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Speed of sound in quark matter with different imbalances

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It has been shown in the framework of effective models that QCD phae diagram as in thee color cas as well as in two color one possesses dualities.
I means that various phenomena are dual with respect to each other. Then dualities were shown in a more and more general setings. And then finally dualities has been shown from first principles,
three dualities as in two color QCD and one in three color one. The fact that dualities have been shown from first principles, i. e. in QCD itself, expanded their possible application much further.
In the talk I discuss two interesting applications. (i) studies of speed of sound at various chemical potentials (ii) studies of inhomogeneous phases, including rather unexpected ones.

The talk is partly based on

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In detail about (i) and (ii):
(i) The equation of state of dense hadronic matter is not known yet, so the speed of sound at large baryon densities. The speed of sound at zero baryon density and non-zero temperature has been obtained in lattice QCD simulations. And the behavior is the following, it rises with increase of temperature but up to asymptotic value of 1/3, but never exceeds that value. It is called conformal bound. At non-zero baryon density, in the region of phase diagram interesting in the context of neutron stars lattice simulations are plagued by the sign problem and is not now possible. There was idea that maybe speed of sound should not exceed conformal bound at non-zero baryon density as well. Though observational data favor the scenario that speed of sound breaks the conformal limit at muB, it is still an open question.

Recently in [B.B.Brandt, F.Cuteriand G.Endrodi, JHEP 07, 055 (2023); R. Abbott et al. [NPLQCD], Phys. Rev. D 108, no.11, 114506 (2023)] it has been shown from first principles (lattice QCD) that the conformal bound is broken in quark matter with isospin density (isospin asymmetric quark matter).
Then using duality mapping it is possible to get sound speed in quark matter with chiral imbalance mu_{I5} and show that conformal bound is also broken in this case.
And having shown duality from first principles it is also first principle robust result.
Then it was also found that there are additional weaker dual symmetries in phase diagram shown only in the framework of effective models. If one uses these dualities, though it would not be first principle results, one can show that conformal bound is also broken in quark matter with chiral imbalance mu5.
Then it was shown in two color QCD lattice calculations [E. Itou and K. Iida, PoS LATTICE2023, 111 (2024); PTEP 2022 (2022) no.11, 111B01] that conformal bound is exceeded in the case of two colors at non-zero baryon density. Then using first principle dualities one can show that conformal bound is broken at (i) isospin chemical potential (ii) chiral chemical potential mu_{I5}. Moreover, using additional dualities found in effective models one can show also that it does at (iii) chiral chemical potential mu5. So it is shown to be broken at all chemical potentials in two color case.

So one can see from all these results on two color and three color QCD that it is not very peculiar and uncommon to break conformal bound at non-zero chemical potentials.

(ii) Inhomogeneous phases has long history on research but it is still open question if there is inhomogeneous phases in QCD at finite baryon chemical potential. Some inhomogeneous phases have been predicted in various approaches. Dualities gives us opportunity to predict plethora of new inhomogeneous phases. The most interesting phase is the one at zero baryon chemical potential, as a rule one is used to the fact that inhomogeneous phases can be present at nno-zeroi mu_B and it is a first example of inhomogeneus phase at zero mu_B (some other chemical potentials are non-zero)

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