**A New Era of Matter**

How do we learn things about quark-gluon plasmas when direct observation, particularly without prior knowledge of what we’re looking for, is almost impossible.

Recent experiments at CERN and at Brookhaven’s Relativistic Heavy Ion Collider 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 exist in no other matter that has been observed, and form plasma that is of fantastic experimental and theoretical importance. For one, quark-gluon plasma is believed to have been the state of all matter shortly after the Big Bang, and thus to have played an important role in the early evolution of our universe. It is also of great interest in high-energy physics because it has previously been possible only to study quarks indirectly through the study of the composite particles in which they are bound. It is currently possible to study free quarks only in quark-gluon plasmas.

The creation and observation of quark-gluon plasmas in heavy ion collisions is a huge step forward, but the plasmas remain exceptionally difficult to study experimentally. They exist for seconds before the energy density decreases enough for protons and neutrons to re-form, and so they can only be studied indirectly in the aftermath of the collision.

Why should I care about elliptic flow?

The recent 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. The experimental data suggests that quark-gluon plasma may have the lowest viscosity of any fluid yet observed [2]. This characteristic brings it into even broader interest in the physics community, because methods in string theory have predicted an absolute lower bound on fluid viscosity [3]. Constraining the viscosity of quark-gluon plasma would put this theory in experimental context.

I am researching the application of computational fluid dynamics to model strongly-coupled quantum systems and elliptic flow. This approach differs from standard theoretical techniques for analyzing these systems because it focuses on their properties as fluids and as matter, instead of on their properties as quantum-mechanical systems. In this way my research bridges the gap between high-energy and condensed matter physics by considering high-energy matter through its relationship to ordinary matter. This approach has several advantages, and is an especially natural technique for understanding the material properties of these systems.

From a condensed matter perspective, 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. Besides the quark-gluon plasma, the unitary Fermi gas is observed to have the next lowest viscosity ([2], [4]). Because their microscopic interactions are in many ways analogous, quark-gluon plasmas and unitary Fermi gases are expected to obey similar fluid transport and diffusion equations, and therefore to behave similarly as fluids. The caveat is that heavy ion collisions and quark-gluon plasmas are certainly a relativistic system, while cold atomic gases are not.

I am currently writing hydrodynamic simulations of unitary Fermi gases as they expand out of harmonic traps. Although the experimental realization of the unitary Fermi gas is as well fairly recent, there exist several sets of experimental data (e.g. [6]) demonstrating elliptic flow in these systems. The expansion of unitary Fermi gases is observed on the scale of hundreds of microseconds, making it possible to image the density profiles directly. It is therefore possible to carefully verify simulation results against many data points taken throughout the expansion of the gas. It is not possible to do this kind of verification for quark-gluon plasmas given the available data set, so this is an important step in the scientific process that puts the non-relativistic limit of our algorithms on a solid experimental foundation. I am in the process of validating my simulations against experimental results and analytic solutions, where possible.

To simulate the fluid properties of quark-gluon plasmas requires a relativistic formulation of hydrodynamics. Relativistic hydrodynamics is a developing field with important applications in astrophysics, magneto-hydrodynamics, and high-energy condensed matter physics. Unfortunately the techniques used to model viscous dynamics of non-relativistic fluids break down in the relativistic limit. Several new models have been proposed (e.g. [5]), but the governing equations of relativistic viscous hydrodynamics are very complicated and numerical solutions are prohibitively computationally-intensive in most cases. Our ability to accurately model the hydrodynamics of heavy ion collisions and quark-gluon plasmas hinges on improvements in the computational efficiency of relativistic hydrodynamic methods. This is an open problem in several disciplines that I hope to contribute to in 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.

**References**

The first reference is Ref. 2!!

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