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物理的なクォーク質量におけるエネルギー運動量テンソルの研究
Study of Energy-Momentum Tensor at Physical Quark Mass

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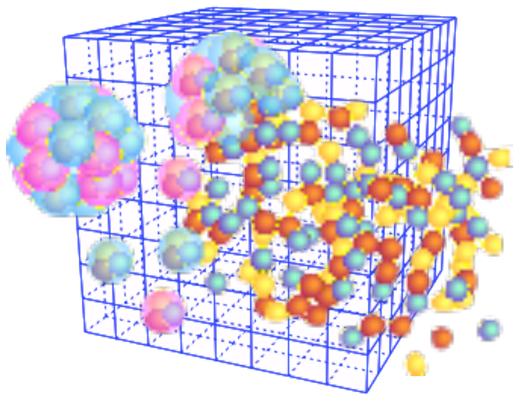
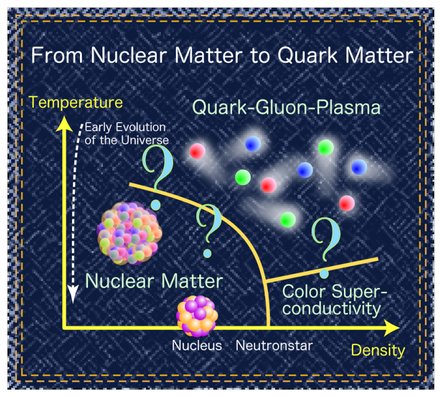


We study quark matter at high temperatures to explore early Universe, by performing numerical simulation of 2+1 flavor QCD on the lattice. We apply gradient-flow method to evaluate Energy-Momentum Tensor from which various thermodynamic properties are extracted.



1. Gradient Flow

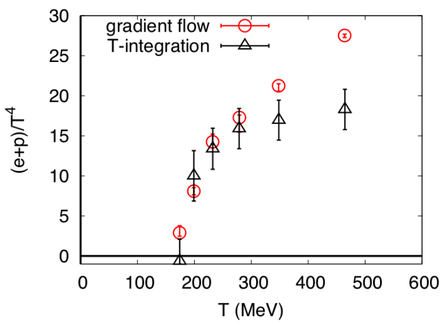
GF is a flow of fields in term of a fictitious time *t* driven by the gradient of the action [Narayanan-Neuburger 2006, Lüscher 2009-]. Using finiteness of flowed operators, Suzuki proposed a general method to compute renormalized quantities on the lattice based on GF, irrespective of symmetry violations due to the lattice regularization [H.Suzuki, PTEP 083B03 (2013)]. We are applying the method to evaluate EMT and chiral observables in QCD at high temperatures.

2. QCD with heavy u, d and physical s quark

As the first systematic application of the method to QCD with dynamical quarks, we first studied the case that u and d quarks are heavier than their physical masses [Taniguchi et al., Phys. Rev. D 95, 054502 (2017); ibid. 96, 014509 (2017)].

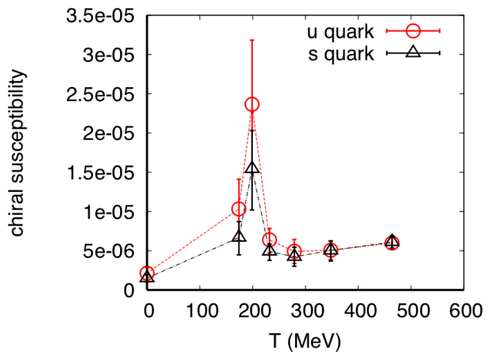
Simulation: Fixed-scale approach at a≈0.07fm, T≈174-697MeV (Nt=4,6,-16), non-perturbatively O(a)=improved Wilson quarks, Iwasaki gauge

2.1 Equation of State (diagonal elements of EMT)



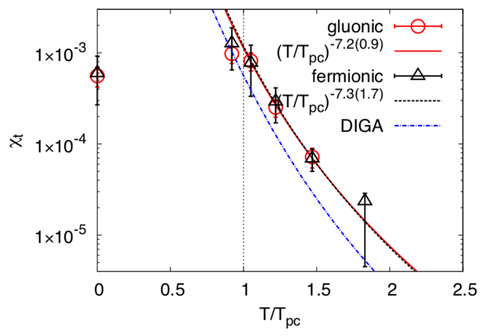
- consistent with conventional T-integration method
- disagreement at T≥350MeV due to O((aT)^2=1/Nt^2) lattice artifacts at Nt<8

2.2 Chiral Susceptibility (disconnected)



- clear peak at Tpc≈190MeV expected from other obs., in spite of explicit chiral violation due to the Wilson quark action

2.3 Topological Susceptibility



- gluonic and fermionic definitions agree with each other, for the 1st time already on finite lattices
- T-dep. consistent with DIGA

Consistency among different methods suggest a≈0.07fm is small enough.

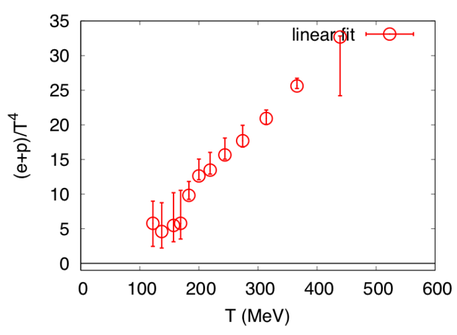
These results suggest that GF is quite powerful.

3. QCD with physical u, d, s quarks (preliminary)

We now extend the study to 2+1 flavor QCD with all quarks with physical mass [preliminary reports: Kanaya et al., EPJ Conf. 175, 07023 (2018)].

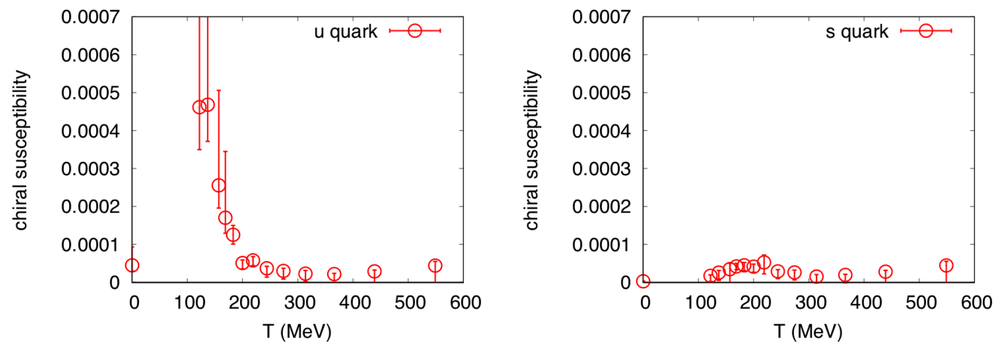
Simulation: Fixed-scale approach at a≈0.09fm, T=122-549MeV (Nt=4,5,-,18)

3.1 Equation of State



- similar to the case of heavy u,d quarks, but much lower Tpc suggested.
- expect large O((aT)^2) lattice artifacts at T>270MeV

3.2 Chiral Susceptibility (disconnected)



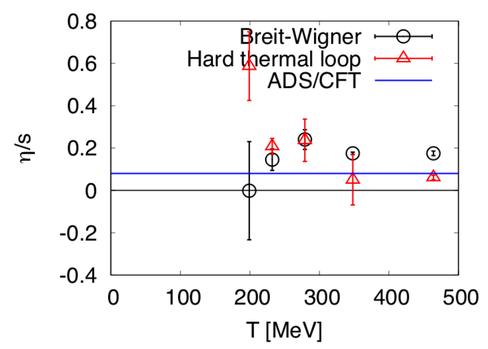
- light u,d quarks show sharper peak, as expected
- suggest Tpc < 157MeV

Need more statistics, in particular at low T's.

4. Other observables (preliminary / on-going)

Because EMT itself is available, we may try to extract many other thermodynamic observables. Transport coefficients may be computed from two-pint correlation functions of EMT.

4.1 Shear viscosity as a function of T



- small and T-indep. eta/s
- consistent with experiment ≈ 0.12
- and also ADS/CFT min. value 1/4π ≈ 0.08

Many other observables are also under study.