Samuel Evans, Class of 2019

Dual Major in Physics and Mathematics

Predictions From a Realistic Simulated Universe: Analyzing Illustris and IllustrisTNG
Abstract:

By creating a realistic simulation of the universe, the Illustris group opened the door to predicting how the cosmic web changes over time. Working under the Lambda Cold Dark Matter paradigm, which assumes the universe is made of normal matter, dark matter, and dark energy, researchers coded a combination of gravitation, chemical interactions, gas dynamics, and other physics, to run a simulation of the universe from soon after the Big Bang until today, and the result is realistic in many ways\textsuperscript{[1]}. With an accurate simulation, it is possible to make predictions about the behavior of galaxies and other large-scale structures over time.

In order to get involved in this research, I will look into the details of the Illustris and IllustrisTNG simulations to understand how they are “realistic,” and in what ways they fail to properly compare to observations. My work will involve looking into both the coding and the physical background of these simulations, to understand the inner workings behind the success of Illustris to manufacture a universe in which most empirically observed quantities agree with the numbers we measure in the real universe. Using this understanding, I will contribute to making predictions based on these simulations, and to perhaps discovering new cosmological truths.
Biographical Sketch:

I am a Junior majoring in both physics and mathematics. Studying math and physics has given me a great outlet to study patterns in nature, and I have enjoyed studying different types of patterns in philosophy and sociology courses as well. I particularly enjoyed my classes “The Philosophy of Science” and “Kids Rule!”, as they focused on studying different types of patterns than I am used to from math and physics. I even worked with professor Jane Juffer over the summer to research how children interact with and within Minecraft and Roblox. However, physics has been my greatest focus since getting hooked after picking up the book *The Elegant Universe* by Brian Greene and experiencing an AP Physics class in high school. In Spring 2017 I also took a serious interest in astronomy while taking “Introduction to Cosmology”, and learning about the likelihood that future technology will soon enable the collection of new types of data.

I am currently one of the Head Tutors in the Math Support Center at Cornell, and I am involved in research. In Spring 2017, I joined Professor Mukund Vengalattore and his group in studying ultracold atomic physics. Colder atoms have less energy and movement, and when there are fewer vibrations the small effects of quantum mechanics are easier to observe and study. In Fall 2016, I began to study combinatorial geometry with Professor Ed Swartz. It is possible to represent a surface by tiling it with triangles in such a way that its qualitative, or topological, features are preserved. My research involves looking for minimal such triangulations of different surfaces using as few vertices as possible.
Statement of Purpose:

I will spend this summer studying cosmological simulations, with Professor Mark Vogelsberger’s group at MIT.

Cosmology is the study of the large-scale structure of the universe and its evolution over time — and there is plenty we still don’t know in this field. It deals with formation and movement of stars, galaxies, galactic clusters, and even the dynamics of the physical space in which all these celestial objects reside. Such a study requires physics for understanding of kinematic interactions, chemistry for describing the evolution of clouds of gas and dust into stars and galaxies, frequently computer science to get approximate answers since the system in question is too complex to fully solve (it is the entire universe, after all!), and of course, mathematics to underlie all of these disciplines and give tools for effective analysis. Observations range from recording the paths of objects to performing spectroscopy on the light these objects shed in order to learn of their chemical composition. Current theory states the universe is expanding, and that the maximum speed at which matter can move is constant. Combined, by looking at light from distant galaxies, we can look “into the past,” since the light we see now from a galaxy X light years away was actually emitted X years ago. Just by analyzing what is visible in the sky and to telescopes in space, we can learn about billions of years of history.

Though the long-standing theory of the universe’s past is the Big Bang Theory, which describes a superhot blob that expanded into the universe today, many of the intricacies of the expansion and its effects are not yet fully understood. Even regarding the widely accepted idea of Inflation, a period of faster-than-light spacial expansion, there is plenty of ambiguity in the set of
predictions based upon this idea. Partly, this is due to the fact that there are different accurate ways to model inflation in the first place, as I learned in my cosmology class last year. Guessing that more of inflation happened earlier and faster could lead to a different prediction of the concentration of elements in the universe, for example. However, whichever model you start with had better lead you to predictions which match what is known due to observation, otherwise there is not much reason to keep said model. In other words, the model you choose should be within the bounds established by observations. There is a sizeable body of work dedicated to starting with different models for inflation and ending up with different predictions: for example, a paper by Garcia-Bellido and Morales\(^2\) predicts a type of older black hole to be responsible for a large portion of the “dark matter” in the universe. Though the effects of these gravitational fluctuations as constituents of dark matter would be different than the effects of any other candidate for the dark matter particle, the reason we cannot yet tell which is correct is that no observation to date has placed strict enough bounds to pick out one candidate over all the others. In fact, one primary reason for positing the existence of dark matter was an observation which didn’t fit with theory. The motion of stars and galaxies is consistent with much more mass being in a galaxy than the approximate sum of the contained stars’ masses, based on luminosity, so it has been posited that there is some “dark,” non-luminous matter to account for this difference.

I am interested in making progress in the field of cosmology by analyzing data carefully enough to get at tighter bounds on what the universe is really like, so that we can move past incorrect theories, and further examine the rest.

One might think the best way to do this is by developing new technology to make more precise observations of the stars and galaxies around us. Indeed, different forms of precise
observations certainly can lead to new discoveries such as the recent observation of gravitational waves due to the collision of black holes or neutron stars[^3][^4]. However, it turns out there are many exciting discoveries to make without even a single new observation of outer space. Following Moore’s Law, humanity’s computational power doubles approximately every 20 months, and in 2014 it finally grew large enough to simulate the evolution of a “statistically significant”[^1] volume of the universe from billions of years ago to today, with enough resolution to make out the structure of individual galaxies. This simulation, named Illustris, takes into account gravitational interactions, chemical interactions of hot gases, dark matter, and more sophisticated physical processes[^1]. A few years later, some refinements to the old code led to an updated version, IllustrisTNG[^5], and by analyzing the data from these simulations, this summer I will contribute to refining predictions about different types of large-scale structures in the universe.

What can we learn about the actual universe from something that’s just a simulation? Obviously the initial conditions of the Illustris simulations are not an exact description of our universe. You couldn’t point to a certain galaxy in these simulations and say, “Look, that one is the Milky Way Galaxy!” because the simulated universe does not have a one-to-one correspondence with our own. The simulation almost seems pointless to examine, then, until you start to look deeper. Sure, you can’t say which galaxy is the Milky Way, but you can point out a galaxy with properties very similar to it. Drawing a red circle around that galaxy, you could run the clock backwards and look for when, how, and where it formed— something which is not possible via physical observation. Though we can survey galaxies of many different ages by looking into the sky, we cannot watch one galaxy evolve over time, since we don’t have millions
of years to dedicate to such a task. There is certainly much more to find within the analysis of these simulations, and I will better understand the scope of this material when I start to study it in-depth.

My goal is to learn more about the relevant physics, mathematics, and cosmological theory regarding the Illustris simulations, and any sort of attempt to create such a large scale simulation of the universe. I will already have a reasonable background in cosmology and celestial mechanics from taking the similarly named classes at Cornell. I am optimistic that this summer I will become an active contributor to the analysis of the simulations, finding new insights about how to use the simulations to make predictions about the universe we live in. I will study the simulation themselves, such as the code behind them, where they could be inaccurate, and how realistic they are. According to the Max Planck Institute for Astrophysics, the simulated universe closely resembles our own[6]. Over the summer I will understand what “closely resembles” really entails, and learn the extent of the predictive power in these simulations. Working among the people who helped put together these simulations, I will learn about how to work with a large scale simulation in the first place; learn what parts are problematic and how to get around these issues; discover how physics, cosmology, chemistry, mathematics, and computer science are integrated into the same study; check that simulation and observation match; and then, based on analyzing these Illustris simulations, make predictions about what we should expect to observe in the future.
Bibliography


