In 2000, CERN announced that the first quark-gluon plasmas had been created in collisions between lead and gold nuclei [1]. This discovery is of fundamental importance to high-energy physics and is revolutionizing modern physical thought, but progress has been slowed by the difficulty of experimental procedures and data analysis, which ~~for one~~ make it challenging to study the physical and material properties of quark-gluon plasma ~~with certainty~~. I am exploring a relationship between the fluid properties of quark-gluon plasma and a similar fluid, the cold Fermi gas, which may allow us to calculate values for the material properties of quark-gluon plasma with more precision than experimental data for quark-gluon plasma itself would allow.

Quarks are bound together with gluons to form protons and neutrons, which in turn are bound in the atomic nuclei that form molecules and macroscopic matter. At temperatures of trillions of degrees however, matter is too high in energy for even neutrons and protons to be stable and they break apart into free quarks and gluons; the resulting state of matter is called quark-gluon plasma. Quark-gluon plasma provides a unique opportunity for the study of individual quarks, as opposed to the study of composites of several quarks. Quark-gluon plasma is also important to the study of the early universe because it is thought to have been the state of all matter shortly after the Big Bang.

The interactions between free quarks and gluons are of great importance to our understanding of the fundamental forces governing these particles. The flow characteristics of a fluid convey abundant information about the microscopic interactions between fluid particles. In this case, the flow of quark-gluon plasma is indicative of the forces between free quarks and gluons. Thus, fluid dynamics is a promising method for the theoretical study of quark-gluon plasmas.

Quark-gluon plasmas currently are exceptionally difficult to study experimentally. They 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. The formation of quark-gluon plasma in a collision cannot be determined directly and must be inferred from the statistical presence of other particles in the collision aftermath. The challenges of these experimental procedures and data analysis complicate the theoretical analysis as well, as they make it difficult to verify results experimentally. An advantage of using fluid dynamics to study quark-gluon plasmas is that studies of other fluids with similar flow dynamics can be used to provide experimental support for theoretical methods. A fluid-dynamical relationship established between quark-gluon plasma and another fluid may allow the material properties of quark-gluon plasma to be studied with less uncertainty.

Merge the former and the latter. “One of the few material properties actually seen experimentally was elliptic flow. Blah”

The surprising analogy between the properties of quark-gluon plasmas and cold atomic gases emerged when elliptic flow was first observed in quark-gluon plasmas in 2005 [2]. Elliptic flow is a phenomenon in which a fluid expands non-uniformly. A fluid with these characteristics that initially has an elliptical shape will expand much more quickly in one direction than the other, thus changing shape over time. Elliptic flow is a relatively rare flow pattern and is characteristic of strongly-coupled quantum fluids with anomalously low viscosity.

A particularly strong relationship has been developed ([2], [3]) between quark-gluon plasmas and unitary Fermi gases. Unitary Fermi gases are ultra-cold collections of fermions (typically Lithium) under the conditions in which the atoms exhibit the strongest coupling. In addition to both exhibiting elliptic flow, experimental data suggests that quark-gluon plasma has the lowest viscosity ever observed and the unitary Fermi gas has the next lowest [3]. The unitary Fermi gas has been studied with low experimental uncertainty (e.g. [4]), so the fact that it obeys very similar fluid dynamics to quark-gluon plasmas is very useful to the study of quark-gluon plasmas.

Although quark-gluon plasmas and unitary Fermi gases have many similarities, quark-gluon plasmas have the added complexity of being a high-energy, relativistic fluid. Relativistic hydrodynamics is a developing field with important applications across several branches of physics, including astrophysics and magneto-hydrodynamics, and is essential to the fluid dynamics of quark-gluon plasma. It describes how fluids behave near very massive objects (like stars) or when they are exceptionally high in energy. Current methods in relativistic fluid dynamics are much more complicated than their non-relativistic counterparts, and in many cases are too difficult for computers to solve numerically in a practical amount of time. The issue of computability and accuracy in relativistic hydrodynamics is central to the effective simulation of quark-gluon plasmas.

In my current research, I am using non-relativistic fluid dynamics to develop simulations of unitary Fermi gases. I write simulations in the computer language C++ using a discrete fluid dynamics algorithm called the lattice Boltzmann method. Simulating any physical fluid on the computer involves many approximations, for example about how temperature varies or about how the fluid dissipates energy or relaxes to equilibrium. I am in the process of writing a set of simulations that make different sets of assumptions about these types of parameters. I compare the results of each simulation to published experimental data for unitary Fermi gases (e.g. [4]) and will determine the set of physical approximations that provide the best fit to experimental data.

The fluid assumptions that are most accurate for cold Fermi gases are supposed to also be nearly correct for quark-gluon plasma. Because of this, it is hoped that developing simulations of quark-gluon plasmas based on the fluid dynamics of cold Fermi gases will be more precise than trying to fit simulations of quark-gluon plasmas directly to the uncertain experimental data on quark-gluon plasma. The eventual goal of my research is to use computational relativistic fluid dynamics to calculate values for the material properties of quark-gluon plasma, like viscosity, that determine how it flows and expands after a heavy-ion collision. After developing simulations of unitary Fermi gases to determine the fluid assumptions, central to achieving this goal is the development of accurate and efficient computational algorithms for relativistic fluid dynamics. In my undergraduate thesis, I hope to contribute to the efficient computer implementation of relativistic hydrodynamics, and to use these methods to calculate theoretical bounds for the viscosity of quark-gluon plasma.

Graduate school in physics and mathematics promises exciting new opportunities to explore my interests in high-energy matter and plasma. Relativistic hydrodynamics is an important field with promising applications in high-energy and plasma physics, but there are also many other approaches to understanding these problems. My undergraduate research has given me a unique perspective on high-energy physics, as well as a strong background in computational methods and theoretical mathematics that will be great assets as a graduate student and researcher. Most importantly, it has given me the opportunity to contribute to an important and fascinating problem in physics. I look forward to further research and education as an opportunity to explore these issues on a deeper level, and to use this depth of knowledge to help solve some of these exciting problems in high energy physics.

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