QCD Equilibrium and Dynamical Properties from Holographic Black Holes

based on: Phys.Rev.D104.3(2021) & arXiv:2203.00139 [nucl-th].

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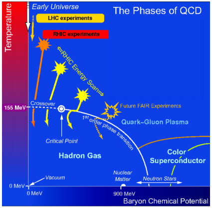
The QCD phase diagram and the Holographic Model

Motivation: Explore the QCD phase diagram to discover whether a hot and dense system of quarks and gluons displays critical phenomena at finite density.



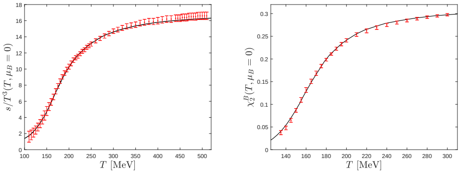
- Lattice QCD simulations provide the equation of state (EoS) for strongly interacting matter at $\mu_B = 0$, but calculations at finite density are limited by the sign problem.
- It is possible to extrapolate the EoS to finite μ_B via Taylor expansion, but it only works for small μ_B.
- Therefore, a large region in the phase diagram remains unknown, and we need a model to explore the baryon rich regime and guide the experimental search for the critical point.
- **We need an effective theory for hot deconfined matter that exhibits nearly perfect fluidity, and agrees with the lattice QCD Equation of state.**

Non-conformal General Relativistic action in 5 dimensions,

O DeWolfe et al. Phys.Rev.D83 2011.
R. Critelli et al., Phys.Rev.D96 2017.
J.G. et al. Phys.Rev.D104.3 2021.

$$S = \frac{1}{2\kappa_5^2}\int_{M_5} d^5x\sqrt{-g}\left[R - \frac{(\partial_\mu\phi)^2}{2} - \underbrace{V(\phi)}_{\text{nonconformal}} - \underbrace{\frac{f(\phi)F_{\mu\nu}^2}{4}}_{\mu_B\neq 0}\right]$$

The free functions $V(\phi)$ and $f(\phi)$ are fixed by matching the solutions from the black hole to the lattice equation of state at $\mu_B = 0$. This holographic model can generate a QCD-like theory at finite μ_B.

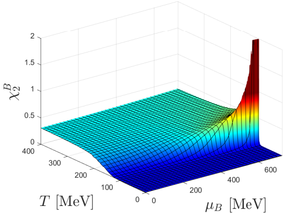


Entropy density s (left panel), and second order baryon susceptibility χ_2^B (right panel) at $\mu_B = 0$. Red points are the lattice data (S. Borsanyi et al. Phys.Lett.B 730 2014) and the solid black curve is the holographic result (J.G. et al. Phys.Rev.D104.3 2021.).

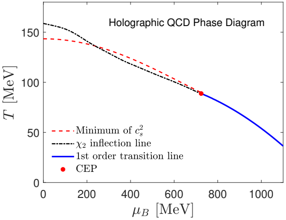
The second order baryon susceptibility is defined as:

$$\chi_2^B = \frac{\partial^2(P/T^4)}{\partial(\mu_B/T)^2} = \frac{\partial(\rho_B/T^3)}{\partial(\mu_B/T)}$$

J.G. et al. Phys.Rev.D104.3 2021.

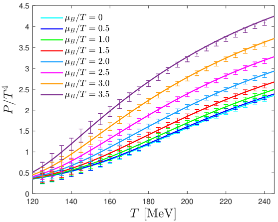


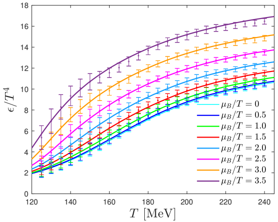
The critical end point (CEP) is located at $T^{CEP} = 89$ MeV and $\mu_B^{CEP} = 724$ MeV, which corresponds to the divergence of the second order baryon susceptibility χ_2^B.



The crossover region in the holographic phase diagram is characterized by the inflection point of χ_2^B and the minimum of the square of the speed of sound, c_s^2.

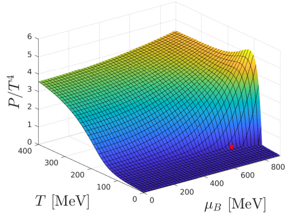
The holographic QCD EoS at finite T and μ_B is in quantitative agreement with the state-of-the-art lattice QCD results (S. Borsanyi et al. Phys.Rev.Lett.126,232001 2021.), which suggests that our prediction for the behavior of the QCD phase transition at nonzero baryon chemical potentials is robust.

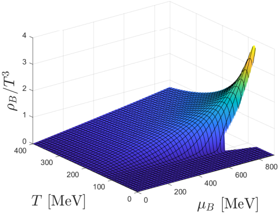




Full Equation of State and Viscosities

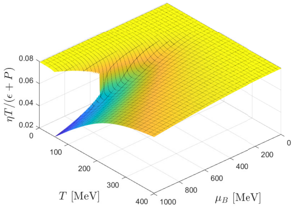
The discontinuity in the baryon density, ρ_B, and other state variables, such as the energy density ϵ, the entropy density s and the susceptibility χ_2^B, corresponds to the line of first order phase transition. The red point on the pressure P marks the location of the CEP.

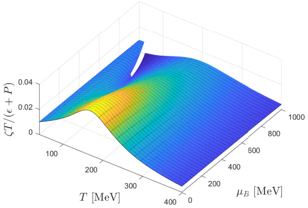




J.G. et al. Phys.Rev.D104.3 2021.

The shear viscosity η/s measures the medium's resistance to sheared flow in the presence of a velocity gradient of the fluid, and the bulk viscosity ζ/s measures the medium's resistance to deformations associated to a compression or to an expansion of the fluid.
Both are computed in the vicinity of the CEP and also, for the first time, crossing a line of first order phase transition at large values of μ_B.





J.G. et al. arXiv:2203.00139 [nucl-th].

Energy Loss and out-of-equilibrium phase diagram

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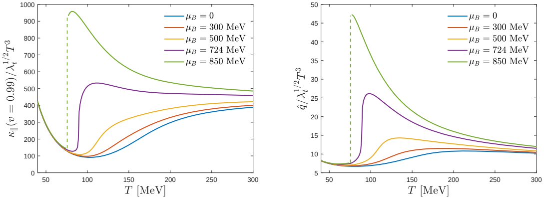
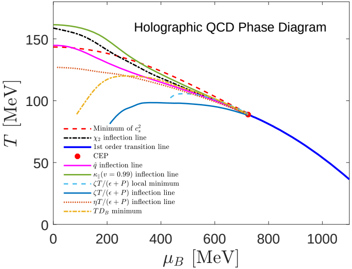


Parallel Langevin diffusion coefficient $\kappa_{\parallel}$ at $v = 0.99$(left panel), and jet quenching parameter $\hat{q}$ (right panel).

For a crossover transition it is possible to have a wide range of pseudo-critical temperatures that depend on what observable one is studying. At the critical point all pseudo-critical temperatures converge.



Conclusions

- The family of five-dimensional holographic black holes, fixed to mimic the lattice EoS at $\mu_B = 0$, is in quantitative agreement with the most recent lattice results at finite μ_B.
- This holographic model predicts that the crossover evolves into a first order phase transition line that ends at a CEP, where the EoS and the transport coefficients were computed.

Acknowledgements

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