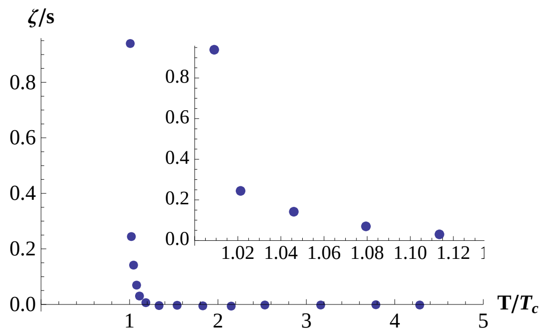

FIG. 3: The bulk viscosity over entropy density ratio as a function of scaled temperature T/T_c. The figure is taken from Ref.[29].

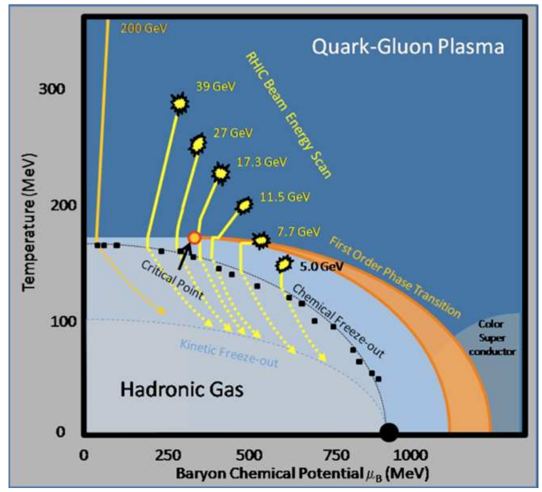

FIG. 4: Searching for the critical end point at RHIC.

The zero bulk viscosity is for a conformal equation of state and also a reasonable approximation for the weakly interacting gas of quarks and gluons. However, recent lattice QCD results show that the bulk viscosity over entropy density ratio ζ/s rises dramatically up to the order of 1.0 near the critical temperature T_c [29–31]. (There are still some subtle issues to determine the bulk viscosity of QCD through calculating the correlations of the energy-momentum tensor on the lattice, see more detailed discussion in Ref. [32].) The sharp peak of bulk viscosity at T_c has also been observed in the linear sigma model [33] and in the real scalar model [34]. The increasing tendency of ζ/s has been shown in a massless pion gas [35] and in the NJL model below T_c [36]. The large bulk viscosity near phase transition is related to the non-conformal equation of state [37, 38], and the correlation between the bulk viscosity and the conformal anomaly has been investigated in Ref. [39].

The sharp rise of the bulk viscosity will lead to the breakdown of the hydrodynamic approximation around the critical temperature. The effect of large bulk viscosity on hadronization and freeze-out processes of QGP created at heavy ion collisions has been discussed in Refs. [40–43]. The authors of Ref. [40] pointed out the possibility that a sharp rise of bulk viscosity near phase transition induces an instability in the hydrodynamic flow of the plasma, and this mode will blow up and tear the system into droplets. Another scenario is pointed out in Ref. [29, 42] that the large bulk viscosity near phase transition might induce "soft statistical hadronization", i.e. the expansion of QCD matter close to the phase transition is accompanied by the production of many soft partons, which may be manifested through both a decrease of the average transverse momentum of the resulting particles and an increase in the total particle multiplicity.

B. Searching for the critical end point

At small baryon chemical potential μ, for QCD with two massless quarks, the spontaneously broken chiral symmetry is restored at finite temperature, and it is shown from lattice QCD [44] and effective QCD models [45] that this phase transition is of second order and belongs to the universality class of $O(4)$ spin model in three dimensions [46]. For real QCD with two quarks of small mass, the second order phase transition becomes a smooth crossover at finite temperature. At finite baryon chemical potential, there are still no reliable results from lattice QCD due to the severe fermion sign problem. However QCD effective models [45] suggest that the chiral phase transition at finite μ is of first order. It is expected that there exists a critical end point (CEP) in the $T-\mu$ QCD phase diagram. The CEP is defined as the end point of the first order phase transition, and belongs to the $Z(2)$ Ising universality class [47]. The signature of CEP has been suggested in Refs. [48]. The precise location of the CEP is still unknown. In the future plan, RHIC is going to lower the energy and trying to locate the CEP as shown in Fig. 4.

Recently, the authors of Ref. [49, 50] suggested using the shear viscosity over entropy density ratio η/s to locate the CEP by observing the ratio of η/s behaves differently in systems of water, helium and nitrogen in first-, second-order phase transitions, see the system of water for example in Fig. 5. The ratio of η/s shows a cusp at T_c for second order phase transition, and a shallow valley near T_c for cross-over, and shows a jump at T_c for first-order phase transition.

Due to the complexity of QCD in the regime of strong coupling, results on hot quark matter from lattice calculation and hydrodynamic simulation are still lack of analytic understanding. In recent years, the anti-de Sitter/conformal field theory (AdS/CFT) correspondence has generated enormous interest in using thermal $\mathcal{N}=4$ super-Yang-Mills theory (SYM) to understand sQGP. The shear viscosity to entropy density ratio η/s is as small as $1/4\pi$ in the strongly coupled SYM plasma [27]. However, a conspicuous shortcoming of this approach is the conformality of SYM: the square of the speed of sound