Starting SQM 2024: Theory state-of-the-art

Jacquelyn Noronha-Hostler[1],*

[1]Illinois Center for Advanced Studies of the Universe, Department of Physics, University of Illinois at Urbana-Champaign, 1110 W. Green St., Urbana IL 61801-3080, USA

Abstract. I discuss the theoretical developments related to Strangeness in Quark Matter (SQM) leading up to the SQM2024 conference. These advances include mapping out the Quantum Chromodynamics phase diagram; puzzles that exist in hadron physics from light to heavy particles; and relativistic hydrodynamics with the inclusion of spin and magnetic fields.

1 Introduction

I will summarize recent advances in high-energy nuclear theory, pressing questions within the field, and make connections to astrophysics, gravity, nuclear structure, and cold atoms.

2 QCD Phase Diagram

The QCD phase diagram cannot be systematically studied in a single experiment or astronomical observation, rather it requires input from heavy-ion collisions [HIC] (high temperatures T, low to intermediate net baryon density n_B, range of electric charge to baryon number $Y_Q = Z/A = n_Q/n_B = [0.38, 0.5]$), cold neutron stars [NS] ($T = 0$, large n_B, $Y_Q \lesssim 0.1$), binary [NS] mergers ($T > 0$, large n_B, $Y_Q \sim [0.01, 0.2]$), and low energy nuclear physics ($T \sim 0$, nuclear saturation density $n_B = n_{sat}$, $Y_Q \sim 0.5$). This range of measurements leave gaps in the QCD phase diagram that may be difficult to interpret. Theoretical input is important e.g. causality and stability constraints $0 \le c_s^2 \le 1$, first principle lattice or perturbative QCD (pQCD) calculations, and well-defined effective field theories (EFT) such as chiral EFT. Constraints are summarized in [1]. *Key questions:* How to interpret new Beam Energy Scan II data? How does QCD matter move at $n_B \neq 0$? How does [HIC]/QCD constrain the [NS] equation of state (EOS)? Can out-of-equilibrium effects shed light on the core of [NS]?

[HIC]/critical point The (potential) QCD critical point [2] separates the boundary between quarks/gluons and hadrons. While current first principle calculations cannot determine its existence/location [3], recent calculations in other theoretical frameworks [4–9] indicate a critical point at $\mu_B/T \sim 4-8$. Preliminary measurements exist for net-proton fluctuations κ_4/κ_1 across $\sqrt{s_{NN}}$ [10] appearing flat. Factorial cumulants show qualitative features predicted from critical point models [11]. Viscous effects may smear out or alter critical fluctuations [12] and the critical region can either cause critical lensing or minimize the effect [12–15]. Theorists are developing frameworks (initial state, fluid dynamics, hadron interactions) that dynamically study $n_B \neq 0$ (and strangeness, $n_S \neq 0$, and electric charge, $n_Q \neq 0$).

---

[*] e-mail: jnorhos@illinois.edu

The Taylor series EOS from lattice is only valid up to $\mu_B/T \sim [2-3]$ [3], which does not cover the entire EOS needed for Beam Energy Scan II. An alternative expansion was developed that improves the reach in μ_B/T [16] and is coupled to 3D Ising [17]. In hydro simulations, every fluid cell must have a valid EOS. In [18] a solution to a limited EOS was developed in 4-dimensions (T, μ_B, μ_S, μ_Q) to smoothly map to a conformal EOS for out-of-bound fluid cells. The MUSES collaboration provides open-source EOS across the phase diagram [19].

Initial conditions include baryon stopping through strings [20], a 3-fluid model [21], color glass condensate [22, 23], or a hadron transport [24]. It is also possible to study BSQ (baron, strangeness, electric charge) fluctuations where net-$n_B = 0$ through gluon splittings into $q\bar{q}$ pairs [25]. These initial states may be far-from-equilibrium and require a pre-equilibrium state incorporating BSQ charges [26, 27]. They are fed into relativistic viscous BSQ hydrodynamic codes, existing open-source codes are `CCAKE` [18], `MUSIC` [28], and `vHLLE` [29], each have different equations of motion, numerical algorithms, and EOS solvers. Stability [30] provides further constraints on BSQ hydro. Phase transitions [31] or critical fluctuations [32, 33] incorporation in relativistic hydrodynamics is underway but not yet implemented in dynamical frameworks. Hadronization also requires criticality [34]. For low $\sqrt{s_{NN}}$ the influence of the QGP may be so short lived such that it is negligible [35]. An alternative is to incorporate potentials within a hadron transport to simulation phase transitions [36].

[NS] Scientists can now extract posteriors of the [NS] EOS ($T = 0$, large n_B, at β-equilibrium). Different approaches are used: functional forms, physics based EOS (often multiple stitched together in different ranges of n_B), or a mixture. There is strong evidence that the speed of sound squared surpasses the conformal limit i.e. $c_s^2 > 1/3$ to support heavy [NS] [37] and may near the causal limit if ultra heavy [NS] exist [38, 39]. A bump in c_s^2 could indicate a cross-over into quarks [40] or a phase transition into hyperons [41]. Functional forms should capture features in c_s^2 that indicate phase transitions/new degrees of freedom, which is not possible with polytropes/spectral EOS [38, 42]. Non-parametric approaches can reproduce these features like Gaussian processes [43], which can also be explicitly included in EOS [44]. Strong phase transitions could be measured via mass twins [45] or the binary love relation [46]. We cannot calculate the EOS directly at large n_B. However, lattice QCD calculations are possible at $T = 0$ with isospin asymmetry, leading to $c_s^2 > 1/3$ [47]. pQCD calculations are relevant at $n_B \gtrsim 40\, n_{sat}$. Using causality and stability, one can obtain bounds that reach to smaller n_B to further constrain the EOS [48]. Bulk viscosity within [NS] mergers arises from weak interactions, affecting different stages of the merger [49], and is influenced by the degrees of freedom [50] and Y_Q [51]. In [52] the first constraints on bulk viscosity in the inspiral of [NS] mergers was extracted, making tests possible with further data.

Groups use low-energy [HIC] flow data to extract the low $T \geq 0$ EOS for $Y_Q \sim 0.5$. It is important to consider structure in c_s^2, as was done first in [53], indicating a large bump in c_s^2 around $[2, 3]n_{sat}$. It is possible to convert a given [NS] EOS into [HIC] using the symmetry energy expansion (and applying saturation and causality/stability constraints) [54], which indicated ultraheavy [NS] are consistent with [HIC]. Next is to expand cold EOS into finite T, which is possible using a T/μ_B expansion [55] or an effective mass (npe matter) [56].

3 Bulk Dynamics

The QGP is well described by a relativistic viscous fluid with small viscosity [57], leading to developments of relativistic *viscous* fluids. At $n_B = 0$ and large systems, the properties can be exacted from a Bayesian analysis [58–60]. However, the QGP medium may begin extremely far-from-equilibrium such that even causality and stability break down [61], which affects the extraction of bulk viscosity [62]. Collisions of light nuclei push the boundaries of fluid dynamics even further [63], spin hydrodynamics is relevant for Λ polarization results

[64, 65], and magnetohydrodynamics is needed to explore large magnetic fields [66]. *Key Questions:* Does [HIC] knowledge of relativistic viscous fluids affect other fields? Could hydrodynamics be relevant for the EIC? What role does spin and magnetic fields play?

Advances in fluid dynamics Predictions between $\sqrt{s_{NN}}$ [67, 68] were confirmed [69], so one could extract nuclear structure information from collisions of deformed ions [70]. One can extract the neutron skin from ^{208}Pb [71] from [HIC], which was more consistent with ab initio [72] than the PREXII data [73]. Collaborations with nuclear structure physicists have led to suggestions of new data to be collected to shed light on α clustering [74] or interesting deformations [75, 76]. Fundamental questions still remain for small systems and peripheral collisions. Correlations between v_2 and $\langle p_T \rangle$ are hard to reproduce [77]. In extremely small systems i.e. a vector meson-ion collisions (ultra peripheral collisions) there are hints of collective behavior [78], which has interesting implications for the Electron Ion Collider. These advances have led to cold atoms connections [79].

Spin and Magnetic Fields [HIC] have extremely large, short lived magnetic fields [80]. Groups are working on developing relativistic magnetohydrodyanmics (MHD) codes for [HIC]. Since ideal MHD is standard in astrophysics, at least two astro codes have been converted to [HIC] [81, 82]. [HIC] physicists and astrophysicists incorporated Israel-Stewart equations of motion into astro MHD codes [83]. Non-linear stability and causality techniques from [HIC] [84], have been extended to MHD coupled to general relativity for accretion disks around black holes [85]. Similar constraints are also available for spin/chiral relativistic hydrodynamics [86, 87]. Λ polarization can further constrain hydrodynamic parameters [88].

4 Hadron Physics

[HIC] cannot directly probe quarks and gluons, rather detectors measure charged hadrons. Understanding their properties provides insight into freeze-out, hadronization, and Brownian motion. *Key Questions:* How is strangeness produced? What causes isospin breaking? Can we understand heavy flavor across system size? Could charm quarks be thermalized?

Puzzles from hadrons The hadron resonance gas (HRG) model helped understand hadronization. HRG is used to extract freeze-out information from thermal fits [89] and fluctuations [90, 91] (c.f. in lattice QCD [92]), although tensions remain between light and strange hadrons [93]. Increasing the number of resonances might have solved the puzzle [94], but the tension remained even with new states [91, 95]. Either there are separate freeze-out temperatures [96] or an S-matrix approach is required [97]. Extensions to the HRG include magnetic fields [98] or surface tension [99]. Experiments found isospin symmetry breaking of kaons across $\sqrt{s_{NN}}$ [100]. One explanation is a disorientated isospin condensate [101].

Puzzles from heavy flavor Heavy flavor provides an interesting probe of the QGP that is normally modeled through a Langevin equation at low p_T, or an energy loss model at high p_T. Most dynamics are described using more weakly coupled approaches [102], but others have used charm as a conserved charge within the fluid [103, 104]. Coalescence is important at low p_T to correctly capture the hadronization process (see [105] for hadronic rescattering). While it was thought heavy flavor models lead to disparate results for the nuclear modification factors R_{AA}, much could be attributed to different medium effects since the same medium led to very similar results [106]. After the first event-by-event studies with heavy flavor [107] and jets [108], soft-heavy [109, 110] and soft-hard [111, 112] correlations advanced. These correlations can constrain the T dependence of diffusion [113]. ALICE experimental data showed that the heavy flavor elliptical flow, v_2, scales with the soft v_2 [110]. Charmonium flow may be more complicated due to its internal structure [114]. Jets' sensitivity to event-by-event fluctuations can be seen by experimental measurements of jet $v_3 \neq 0$ [115]. Groups are trying to unify the soft-heavy [116] and soft-hard [117] frameworks.

Small systems have perplexing behavior for heavy flavor. $R_{AA} \sim 1$, while pPb D meson v_2 is large [118] but charmonium [119] and bottomonium $v_2 \sim 0$ [120] and in pp D mesons $v_2 > 0$ and B mesons $v_2 < 0$ [121]. A heavy flavor system size scan was proposed [122] with multicharm hadron predictions in [123] . Corrections to the short path length may be required [124]. Heavy flavor requires longer formation times [125] due to their masses. The interplay between the early far-from-equilibrium stage and heavy flavor is intriguing, such as how $c\bar{c}$ and $b\bar{b}$ pairs disassociate in the glasma [126].

Acknowledgments J.N.H thanks SQM24 for providing child care and acknowledges support from DOE Grant No. DE-SC0023861, Saturated Glue (SURGE) Topical Theory Collaboration, and NSF Grant No. OAC-2103680 within the framework of MUSES collaboration.

References

[1] R. Kumar et al. (MUSES), Living Rev. Rel. **27**, 3 (2024), `2303.17021`.
[2] M.A. Stephanov, K. Rajagopal, E.V. Shuryak, Phys. Rev. Lett. **81**, 4816 (1998).
[3] D. Bollweg, et al. (HotQCD), Phys. Rev. D **105**, 074511 (2022).
[4] W.j. Fu, et al., Phys. Rev. D **101**, 054032 (2020).
[5] P.J. Gunkel, C.S. Fischer, Phys. Rev. D **104**, 054022 (2021), `2106.08356`.
[6] G. Basar, Phys. Rev. Lett. **127**, 171603 (2021), `2105.08080`.
[7] P. Dimopoulos, et al., Phys. Rev. D **105**, 034513 (2022).
[8] M. Hippert, et al (2023), `2309.00579`.
[9] A. Sorensen, P. Sorensen (2024), `2405.10278`.
[10] Y. ZHANG, This SQM2024 proceedings (2024)
[11] A. Bzdak, et al, Phys. Rept. **853**, 1 (2020).
[12] T. Dore, et al, Phys. Rev. D **106**, 094024 (2022).
[13] C. Nonaka, M. Asakawa, Phys. Rev. C **71**, 044904 (2005), `nucl-th/0410078`.
[14] M.S. Pradeep, N. Sogabe, M. Stephanov, H.U. Yee, Phys. Rev. C **109**, 064905 (2024).
[15] J.M. Karthein, V. Koch, C. Ratti (2024), `2409.13961`.
[16] S. Borsányi, et al, Phys. Rev. Lett. **126**, 232001 (2021).
[17] M. Kahangirwe, et al, Phys. Rev. D **109**, 094046 (2024).
[18] C. Plumberg et al. (2024), `2405.09648`.
[19] MUSES calculation enginge (2024), `https://musesframework.io/`
[20] C. Shen, B. Schenke, Phys. Rev. C **97**, 024907 (2018), `1710.00881`.
[21] J. Cimerman, et al, Phys. Rev. C **107**, 044902 (2023).
[22] O. Garcia-Montero, et al, Phys. Rev. C **109**, 044916 (2024).
[23] O. Garcia-Montero, S. Schlichting (2024), `2409.06788`.
[24] A. Schäfer, et al (SMASH), Eur. Phys. J. A **58**, 230 (2022).
[25] P. Carzon, et al, Phys. Rev. C **105**, 034908 (2022).
[26] P. Carzon, et al, Phys. Rev. C **108**, 064905 (2023).
[27] T. Dore, This SQM2024 proceedings (2024)
[28] A. Monnai, G. Pihan, B. Schenke, C. Shen (2024), `2406.11610`.
[29] I. Karpenko, et al, Comput. Phys. Commun. **185**, 3016 (2014).
[30] D. Almaalol, T. Dore, J. Noronha-Hostler (2022), `2209.11210`.
[31] J. Kapusta, M. Singh, T. Welle (2024), `2409.16525`
[32] J.M. Karthein, et al (2024), `2409.16249`
[33] X. An, G. Basar, M. Stephanov, H.U. Yee, Phys. Rev. C **108**, 034910 (2023).
[34] M.S. Pradeep, M. Stephanov, Phys. Rev. Lett. **130**, 162301 (2023), `2211.09142`.

[35] G. Inghirami, H. Elfner, Eur. Phys. J. C **82**, 796 (2022), `2201.05934`.
[36] A. Sorensen, V. Koch, Phys. Rev. C **104**, 034904 (2021), `2011.06635`.
[37] P. Bedaque, A.W. Steiner, Phys. Rev. Lett. **114**, 031103 (2015), `1408.5116`.
[38] H. Tan, et al, Phys. Rev. Lett. **125**, 261104 (2020), `2006.16296`.
[39] T. Kojo, AAPPS Bull. **31**, 11 (2021), `2011.10940`.
[40] L. McLerran, S. Reddy, Phys. Rev. Lett. **122**, 122701 (2019), `1811.12503`.
[41] N. Cruz-Camacho, et al (2024).
[42] H. Tan, et al, Phys. Rev. D **105**, 023018 (2022).
[43] R. Essick, et al, Phys. Rev. D **108**, 043013 (2023).
[44] D. Mroczek, M.C. Miller, J. Noronha-Hostler, N. Yunes (2023), `2309.02345`.
[45] M.G. Alford, S. Han, M. Prakash, Phys. Rev. D **88**, 083013 (2013), `1302.4732`.
[46] H. Tan, et al, Phys. Rev. Lett. **128**, 161101 (2022).
[47] B.B. Brandt, F. Cuteri, G. Endrodi, JHEP **07**, 055 (2023), `2212.14016`.
[48] O. Komoltsev, A. Kurkela, Phys. Rev. Lett. **128**, 202701 (2022), `2111.05350`.
[49] E.R. Most, et al, Mon. Not. Roy. Astron. Soc. **509**, 1096 (2021).
[50] M.G. Alford, A. Haber, Phys. Rev. C **103**, 045810 (2021), `2009.05181`.
[51] Y. Yang, M. Hippert, E. Speranza, J. Noronha, Phys. Rev. C **109**, 015805 (2024).
[52] J.L. Ripley, A. Hegade K. R., R.S. Chandramouli, N. Yunes (2023), `2312.11659`.
[53] D. Oliinychenko, et al, Phys. Rev. C **108**, 034908 (2023).
[54] N. Yao, et al, Phys. Rev. C **109**, 065803 (2024).
[55] D. Mroczek, et al (2024), `2404.01658`.
[56] C.A. Raithel, F. Ozel, D. Psaltis, Astrophys. J. **875**, 12 (2019), `1902.10735`.
[57] U. Heinz, R. Snellings, Ann. Rev. Nucl. Part. Sci. **63**, 123 (2013), `1301.2826`.
[58] J.E. Bernhard, J.S. Moreland, S.A. Bass, Nature Phys. **15**, 1113 (2019).
[59] D. Everett et al. (JETSCAPE), Phys. Rev. C **103**, 054904 (2021), `2011.01430`.
[60] G. Nijs, et al, Phys. Rev. C **103**, 054909 (2021).
[61] C. Plumberg, et al, Phys. Rev. C **105**, L061901 (2022).
[62] T.S. Domingues, et al (2024).
[63] C. Aidala et al. (PHENIX), Nature Phys. **15**, 214 (2019), `1805.02973`.
[64] L. Adamczyk et al. (STAR), Nature **548**, 62 (2017), `1701.06657`.
[65] W. Florkowski, B. Friman, A. Jaiswal, E. Speranza, Phys. Rev. C **97**, 041901 (2018).
[66] U. Gursoy, D. Kharzeev, K. Rajagopal, Phys. Rev. C **89**, 054905 (2014), `1401.3805`.
[67] H. Niemi, K.J. Eskola, R. Paatelainen, K. Tuominen, Phys. Rev. C **93**, 014912 (2016).
[68] J. Noronha-Hostler, M. Luzum, J.Y. Ollitrault, Phys. Rev. C **93**, 034912 (2016).
[69] J. Adam et al. (ALICE), Phys. Rev. Lett. **116**, 132302 (2016), `1602.01119`.
[70] B. Bally et al. (2022), `2209.11042`.
[71] G. Giacalone, G. Nijs, W. van der Schee, Phys. Rev. Lett. **131**, 202302 (2023).
[72] B. Hu et al., Nature Phys. **18**, 1196 (2022), `2112.01125`.
[73] D. Adhikari et al. (PREX), Phys. Rev. Lett. **126**, 172502 (2021), `2102.10767`.
[74] N. Summerfield, et al, Phys. Rev. C **104**, L041901 (2021).
[75] G. Giacalone et al. (2024), `2402.05995`.
[76] G. Giacalone et al. (2024), `2405.20210`.
[77] ALICE, Ali-prel-491854
[78] W. Zhao, C. Shen, B. Schenke, Phys. Rev. Lett. **129**, 252302 (2022), `2203.06094`.
[79] S. Floerchinger, et al, Phys. Rev. C **105**, 044908 (2022).
[80] G. Inghirami, et al, Eur. Phys. J. C **80**, 293 (2020).

[81] G. Inghirami, et al, Eur. Phys. J. C **76**, 659 (2016).
[82] M. Mayer, L. Rezzolla, H. Elfner, G. Inghirami, D.H. Rischke (2024), `2403.08669`.
[83] E.R. Most, J. Noronha, Phys. Rev. D **104**, 103028 (2021), `2109.02796`.
[84] F.S. Bemfica, et al, Phys. Rev. Lett. **126**, 222301 (2021).
[85] I. Cordeiro, et al, Phys. Rev. Lett. **133**, 091401 (2024).
[86] N. Abboud, E. Speranza, J. Noronha, Phys. Rev. D **109**, 094007 (2024), `2308.02928`.
[87] A. Daher, et al, Phys. Rev. D **109**, 114001 (2024).
[88] A. Palermo, This SQM2024 proceedings (2024)
[89] A. Andronic, et al, Nature **561**, 321 (2018).
[90] R. Bellwied, et al, Phys. Rev. C **99**, 034912 (2019).
[91] P. Alba, et al, Phys. Rev. C **101**, 054905 (2020).
[92] S. Borsanyi, et al, Phys. Rev. Lett. **113**, 052301 (2014).
[93] M. Floris, Nucl. Phys. A **931**, 103 (2014), `1408.6403`.
[94] A. Bazavov et al., Phys. Rev. Lett. **113**, 072001 (2014), `1404.6511`.
[95] J.S. San Martin, et al (2023), `2309.01737`.
[96] R. Bellwied, et al, Phys. Rev. Lett. **111**, 202302 (2013).
[97] A. Andronic, et al, Phys. Lett. B **792**, 304 (2019).
[98] V. Vovchenko, Phys. Rev. C **110**, 034914 (2024), `2405.16306`.
[99] E. Zherebtsova, This SQM2024 proceedings (2024)
[100] W. Brylinski, et al (2023).
[101] J.I. Kapusta, S. Pratt, M. Singh, Phys. Rev. C **109**, L031902 (2024), `2306.13280`.
[102] S. Bass, This SQM2024 proceedings (2024)
[103] F. Capellino, et al, Phys. Rev. D **106**, 034021 (2022).
[104] F. Capellino, et al, Phys. Rev. D **108**, 116011 (2023).
[105] R. Hirayama, This SQM2024 proceedings (2024)
[106] S. Cao et al., Phys. Rev. C **99**, 054907 (2019), `1809.07894`.
[107] M. Nahrgang, et al, Phys. Rev. C **91**, 014904 (2015).
[108] J. Noronha-Hostler, et al, Phys. Rev. Lett. **116**, 252301 (2016).
[109] C.A.G. Prado, et al, Phys. Rev. C **96**, 064903 (2017).
[110] M.L. Sambataro, et al, Eur. Phys. J. C **82**, 833 (2022).
[111] L. Barreto, et al (2022), `2208.02061`.
[112] A. Holtermann, et al, Phys. Rev. C **108**, 064901 (2023).
[113] M.L. Sambataro, V. Minissale, S. Plumari, V. Greco, Phys. Lett. B **849**, 138480 (2024).
[114] S. Cho, Phys. Rev. C **109**, 054904 (2024), `2307.14765`.
[115] G. Aad et al. (ATLAS), Phys. Rev. C **105**, 064903 (2022), `2111.06606`.
[116] J. Zhao, et al, Phys. Rev. C **110**, 024909 (2024).
[117] B. Karmakar, et al (2024), `2403.17817`.
[118] A.M. Sirunyan et al. (CMS), Phys. Rev. Lett. **121**, 082301 (2018), `1804.09767`.
[119] A.M. Sirunyan et al. (CMS), Phys. Lett. B **791**, 172 (2019), `1810.01473`.
[120] A. Tumasyan et al. (CMS), Phys. Lett. B **850**, 138518 (2024), `2310.03233`.
[121] G. Aad et al. (ATLAS), Phys. Rev. Lett. **132**, 202301 (2024), `2308.16652`.
[122] R. Katz, et al, Phys. Rev. C **102**, 024906 (2020).
[123] V. Minissale, et al, Eur. Phys. J. C **84**, 228 (2024).
[124] C. Faraday, A. Grindrod, W.A. Horowitz, Eur. Phys. J. C **83**, 1060 (2023).
[125] G.D. Moore, D. Teaney, Phys. Rev. C **71**, 064904 (2005), `hep-ph/0412346`.
[126] Pooja, M.Y. Jamal, P.P. Bhaduri, M. Ruggieri, S.K. Das (2024), `2404.05315`.