# A New Era of Matter

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. However, progress has been slowed by the difficulty of experimental procedures and data analysis, which make it challenging to study the physical and material properties of quark-gluon plasma. We are 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 exceeding about $2 \cdot 10^{12}$ K however, matter is too high in energy for even neutrons and protons to be stable, so 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 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. One of the few properties observed in experiment was that of elliptic flow, first seen 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. There is therefore reason to believe that fluids exhibiting elliptic flow may share other physical properties.

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 fluids 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 exhibits very similar fluid dynamics to quark-gluon plasmas makes it 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 describes how fluids behave near very massive objects (like stars) or when they are exceptionally high in energy. It is a developing field with important applications across several branches of physics, including astrophysics and magneto-hydrodynamics, and is essential for studying the fluid dynamics of quark-gluon plasma. Current methods in relativistic fluid dynamics are much more complicated than their non-relativistic counterparts, and are often too difficult for computers to solve numerically in a practical amount of time. Improving 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. Simulating any fluid on the computer involves many approximations, including how temperature varies and 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 use a discrete fluid dynamics algorithm called the lattice Boltzmann method in my simulations, which approximates microscopic fluid particles as being able to move only on a discrete "lattice" of points in space, instead of in the infinite directions of continuous space. 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 assumptions that provide the best fit to experimental data.

The fluid assumptions that are most accurate for cold Fermi gases are believed to be nearly correct for quark-gluon plasma. Thus, it is hoped that basing simulations of quark-gluon plasmas on the fluid dynamics of cold Fermi gases will be more precise than fitting quark-gluon plasma simulations directly to uncertain experimental data. The 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. The first step is to determine a set of fluid assumptions based on simulations of the unitary Fermi gas, and next to use similar assumptions in relativistic fluid dynamics to develop simulations of quark-gluon plasmas. In my future work, 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.

**References**

[1]. CERN claims first experimental creation of quark-gluon plasma **Abbott, Alison.** Nature **403.6770 (Feb 10, 2000): 581.**
[2]. Schaefer, Thomas. *What Atomic Liquids Can Teach Us about Quark Liquids*. ArXiv e-print, March 13, 2007. http://arxiv.org/abs/hep-ph/0703141.
[3]. Schäfer, Thomas, and Derek Teaney. "Nearly Perfect Fluidity: From Cold Atomic Gases to Hot Quark Gluon Plasmas." *Reports on Progress in Physics* 72, no. 12 (December 1, 2009): 126001. doi:10.1088/0034-4885/72/12/126001.
[4]. C Cao, E. Elliott. "Universal Quantum Viscosity in a Unitary Fermi Gas." *Science (New York, N.Y.)* 331, no. 6013 (2011): 58–61. doi:10.1126/science.1195219