# Open Questions in Theory, Why They are Interesting, and the Tools to Address Them

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# Apologies...

- This talk will not be self-contained. Apologies to friends from the QCD and Hadron Physics Town Meeting...
- There are many talks to come later in the Phases of QCD Town Meeting, talks given by both theorists and experimentalists, in which you will see many results obtained from theory calculations. Apologies, but this talk will contain no results, no plots, no data.
- This talk will be about questions, which was my charge. Answering any of the questions will take both experiment and theory, though. So I am not sure the questions should be called "questions in theory", as in my title.
- Before I turn to open questions (my charge) I'll take a look back at some questions that are settled, or will be settled within a couple of years, so we can remind ourselves of the role of theory in how they are answered, and were asked.

# What kind of stuff is QGP?
# What does QGP Do?

- Answer 1: It is a liquid. It flows.
- It flows with remarkably little dissipation: $\eta/s$ smaller than that of any other known liquid. A droplet of QGP that falls apart into $\sim 1000$ hadrons behaves hydrodynamically; a droplet of $\sim 1000$ water molecules does not.
  It is the most liquid liquid in the universe, in addition to being the hottest liquid in the universe.
- Theory played a very important role in posing questions that motivated the construction of RHIC, but the question above was not posed in this way before RHIC.
- The answer, and the question, came from experimental data and theory, in concert. On the theory side: hydrodynamics, and lattice QCD which provides the equation of state as input to hydro.

# What kind of stuff is QGP?
# What does QGP Do?

- Answer 1: It is a liquid. It flows.
- The realization that quantifying $\eta/s$ of QGP is such an important way of answering what QGP is and does came from experiment, theory as above, and the discovery via holographic calculations that $\eta/s = 1/(4\pi)$ arises in the strong coupling limit of very many gauge theory plasmas and may be a bound in addition to being a limit.
- The answer, and the question, have taken on an importance that extends beyond the boundaries of nuclear physics. Connections to, and impacts on, string theory, cold atom physics, and condensed matter physics.
- Sometimes we get lucky. But, fortune favors the prepared: we ventured into the new landscape that RHIC opened up with a good kit of tools to start with, and new questions stimulated the creation of new tools.

# What kind of stuff is QGP? What does QGP Do?

- Answer 1: It is a liquid. It flows.
- Current, and near future: advances in quantifying $\eta/s$, and perhaps its temperature dependence.
- New observables, large and precise data sets from RHIC and LHC. (Snellings' talk.)
- Theory: need *much* more than just the lattice EoS plus hydrodynamics. Rapid recent advances in theory: 3D hydro; fluctuations in the initial state; improved description of the "hadrodynamic" final state. (Schenke's talk.)
- Several groups developing the theoretical framework within which to use the new data on $v_n$'s and correlations of $v_n$'s to get a model-independent determination of the visible features of the fluctuating initial state, together with $\eta/s$.

# What kind of stuff is QGP? What does QGP Do?

- Answer 1: It is a liquid. It flows.
- Remarkable that we can see anything of the initial state, long after hydrodynamization. Only possible because the liquid is so liquid, together with explosive expansion.
- Answers beget new questions: How does hydrodynamization happen? And happen so quickly?
- Answers beget new questions: What is the smallest possible droplet of QGP that behaves hydrodynamically?
  Anyone doing holographic calculations in toy models in which there is no smallest droplet, or anyone seeing effects of rather small lumps in the initial state visible in the final state, could have asked this question, but didn't.
  Question was asked by data: pPb collisions @LHC, then dAu data from RHIC, and soon $^{3}$HeAu @RHIC.

# What kind of stuff is QGP?
# What does QGP Do?

- Answer 2: It is highly opaque to colored, energetic, non-hydrodynamic, probes. It can quench jets. It can stop heavy quarks, which then diffuse in it, going with the flow. (Talks by Wang, Roland, Nagle, Ruan, Teaney.)

- Here too, the posing of this variant of the question emerged from an interplay between experimental data and theoretical calculations. Its importance was not foreseen before RHIC.

- Here too, current and near future advances in quantifying answers. For example, $\hat{q}$ and parton energy loss.

- Measurements of fully reconstructed jets at the LHC allow/drive us to analyze and understand jet modification, not only parton energy loss. Modification of jet shapes. Modification of fragmentation functions.

# What kind of stuff is QGP? What does QGP Do?

- Answer 2: It is highly opaque to colored, energetic, non-hydrodynamic, probes. It can quench jets.

- More than 15 years of development of the perturbative QCD framework, to be used for those aspects of jet quenching where large momentum transfers arise. Now several groups are incarnating these theoretical advances in Monte Carlos, needed to confront jet data.

- It is also clear that there are aspects of jet quenching that work as they do because the plasma is strongly coupled, and that involve small momentum transfer. Effective field theory methods are needed, and are being developed.

# What kind of stuff is QGP? What does QGP Do?

- Answer 2: It is highly opaque to colored, energetic, non-hydrodynamic, probes. It can quench jets.
- Qualitative insights from holographic calculations. In strongly coupled plasma: transverse momentum broadening and $\hat{q}$ do not count scattering centers — there aren't any; lost energy goes into damped hydrodynamic modes, which is to say heat; heavy quarks dragged and diffuse; light quark maximal stopping length $\propto E^{1/3}$, and nontrivial but understood $dE/dx$ curve with a "Bragg peak."
- New challenge: how to combine Monte Carlos that describe perturbative aspects of jets and jet quenching, with model descriptions of strongly coupled phenomena, and confront with jet data. To date, first steps.
- Jet data from sPHENIX will add leverage in temperature and jet energy.

# What kind of stuff is QGP? What does QGP Do?

- Answer 2: It is highly opaque to colored, energetic, non-hydrodynamic, probes. It can quench jets. It can stop heavy quarks, which then diffuse in it.

- Answers beget new questions: a heavy quark that is not too energetic gets dragged and ends up diffusing; a sufficiently energetic heavy quark behaves like a light quark. But, nobody has yet found a way of doing a holographic calculation of an energetic heavy quark that slows down and goes from one regime to the other.

- New insights, as well as quantification of the heavy quark diffusion constant, will come from 2014-16 runs at RHIC and b-hadron and b-jet data to come at the LHC.

# What kind of stuff is QGP? What does QGP Do?

- Answer 3: It screens the fundamental QCD force between a quark and an antiquark. A variant of the question that long predates RHIC.
- To date, the answer comes from lattice calculations. How can we see experimental evidence for screening?
- Not easy with charmonia. E.g. at the LHC most charmonia formed as the QGP, peppered with diffusing $c$ and $\bar{c}$, hadronizes. Tells us a lot, but not about screening.
- LHC data on production of $\Upsilon$(1S), $\Upsilon$(2S) and $\Upsilon$(3S) show that the dissociation pattern of quarkonia states depends on their binding energy, which is to say on their size, as long expected. Data to come on $p_T$-dependence will help to quantify this. But the real test of the screening interpretation requires repeating this measurement in either hotter (LHC?) or colder (sPHENIX) QGP.

# Open Questions

- We know a lot about what QGP does, and have a strong campaign at RHIC, the LHC, and via a broad range of theoretical calculations using varied frameworks, that will answer the open questions I have described and that will further quantify fundamental properties of the liquid: $\eta/s$, $\hat{q}$, heavy quark diffusion constant, screening length $\ldots$

- But, how does QGP *work*? What is its microscopic structure? The properties above characterize the liquid at its natural lengthscale $\sim 1/(\pi T)$. How do we "look under the hood"? How does the liquid-ness of the liquid, and its other properties, emerge from microscopic dynamics?

- How does this liquid change across its phase diagram?

- What access do we have to the quantum mechanical aspects of QGP itself? How? What can be learned?

- QGP is not present in the incident nuclei, is it? So, how does it form? What are its dynamical origins?

# How does QGP work?

- What is its microscopic structure? This we know. QCD is asymptotically free. When looked at with sufficiently high resolution, QGP must be made of weakly coupled quarks and gluons.
- How does the strongly coupled liquid, that does what we see it doing, emerge from an asymptotically free gauge theory?
- Maybe answering this question could help to understand how strongly coupled matter emerges in contexts in condensed matter physics where this is also a central question.
- The first step to addressing this question experimentally is finding experimental evidence for the presence of point-like scatterers when the QGP is probed with large momentum transfer. Which is to say we need a high-resolution microscope trained upon a droplet of QGP.

# How does QGP work?

- The open theory questions are still big. How best to see point-like scatterers? And, then, how best to operationalize the question of how the liquid emerges?

- Ideas to date focus on jet quenching phenomena, as they involve physics at varied scales. A Gaussian distribution of typical transverse momentum broadening arises in a strongly coupled liquid, or via point-like scatterers. A power-law tail in the distribution of rare harder transverse scattering can only come from point-like scatterers. Need to look for the scattering of moderate-momentum partons within a jet. Need precise measurements of how the medium modifies the angular distribution of those partons with a given momentum within a jet.

- First steps, both experiment and theory, have been taken. But only first steps. Need higher statistics dijet and gamma-jet data coming at the LHC. And, need to be able to compare the modification of the structure of jets at LHC and RHIC (sPHENIX). And, need new ideas.

# Mapping the QCD Phase Diagram

- How does QGP change as you "dope" it with a larger and larger excess of quarks over antiquarks, i.e. larger and larger $\mu_B$? Substantial recent progress in answering questions like this on the lattice, e.g. doping-dependence of equation of state and susceptibilities, as long as the doping is not too large. Combining lattice and BES-I results to map the crossover region. (Talks by Mukherjee, Cebra.)

- How is the crossover between QGP and hadrons affected by doping? Does it turn into a first order transition above a critical point? (Talk by Stephanov.)

- Answering this question via theory will need further advances in lattice "technology". Impressive recent progress advancing established Taylor-expansion methods. New ideas (complex Langevin) also being evaluated. Nevertheless, at present theory is good at telling us what happens near a critical point or first order transition, but cannot tell us where they may be located.

# Mapping the QCD Phase Diagram

- Exploring the phase diagram is the goal of the RHIC Beam Energy Scan. Beautiful results from BES-I, 2011-14. Suggestive variations in flow and fluctuation observables as a function of $\sqrt{s}$, and hence $\mu_B$. Strong motivation for higher statistics data at and below $\sqrt{s} = 20$ GeV. (Cebra's talk.)

- BES-I results present an outstanding opportunity for theory. E.g. intriguing $\sqrt{s}$-dependence of $dv_1/dy$, plausibly due to a softening of the EoS. Validating/quantifying this interpretation *requires* hydrodynamic calculations at BES energies, since "EoS" only has meaning in the context of hydro. And, hydro calculations at these lower energies present new challenges ($j_B^\mu$ in addition to $T^{\mu\nu}$) and must include state-of-the-art treatment of the hadrodynamics: relative importance of hadrodynamic effects on all observables grows. Also need state-of-the-art initial state fluctuations. BES-I data demand that the sophistication that has been applied at top energies be deployed at BES energies. (Talk by Petersen.)

# Mapping the QCD Phase Diagram

- Once you have a validated hydrodynamic + hydrodynamic model at BES energies, then you can add fluctuations of the chiral order parameter. Need hydro+hadro+chiral treatment in order to allow quantification of the finite-time limitation on the growth of the correlation length near, and the signatures of, a possible critical point. (Talks by Petersen and Stephanov.)

- Theory needs to be ready in time for BES-II in 2018-19, when error bars will shrink and today's tantalizing hints, e.g. of non-monotonic behavior in $dv_1/dy$ and in the kurtosis of the proton multiplicity distribution, will become $\ldots$ ?

# Quantum Aspects of QGP?

- In the strongly coupled "electron fluids" that are the subject of intense interest in condensed matter physics, much recent work on the importance of quantum entanglement. Is this important in QGP? Not known. This question is inaccessible if all you know is hydrodynamics and transport coefficients. I doubt that it is accessible via jet quenching, or screening. Could it somehow be addressed via corrections to diffusion for heavy quarks? Or via correlations in EM radiation? Seems very hard.

- But we may have access to a different quantum mechanical feature of QGP, namely the topological fluctuations of the gluon fields within QGP that result in fluctuations in chirality. In QGP in a $\vec{B}$ or $\vec{L}$ these topological fluctuations, together with the chiral anomaly, yield Chiral Magnetic Effects or Chiral Vortical Effects. Possible signatures of both have been seen. Many open questions here...

# Quantum Aspects of QGP?

- On the experimental side, how to subtract other effects? And, do the effects of potential interest turn off at low $\sqrt{s}$ where no QGP forms? $\rightarrow$ BES-II.

- On the theory side, how to calculate the topological fluctuations in an expanding cooling finite droplet? How big are the sphalerons and how are they spaced, in space and time? Many more questions.

- A first step to gaining confidence would be detection of prosaic effects of $\vec{B}$, via Faraday and Hall with no 20th or 21st century physics needed.

- A second step to gaining confidence would be a quantitative calculation of the Chiral Magnetic Wave effect, namely the generation of a charge quadrupole in slices of an event in which there is a net charge. This effect has been seen, and the theory behind it is more robust in that it requires $\vec{B}$ and the chiral anomaly but it does not involve the hard-to-calculate topological fluctuations.

# Quantum Aspects of QGP?

- Progress requires the development of relativistic viscous chiral magnetohydrodynamics codes that incorporate the anomalous couplings between $\vec{B}$, hydrodynamic flow, and gauge field fluctuations. Early work in this direction, learning how to formulate this, is already being applied to simpler chiral systems in condensed matter physics.

- Success in the larger program would constitute the discovery of the QCD analogue of the quantum fluctuations of the electroweak gauge fields that are thought to have generated the matter-antimatter asymmetry of the universe, at temperatures 1000 times hotter than we can recreate in the lab.

# Origins of QGP in HIC?

- Wave functions of incident hadrons and nuclei are of fundamental interest. Experimental study of the initial state via pA collisions and eA collisions at an EIC. (Talks by Kang, Lajoie and by many in the Joint Session)
- The decoherence of these wave functions in HIC and the evolution of this initial state to the strongly coupled liquid are as yet poorly constrained, and offer a window into the physics of equilibration in QCD.
- Recent advances in weakly coupled calculations, that connect smoothly onto a weakly coupled initial quantum state but can have difficulty connecting to hydrodynamics.
- Recent advances in strongly coupled calculations — collisions of sheets and now disks of cold strongly coupled matter — that yield hydrodynamic fluids smoothly and automatically but that assume a strongly coupled initial quantum state. New hybrid holographic$\rightarrow$hydro$\rightarrow$hadro calculations. Need holographic calculations with more realistic initial states.

# Origins of QGP in HIC?

- In reality, almost certainly the initial state is weakly coupled gluons well above $Q_s$ and strongly coupled gluons well below $Q_s$. How can we use eA collisions at an EIC to provide direct experimental evidence that the initial state is not just lots of gluons, counted up in a gluon pdf? That when you tickle one below-$Q_s$ gluon, many of them sneeze?

- Need the analogue in our field of what ARPES has done for strongly correlated electron systems. Which is to say we need direct experimental evidence of what those below-$Q_s$ gluons are *doing*. $\rightarrow$ EIC.

- Could it be that the reason hydrodynamization in HIC is so fast is that the below-$Q_s$ gluons are in a strongly coupled, maybe strongly entangled, state to start with?

- Can a scale $Q_s$, below which one has strongly coupled gluons but not above, be built into the initial state of the colliding disks in the holographic calculations?

# Origins of QGP in HIC?

- Thinking of the lessons of history, odds are very good we have not yet asked the most interesting questions about the initial state that an EIC will answer. I certainly hope so. Terra incognita awaits.

# Theory Today, and Tomorrow

- Since the last LRP, much progress on many fronts, in concert with experimental discoveries, using many different theoretical tools including some that have been newly developed.

- A rich panoply of open questions, many of them newly opened. What will it take to answer them?

- Computational resources are becoming more and more important in many areas of theory. Resources = people, as well as Flops. (Talks by Petreczky, Savage.)

- A base program, incorporating people pursuing varied approaches, using varied tools, crafting new tools, is the basis of it all. That is where new people, and new ideas, come from.

- But, in this day and age, computational resources plus a healthy base program are not enough in and of themselves...

# Theory Today, and Tomorrow

- Progress on many of the most important questions requires knitting together calculational methods that work at different epochs in a heavy ion collision. Certainly this is true whenever the goal is quantification, but often it is also true when the goal is exploration. This requires coordinated, cooperative, exchange or perhaps collaboration, among theorists with different tools, and experimentalists. E.g. topical collaborations...
- Look at how successful the JET Collaboration has become. Their signature accomplishment is their determination of $\hat{q}$, but in pulling together the people and tools to do that their members have made advances in many different regimes, from hydro to hard probes, from initial state to final state. And, they have stimulated the creation of 2-3 new faculty positions, supported students and postdocs, and engaged and advanced the work of many more students and postdocs via summer schools, visits, workshops.

# Theory Today, and Tomorrow

- Just think how much farther ahead we would be if there were two or three topical collaborations addressing different big open questions about the Phases of QCD Matter, instead of just one!

- There is also a real need for much-smaller-scale variants of the topical collaboration model. Think 3 PIs from different places with a good new idea that links two previously different approaches or perspectives together in a way that will benefit both. Think supporting 2 students, a couple of sabbatical visits by key people from overseas or one of the PIs. Think exploratory. Think nimble. Think quick to start, then 4-year duration at most. Think inexpensive. Think many of them. Maybe down the road several of these, whose ideas have paid off, flourished, grown, and whose results need to be connected and expanded, get together and propose a full-fledged topical center.