You should be able to read the first sentence of every paragraph, skip the rest, and still get the paper.

In 2000, CERN announced that the first quark-gluon plasmas had been created in collisions between lead and gold nuclei [0]. This discovery is of central importance in both high-energy physics and early-universe cosmology and is revolutionizing modern physical thought. I would like to contribute to this new and exciting field of study through theoretical research of the fluid behavior of this novel material. Try to put in a sentence about your research in here…

Why you should care paragraph. There is no reason why you should care about splitting atoms until you do it, and get nuclear energy, radiation treatment, etc. Something about how mankind’s insatiable curiosity leads to great developments. Even without some further idea of the eventual applications, a better understanding of the fundamental forces at play in our universe have without fail (?) improved the quality of life of mankind. Whether you’re driven by curiosity of by desire for quantifiable gain, theoretical physics research is a valuable (and rewarding!) pursuit (!)

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.

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 make the theoretical study of quark-gluon plasmas particularly important.

Start off with “The flow of quark-gluon plasma is indicative of the interactions between free quarks and gluons…” and put this paragraph before the previous one. Thus… fluid dynamics is a promising method for the theoretical study of quark-gluon plasmas. 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 interactions between free quarks and gluons, which are of great fundamental interest. An advantage of studying quark-gluon plasma and the interaction between free quarks and gluons with fluid dynamics is that fluids that exhibit similar macroscopic flow properties demonstrate that they obey similar fluid dynamics. Therefore, although the microscopic interactions (between quarks and gluons) are not well understood, it is possible to draw valid analogies (in the context of fluid dynamics) between fluids that exhibit similar macroscopic flow even if it is not known how each is interacting microscopically. For quark-gluon plasmas, these analogies provide an experimentally-verifiable context in which to test theoretical methods.

A surprising analogy between the material properties of quark-gluon plasmas and cold atomic gases was developed when elliptic flow was first observed in quark-gluon plasmas in 2005 [1]. 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, so the shape of the fluid changes in 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 … between quark-gluon plasma and unitary Fermi gases. These are an ultra-cold collection of fermions (typically Lithium) under the conditions in which the atoms exhibit the strongest coupling. A particularly strong relationship has been developed ([1], [2]) between quark-gluon plasma and one cold atomic gas called the unitary Fermi gas, which is an ultra-cold collection of fermions (typically Lithium) under the conditions in which the atoms exhibit the strongest coupling. In addition to exhibiting elliptic flow… This is in part because experimental data suggests that quark-gluon plasma may have the lowest viscosity ever observed, and the unitary Fermi gas is thought to have the next lowest [2]. The unitary Fermi gas has been studied with low experimental uncertainty (e.g. [3]), so the fact that it obeys very similar fluid dynamics to quark-gluon plasmas is very useful to the study of quark-gluon plasmas.

Despite the similarities between the quark-gluon plasmas and unitary Fermi gasses, quark-gluon plasmas have the added complexity of existing in extremely high-energy, relativistic conditions.~~The primary difference between the fluid dynamics of the unitary Fermi gas and quark-gluon plasma is that quark-gluon plasmas are exceptionally hot and expand from the point of a heavy-ion collision at very high speeds, and therefore have too high of energy density to be well-approximated by classical (non-relativistic) physics. Quark-gluon plasmas therefore must be modelled by relativistic fluid dynamics.~~  Relativistic hydrodynamics is a developing field with important applications across several branches of physics, including astrophysics, magneto-hydrodynamics, and high-energy condensed matter physics, and appears to be essential for the study of quark-gluon plasmas. It describes how fluids behave near very massive objects (like stars) or when they are exceptionally high in energy (which is the case for quark gluon plasmas). 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 decent amount of time. ~~Solving~~ Thus… the issue of computability and accuracy in relativistic hydrodynamics ~~will be~~ is central to the effective simulation of quark-gluon plasmas~~, and is also an open problem across several other areas of physics~~.

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. For this reason, I am currently using computational fluid dynamics to simulate unitary Fermi gases, calculate values for their material properties, and compare results with experiment (e.g. [3]). This forms a solid foundation on which I will begin to develop simulations of quark-gluon plasmas in the next several months. My adviser, Dr. Paul Romatschke, has made significant contributions to efficient computational algorithms in relativistic fluid dynamics, and I hope to contribute to the resolution of this important issue 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 because hydrodynamics is a non-traditional method in the field. It has given me 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**

## [0]. 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.

[1]. Schaefer, Thomas. *What Atomic Liquids Can Teach Us about Quark Liquids*. ArXiv e-print, March 13, 2007. <http://arxiv.org/abs/hep-ph/0703141>.

[2]. 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.

[3]. 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

[4]. Romatschke, Paul. “New Developments in Relativistic Viscous Hydrodynamics” (2009). doi:10.1142/S0218301310014613.

Paragraphs 3 and 5 have the same topic sentence; quark-gluon plasmas are hard to study. Devin’s thought: flop paragraphs 3 and 4, talk about theory, say they’re hard to do experimentally, then say “since they are hard to study experimentally, more stable analogs are needed to verify theoretical results”.

First paragraph seems to fly conceptually. Another sentence between sentence 2 and 3?

Last sentence of second paragraph doesn’t seem to fit with the rest of the paragraph. Maybe that sentence would go better in the intro, and replace it with another background sentence on quarks and gluons.

The only matter that contains free quarks and gluons – by definition QGP, so kinda awkward. Maybe rephrase to “Study of quark-gluon plasmas is a unique opportunity to study the individual quarks, as opposed to composites of quarks”.

Keep in mind that it is a little funny that cold atomic gases and hot QGP would be analogous. Maybe touch briefly on this to help everybody. Possibly talking about the temperature and pressure requirements for degeneracy might help bridge the gap.

Sentences about “my research” are awkward; an abrupt change of content. Consider grabbing all of the various scattered sentences about your research and grouping them into one paragraph.

Experimental data suggests that quark-gluon plasma may have the lowest viscosity ever observed. The fluid that is thought to have the next lowest viscosity is a cold atomic gas called the unitary Fermi gas, which is an ultra-cold collection of fermions (typically Lithium) under the conditions in which the atoms exhibit the strongest coupling [2].

However, a primary challenge in the theoretical study of systems, like quark-gluon plasmas, that have high experimental uncertainty is finding ways to verify theoretical methods experimentally.