Heavy quarks are produced primarily during early stages of the collision and are important probes of QGP. While traversing through QGP, they lose energy and momentum as they scatter with light quarks and gluons, but do not change their direction much. Jamil discussed nuclear suppression factor with consideration of both radiative and collision energy loss along with longitudinal expansion of the medium. Sarkar discussed effects of flow on heavy quark damping rate in hot QCD plasma including viscous effects of the plasma. Effect of viscosity enters into the damping rate calculation through the phase-space distribution functions. Gluon Radiation off Heavy Flavor Jets was discussed by Bhattacharyya in an improved approximation scheme, essentially keeping only the approximations of soft jet (energy of jet much larger than the energy of emitted gluon) and the approximation of no recoil of jet due to scattering. The scattering of heavy quark by the medium was discussed by Greco addressing the difference of Boltzman vs. Langevin dynamics. Early expectations (pre-RHIC) of heavy quark not being much affected by flow have not turned out to be true, as charm seems to flow like light quarks. Thus heavy Quarks appear to be strongly dragged by interaction with light quarks. Fig. 9 shows the difference in the evolution of momentum distribution for the charm quark in the Langevin and and Boltzman dynamics. It is seen that the kinematics of collisions (Boltzmann dynamics) shifts the peak to low p. Difference from the heavier bottom quark can be seen from Fig. 10 where this shift is absent and the difference between the two types of dynamics is not significant.

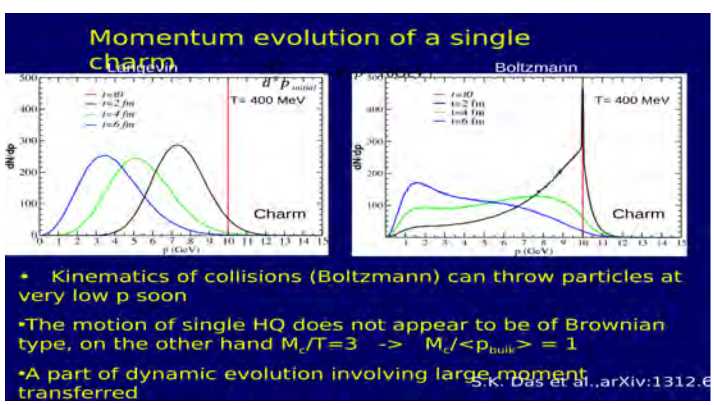

Fig. 9: Difference in the evolution of momentum distribution for the charm quark in the Langevin and Boltzman dynamics

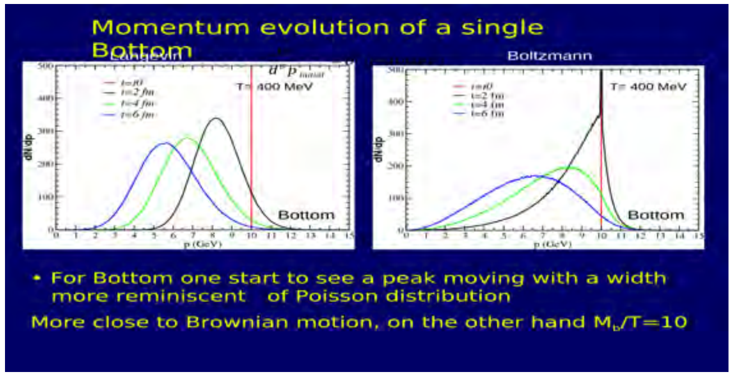

Fig. 10: Same as Fig. 9, for bottom quark

Jet quenching was discussed in several talks. Blaizot discussed di-jet asymmetry by associating the missing energy being associated with turbulent in-medium QCD cascade (similar to the Richardson cascade in fluids) where energy flows from large to low frequencies and large angles.

Correlation Functions and Fluctuations

Purneau brought out the importance of correlation functions and fluctuations. Some time ago there were discussions of disoriented chiral condensates with searches for large fluctuations in neutral to charge particle ratio. Fluctuations and correlations have been at the center stage in search for QGP phase. Search for critical fluctuations corresponding to the critical end point in the QCD phase diagram has been the driving force for the RHIC beam energy scan program (see, Fig. 3). Fluctuations of particle ratios (especially k to π ratio) and charges have been discussed for some time as signals for a QGP phase. Three particle correlations show the evidence of a Mach cone, see Fig. 11. There has been a paradigm shift regarding importance of fluctuations.

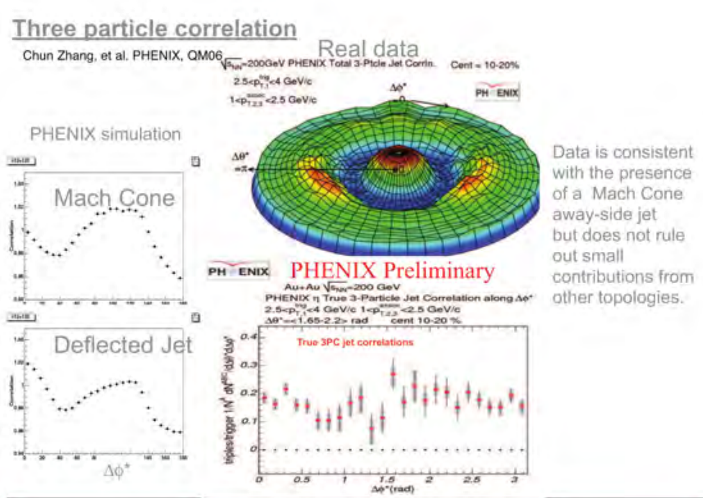

Fig. 11: Three particle correlations and Mach cone

Initial state fluctuations lead to spatial anisotropies which get transferred to momentum anisotropies, hence flow fluctuations, via hydrodynamical evolution. Long range rapidity correlations in the color glass condensate model have been discussed in the literature in connection with the near-side Ridge extending over large rapidity regions.

Perturbative QCD Calculations

The study of parton distributions at small-x is very important, especially in view of the saturation of the parton density at small-x. Precise knowledge of the gluon distribution at small-x, where gluons are expected to be dominant, is essential for reliable predictions of important high energy processes at RHIC and LHC, e.g. for the color glass condensate formalism. Devee discussed an approximate approach for the solution of gluon distribution function with non-linear equations due to gluons recombination. Main features of the results are saturation of gluon distribution at very small-x and prediction of a critical line separating the perturbative regime from the saturation regime.

Three Loop hard thermal loop thermodynamics at finite T and μ was discussed by Haque. Calculations of fluctuations of conserved charges, second order, fourth order baryon fluctuations, speed of sound, trace anomaly were discussed. Chakroborty discussed perturbative QCD at finite temperature and baryon density. Perturbative calculations of the equation of state and dilepton production and photons production at high baryon density, with varying chemical potential were discussed. A Sequential Chain Model for direct photon emission with intermediate ρ and π mesons was discussed by Guptaroy. Somnath De discussed calculations of jet-medium back-scattering photons at LHC which can provide a probe of thermalized matter.

Lattice QCD

Lattice QCD calculations were discussed in two talks. Mathur presented state of the art calculations of hadron spectrum as well as nuclear forces. Results on exotic hadrons were also presented. Quark model does not account for these exotics such as, states with excited gluon: hybrid mesons (meson + excited glue), hybrid baryons (baryon + excited glue), glueballs (constituent glue), multi-quark states: tetraquark, pentaquark and higher number of quark states. Lack of understanding of these states makes experimental identification difficult. Fig. 12 give lattice results for the exotic glueball states.

Latest lattice results on the QCD equation of state at finite chemical potential was discussed by Gupta. The technique of search for critical point using Taylor expansion method was discussed. Results are strongly indicative of identification of critical regime with increasing computer time required in calculations signaling critical slowing down. Estimates of pressure with suitable account of the critical regime were discussed.

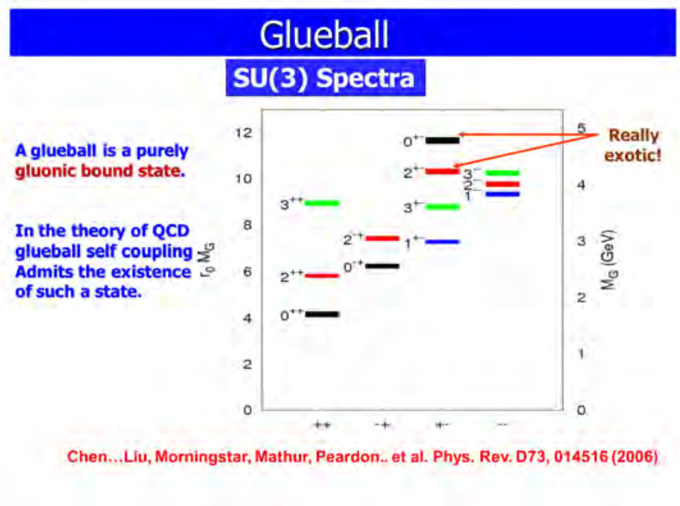

Fig. 12: Glueball states from lattice

Deconfinement Transition, Chiral Symmetry Restoration

Clustering of color sources and percolation was discussed by Srivastava as a model for deconfinement. Multiple color strings stretching between colliding nuclei were taken to form localized color disks in the transverse plane and percolation techniques for cluster formation were used to estimate the deconfinement stage of color charges. The model has similarities with color glass condensate model. Here also, color strings lead to long range rapidity correlations and ridge structure. Jayaprakash discussed thermodynamics of non-ideal quark gluon plasma using Mayer's cluster expansion method. The equation of state was studied using Cornell potential. The number density of quark cluster system at which a non-ideal quark-antiquark plasma condense into cluster of two and three (heavy) quarks, that is, into a fluid of mesons, was calculated.

Lee discussed chiral symmetry restoration from a different angle by focusing on the UA(1) effect and the η' mass. Question addressed was whether UA(1) symmetry breaking effects remain at high T. Relation between Quark condensate and the η' mass was discussed.

Effective models incorporating QCD symmetries have given important insights for the behavior of transitions at finite baryon density where perturbative methods as well as lattice calculations have had limited success. Tiwari discussed calculations of critical end-point and critical regime in the Polyakov loop extended quark-meson (PQM) effective model. Incorporating the fermionic vacuum term increased the critical value of the chemical potential, with the critical regime spanning along the first order transition line. Multiple freezeout scenarios are natural to expect in heavy-ion collision experiments. Chatterjee discussed the estimates of temperatures and volumes for the situation when strange and non-strange hadrons are assumed to freezeout at different stages.

Nuclear Astrophysics

Cores of neutron stars provide a natural laboratory where exotic phases of QCD at high baryon density may be realized. There have been many discussions about various phases such as CFL phase, color superconductor phase etc. (Alford *et al.*, 1988, 2008). Fig. 13 from Hatsuda's talk shows the symmetry structure of some of the phases in the QCD phase diagram.

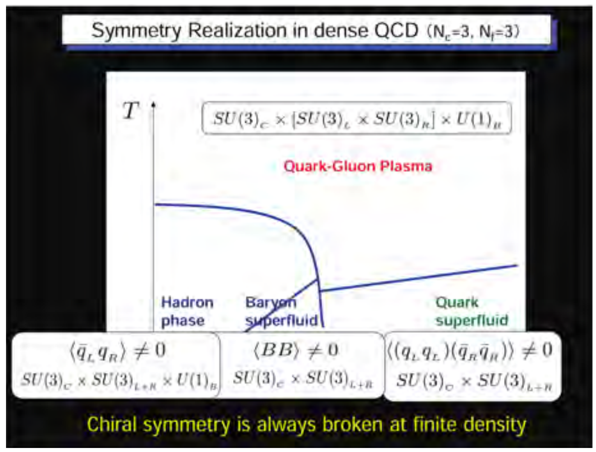

Fig. 13: Symmetry structure of various QCD phases

Allowed equations of state for the neutron star cores severally constrain mass-radius relationship for the star. As discussed by Hatsuda, this can be used to constrain the equation of state, and in turn the effective models. There are recent observations of 2 solar mass neutron star. It is argued that such heavy neutron star requires a core with stiff quark-matter equation of state. A model is proposed where 2 solar mass neutron star can be incorporated by requiring that crossover transition should occur at ρ = (2-4) times the normal nuclear density ρ_0. NJL model with vector mean field with a cross-over regime can incorporate such heavy neutron stars, see Fig. 14.

Panda discussed hybrid stars (neutron stars with quark cores) in high magnetic field which modifies the properties of nuclear and deconfined quark matter of hybrid star. Oscillations of star were discussed in the presence of magnetic field. It was shown that magnetic field increases period of oscillation. Adhya discussed calculations of the pulsar kick velocity including the non-fermi liquid corrections to the specific heat of the degenerate quark matter core. The effects of the external magnetic field were included into the specific heat of the degenerate quark matter for the calculation of the pulsar kick velocity.

An alternate scenario for the formation of quark nuggets in the universe was discussed by A. Atreya. It was argued that baryon anti-baryon segregation can result in the early universe due to spontaneous CP violating Z(3) walls, which can lead to quark nugget formation irrespective of the order of QCD phase transition.

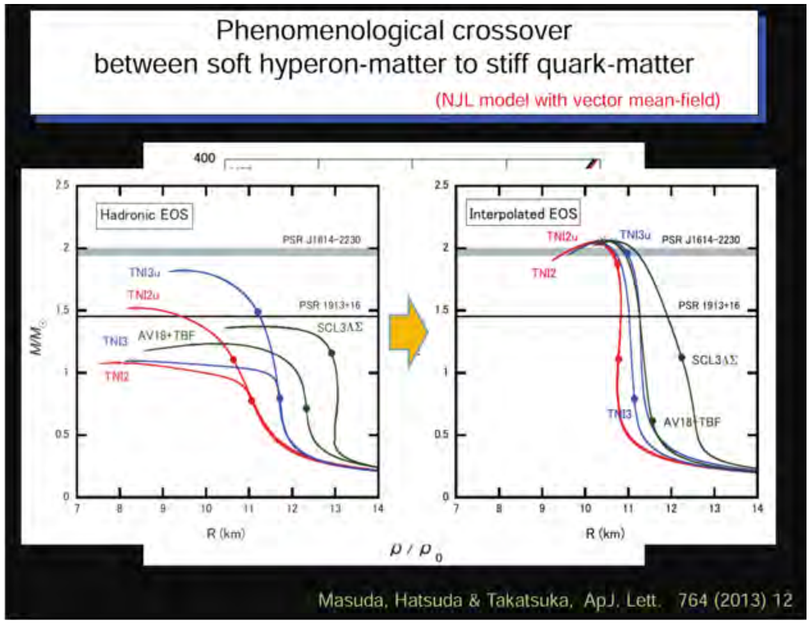

Fig. 14: Mass vs radius relationship for neutron star. Note that NJL model with vector mean field and a cross-over regime can incorporate 2 solar mass neutron star

Ananda brought in the discussion of acoustic black holes which have been discussed as analogue models for black hole physics. The talk discussed matter flow in black hole, focusing on the realizability of relativistic acoustic geometry for matter flow onto a Schwarzschild black hole. It was speculated that similar analogue models may be constructed for Big-Bang cosmology as well as for relativistic collisions of elementary particles and heavy ions. Chakraborti discussed physics of gamma-ray bursts (GRBs). In a cartoon map for explosions, with ejected mass vs. apparent velocity, the observed events were classified in Nova, Supernova, and GRB. There was an apparent large gap between these prompting for missing candidates. Observations of some new candidates were reported which seem to bridge this gap.

At the end of this summary we conclude that the outlook is very exciting. Especially very rich physics is coming up with FAIR. From LHC to FAIR, the broad spectrum of QCD matter in extreme conditions will be probed. New challenges are to pursue the old signals, but also there seems ample scope for looking at qualitatively new phenomena. (For example, UA(1) symmetry breaking effects at high temperatures focuses on a very different aspects of the chiral transition. High baryon density behavior of this may lead to new insights). Tremendous scope also exists for probing astrophysics in laboratory conditions. Evolution of initial fluctuations at high temperatures have been studied to some extent. High baryon density behavior of fluctuations (with FAIR) will lead to insights of more detailed picture of the cores of dense astrophysical objects. Gravity of stars cannot be created in Lab, but the compression created in (relatively low energy) collisions may simulate effects of gravity to some extent.

Acknowledgments

I am very grateful to the organizers for a great conference. Thanks to all the participants for extremely stimulating discussions. Pictures for this article have been taken from various presentations in this conference. This talk is dedicated to the memory of Abhee K. Dutt-Mazumder.

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