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**Nominee Essay, Goldwater 2014**

**Introduction and Social Relevance** Nuclear particles like protons and neutrons are composed of elementary particles called quarks bound together by gluons. At temperatures below trillions of degrees, this binding is so strong that quarks only exist as constituents of other particles and cannot exist by themselves. Recent experiments at CERN and at Brookhaven’s Relativistic Heavy Ion Collider have realized a state of matter with such high energy that protons and neutrons cannot exist, because quarks and gluons are no longer bound strongly together.

This state of matter, quark-gluon plasma, is of fantastic importance because it is the only experimental realization to date of free quarks.

Unbound quarks and gluons in these experiments form a plasma that is of fantastic theoretical importance. It is believed that all matter existed as quark-gluon plasma for a period of time shortly after the Big Bang. Among many other reasons, the properties of quark-gluon plasma are of interest to the physics community because they provide insight into the evolution of the universe at one of its earliest stages.

**Problem Statement** Quark-gluon plasmas remain exceptionally difficult to study experimentally. The plasmas exist for quadrillionths of a second before protons and neutrons to re-form, so observational techniques are indirect and plagued with statistical uncertainty. In the wake of astonishing experimental progress, these experiments need to be interpreted and incorporated into the relevant physical theories.

**Relevance to Physics** The experimental observation of elliptic flow in quark-gluon plasmas was therefore a major success and sparked significant theoretical interest. 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. In fact, experimental data suggests that quark-gluon plasma may have the lowest viscosity of any fluid yet observed [2]. Particularly in light of an absolute lower bound on fluid viscosity proposed recently through string-theoretic methods [3], there is much interest in finally constraining the viscosity of quark-gluon plasma. Hydrodynamics is one promising method for the theoretical study of viscosity in quark-gluon plasmas.

**My Contribution** The observation of elliptic flow in quark-gluon plasma allows analogies to be drawn with other systems that exhibit elliptic flow, which include several strongly-coupled cold atomic fluids. 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. This system is a non-relativistic, but has analogous material properties to quark-gluon plasmas. Both are strongly-coupled quantum fluids, and so are expected to obey similar transport and diffusion characteristics (that both exhibit elliptic flow is evidence of this). Besides the quark-gluon plasma, the unitary Fermi gas is also observed to have the next lowest viscosity ([2], [4]).

Relativistic hydrodynamics is a developing field with important applications in astrophysics, magneto-hydrodynamics, and high-energy condensed matter. The Navier-Stokes equations are a first-order diffusion relation typically used in non-relativistic hydrodynamics to model viscous flows. Unfortunately, relativistic formulations of the Navier-Stokes equations violate causality [5]. Various techniques for re-working this model exist in the literature, 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. This problem certainly has not been solved and is an issue I hope to contribute to in my undergraduate thesis.

My current contribution to the study of quark-gluon plasmas is to study the material properties of unitary Fermi gases through hydrodynamic simulations. The advantage of studying this system is that it is experimentally-verifiable: elliptic flow in Fermi gases is observed on the scale of hundreds of microseconds [6], which is about 12 orders of magnitude longer of a time scale than the one on which the expansion of quark-gluon plasmas can be observed. Developing simulations of quark-gluon plasmas out of simulations of Fermi gases that have been verified through experiment puts the non-relativistic limit on a solid experimental foundation.

**Future Plans** 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. 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.

**References**

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