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. I hope to use computational fluid dynamics to solidify the theoretical backing for this new and exciting field of research. PROBLEM / SOLUTION

Until the late 1800’s, the atom was thought to be indivisible. Since then, research motivated by curiosity has led to important technologies such as nuclear energy and radiation treatments that have changed the face of humanity. This demonstrates the value of pursuing research into the fundamental nature of matter even without knowledge of the uses it will provide. Atoms have since been shown to be composed of protons and neutrons, which, more recently, have been found to be composed of even more fundamental particles called quarks.

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 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.

What do I do?? I use fluid dynamic simulations in the non-relativistic limit of elliptic flow and compare the results to experimental data collected on cold Fermi gases to refine physical parameters relevant for the study and simulation of quark gluon plasmas. Maybe say a simplified version of this in the intro? Put a problem sentence and a solution sentence back-to-back in the intro.

PROBLEM: we have trouble determining the material properties of quark-gluon plasmas because the experimental data has high uncertainty.

SOLUTION: I am using higher-precision experimental data from a similar fluid, the cold Fermi gas, to determine the values of these physical parameters in the non-relativistic limit so that they can then be applied to simulations of quark-gluon plasmas.

The basics: I simulate cold Fermi gases, and decide what physical approximations to the fluid dynamics equations best fit the experimental data. Then I stick these physical parameters into relativistic hydro and simulate quark-gluon plasmas.

SPECIFICALLY MENTION FINDING BETTER VALUES FOR EXPERIMENTAL PARAMETERS

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. I am currently using non-relativistic fluid dynamics to simulate unitary Fermi gases and compare the results against experimental data (e.g. [4]) for several different physical approximations of the fluid. Theoretical values for the fluid viscosity and other material parameters can be extracted from these simulations. These simulations also verify my non-relativistic methods experimentally, and so provide a solid foundation for my future relativistic methods. The next step in my research is to develop a relativistic fluid model out of my existing simulations of the unitary Fermi gas in order to simulate quark-gluon plasmas. Central to achieving this goal is the development of accurate and efficient computational algorithms for relativistic fluid dynamics. I hope to contribute to the theoretical study of viscosity in quark-gluon plasmas and to the efficient implementation of relativistic hydrodynamics in my undergraduate thesis.

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](https://cuvpn.colorado.edu/indexinglinkhandler/sng/au/Abbott,+Alison/,DanaInfo=0-search.proquest.com.libraries.colorado.edu+$N?accountid=14503). [**Nature**](https://cuvpn.colorado.edu/pubidlinkhandler/sng/pubtitle/Nature/$N/40569/DocView/204499120/abstract/$B/,DanaInfo=0-search.proquest.com.libraries.colorado.edu+1?accountid=14503)[403.6770](https://cuvpn.colorado.edu/indexingvolumeissuelinkhandler/40569/Nature/02000Y02Y10$23Feb+10,+2000$3b++Vol.+403+$286770$29/403/,DanaInfo=0-search.proquest.com.libraries.colorado.edu+6770?accountid=14503) (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