Recent experiments at CERN and at Brookhaven’s Relativistic Heavy Ion Collider (RHIC) have realized a state of matter with such high energy that quarks and gluons cannot form fundamental nuclear particles like protons and neutrons. Unbound quarks and gluons form plasma that is of fantastic experimental and theoretical importance for many reasons. Among these, quark-gluon plasma is thought to have been the state of matter very shortly after the Big Bang and is also suspected to exist at the core of neutron stars.

Quark-gluon plasmas remain exceptionally difficult to study experimentally. The plasmas exist for 10-15 seconds before the energy density decreases enough for protons and neutrons to re-form, so observational methods are indirect and plagued with statistical uncertainty. My research tackles the question: in what ways can we learn about quark-gluon plasmas when direct observation, particularly when we don’t know beforehand what we’re looking for, is essentially impossible?

To this end, the experimental observation of elliptic flow in quark-gluon plasmas was a major step forward. Elliptic flow is a phenomenon in which the wide dimension of an elliptical density profile changes as time evolves, and is a characteristic of strongly-coupled quantum fluids with anomalously low viscosity. The observation of elliptic flow in quark-gluon plasmas allows analogies to be drawn with other systems that exhibit elliptic flow but which are easier to study experimentally. In flowing elliptically, these fluids exhibit similar fluid transport and diffusion and therefore are expected to have similar material properties.

Several strongly-coupled cold atomic fluids exhibit elliptic flow and are promising parallels for the study of quark-gluon plasmas. One such system is the unitary Fermi gas, which is an ultra-cold collection of fermions (often Lithium) in the limit (called unitarity) where the Fermi gas exhibits the strongest coupling. Experimental data suggests that quark-gluon plasma may have the lowest viscosity of any fluid yet observed, and the unitary Fermi gas has the second lowest [2]. Hydrodynamics is a natural method for studying the material correspondence between unitary Fermi gases and quark-gluon plasmas because it deals explicitly with the fluid transport and diffusion on which our analogy is based.

In my research, I am developing a set of hydrodynamic simulations of unitary Fermi gases from which to extract their material properties (such as viscosity). The expansion and elliptic flow of unitary Fermi gases has been observed in several experiments (e.g. [6]) and occurs on the scale of hundreds of microseconds. Density profiles of the fluid can be imaged many times over the lifetime of the expansion, and so the data is fairly thorough and has relatively low experimental uncertainties. I am therefore able to compare the results of my simulations carefully with experiment, analyze deviations, and improve my methods. The limited experimental data set for the expansion of quark-gluon plasmas does not make a similar analysis possible for this system. Simulating unitary Fermi gases and verifying the results against experiment is an important part of the scientific process because it puts our methods on a solid experimental foundation.

Although quark-gluon plasmas and unitary Fermi gases share analogous material properties, heavy ion collisions and quark-gluon plasmas are certainly a relativistic system while unitary Fermi gases are not. Not only are quark-gluon plasmas moving at a significant fraction of the speed of light, but in fact the energy density is so large in these collisions that general relativity, which is traditionally used to model black hole collisions and other high-energy astrophysical phenomenon, is also important.

Relativistic hydrodynamics is a developing field with important applications across several branches of physics, including astrophysics, magneto-hydrodynamics, and high-energy condensed matter physics. In non-relativistic hydrodynamics viscous flows are typically modeled by the Navier-Stokes equations, which are well-studied and strike a nice balance between computability and accuracy. Unfortunately, relativistic formulations of the Navier-Stokes equations cannot be used because they violate causality, the directionality of time [5]. Various techniques for re-working this model have been proposed, but the equations for relativistic viscous hydrodynamics remain very complicated and numerical solutions are prohibitively computationally-intensive in most cases. Advances in hydrodynamic modeling of quark-gluon plasmas and other high-energy matter will require improvements in the computational efficiency of relativistic hydrodynamic methods.

Transitioning my study of elliptic flow in unitary Fermi gases into the direct study of quark-gluon plasmas will involve principally the implementation of relativistic hydrodynamic methods in my existing simulations. The issue of computability and accuracy in relativistic hydrodynamics is central to the effective simulation of quark-gluon plasmas, but is also an open problem across several other areas of physics. This is the problem I hope to contribute to in the work for my undergraduate thesis.

Moving forward in my physics and mathematics education into graduate school, a wider diversity of methods will become available to me for the study of high-energy matter and plasmas. Relativistic hydrodynamics is a promising model for studying particular aspects of these experiments, but high-energy physics is centrally based on quantum field theories that are not typically taught on an undergraduate level. My undergraduate research gives me a unique perspective on high-energy physics from which to approach graduate classes in more traditional methods like quantum field theory. It has furthermore given me a strong background in numerical and computational methods that are very important in much of theoretical physics. I look forward to my future research and education as an opportunity to appreciate these issues on a deeper level, and to use this diversity of knowledge to more effectively solve problems in high energy physics.

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