Second Semester Report

Student Information

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Thesis Title	Mapping the Cosmic Web: From Simulations to the Deepest Galaxy Surveys

Overview

One of my primary goals in this PhD project has been, and continues to be, attempting to develop new tools for the comprehension of the dark energy component of the current cosmological model. This semester, similar to the first, my focus has been to explore utilizing AI as these potential tools. I continued my efforts to do so by practicing my coding skills with small side-projects of my own, and delving deeper into the literature on cosmology and deep learning models currently popular within the field. Additionally, I enrolled in three different classes, one of them was the continuation of Astrostatistics, and the other two were related topics in astronomy and astrophysics. I maintained my participation in regular journal review and exploratory seminar groups as well. Furthermore, I continued to participate in Euclid Consortium events when possible, while managing the consortium's LinkedIn page. My work toward developing tools for use in analysis and further understanding of dark energy for this semester took a step in the right direction as I managed to successfully train a Graph Convolutional Neural Network (GCNN), known as DeepSphere, to estimate average redshift and cosmological parameters of a given patch of the sky. I shall provide further information on this work–as well as all the other efforts mentioned above–in the Details section below.

Details

Coding Projects

After completing a slew of online coursework for coding last semester, I decided this semester to take a more diverse approach to my continued coding education. Many of the courses I completed left me with "continued learning" suggestions; most of them were self-exploratory projects that could be undertaken as a means of developing one's coding skills and "instincts" (so to speak). Everything from preparing large amounts of data, to creating functions and pipelines to streamline work, to altering and improving machine learning models was included. Many of the projects provided insight that I was able to carry over into my research, allowing me to take further steps towards building the kind of tools that will be most helpful for understanding dark energy.

Literature Review

I continued to deepen my understanding of mainstream research in machine learning and cosmology by delving further into literature. I continued to work towards finishing "Cosmology," by Daniel Baumann, dedicating some time between classes to study its content and practice some of the problems it provided. Beyond the textbook, I regularly read papers covering content from machine learning models (specifically convolutional neural networks (CNNs)), to exploration of the ISW effect, and to various cross-correlations already being made by various teams around the world. Due to this semester being far more focused on my strides in development of an AI tool, much of the literature I explored was geared towards determining the sorts of measurements and correlations I ought to be structuring my model to be making. Between my supervisor and myself, we found that there have been a few correlations already made between CMB and density maps involving AI; however, there seems to be a gap in using AI to make correlations between ISW and density maps using AI. Therefore, I have begun to structure much of my AI application towards making such a correlation, as well as continuing to find a way to use it to constrain cosmological parameters.

University Coursework

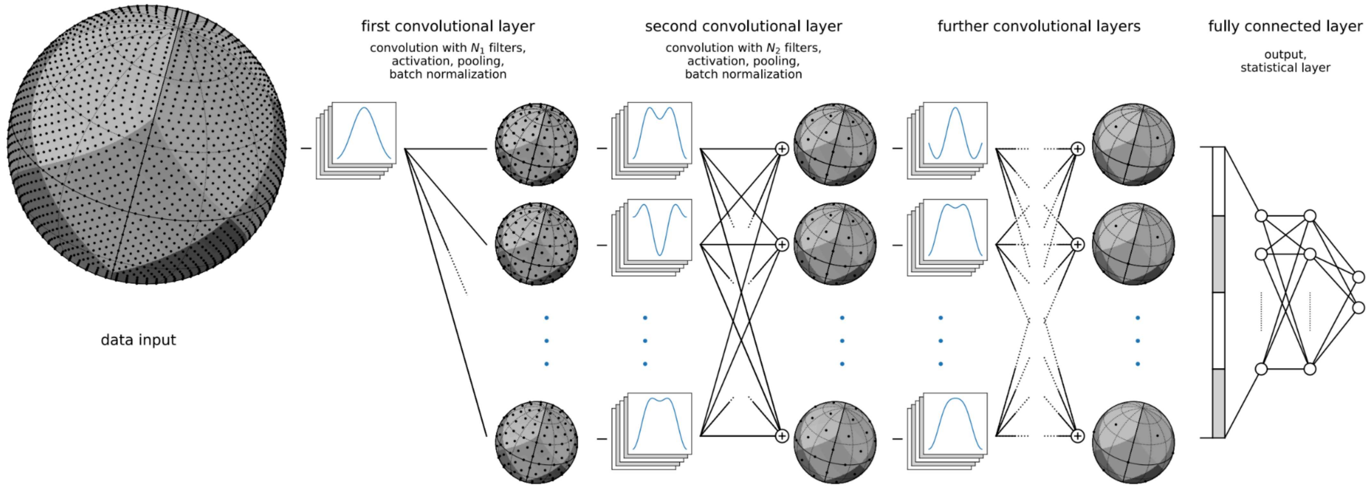
At the university, I enrolled in three courses: "Astrostatistics II," "(Exo)Planetary Atmospheres II," and "Compact Stars." The first class was a continuation of the exploration of statistical methods used in astronomy and astrophysics, taking off from where the previous class finished. Much of the content was based on what the professor decided to implement, rather than the provided content of a given book. The class ended up covering a great many concepts important to machine learning, such as principal component analysis, grouping methods, and (most directly applicable for me) neural networks. It was a pleasant surprise to receive a tailored exploration of such modernly pertinent content. The second class was partially applicable to my own research. It was a seminar in which students took turns researching planets' atmospheres for a few weeks, and then presenting their findings to the class. It involved reviewing more than one scientific article at a time (which was a great practice as a graduate student and researcher), understanding modern astronomical/planetary scientific methods, and compiling them into a neat summary to present. The third and final class was also only partially applicable to my current research, however, it was of significant interest to myself. I have always had a soft spot in my heart for compact stars, and beyond my current studies, I hope to someday find a way to apply the study of compact stars to cosmology. I have already read a few articles that have attempted to try something along those lines (such as one-star or one-galaxy cosmology, or theories involving a rotating relativistic universe), and perhaps some other project in my future will be able to incorporate such ideas.

Seminars and Groups

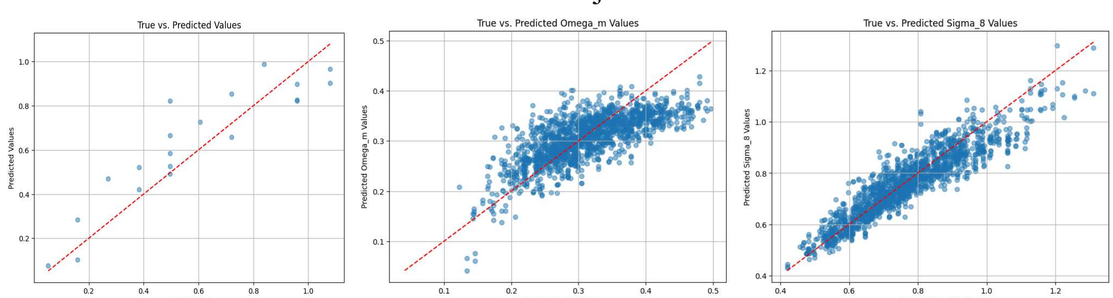
My time participating in various seminars and journal review groups was more limited this semester, as I found myself more engrossed in my research during the time between my classes. I kept up with CosmoVerse: the group of scientists from across Europe that holds regular virtual meetings to explore and discuss current research and new journal articles. I also maintained attendance and participation at the Konkoly observatory (CSFK) AI meetings every other week. Furthermore, during the regular meetings with both my supervisors and team of PhD students, I presented findings from some key papers on CNNs that have been applied to astronomy and cosmology. Each week, whether we met at ELTE or at Konkoly, we all continued to discuss topics for further investigation, present journal articles, and/or propose projects to take further steps in our research. Many of these meetings brought about key influences for specific steps I took to further my research.

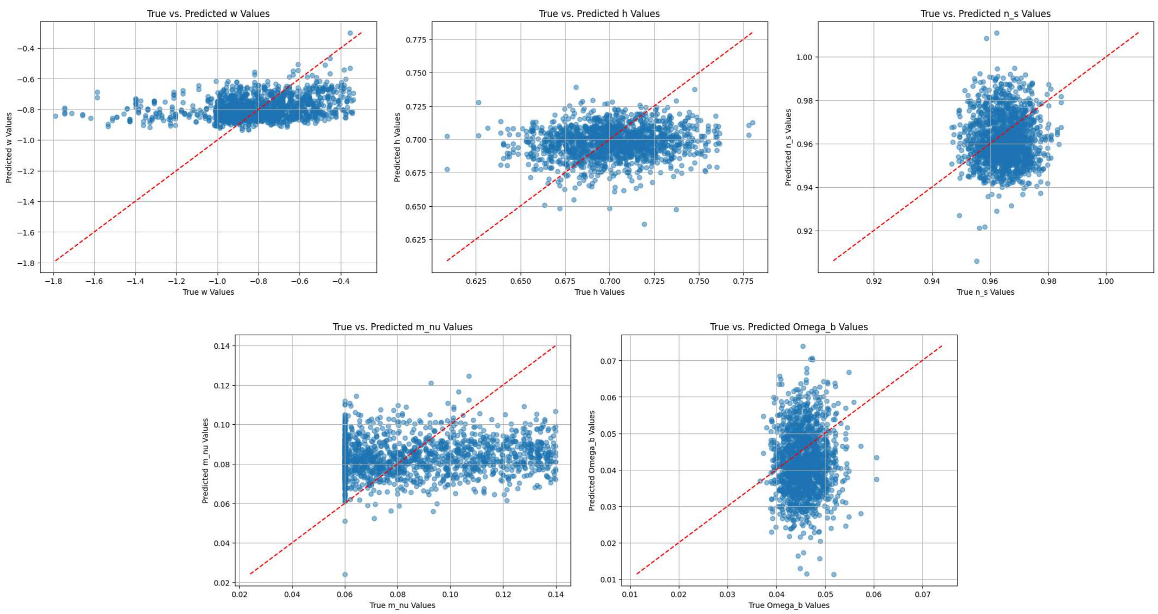
Research Progress

Throughout the semester I made multiple small steps towards crafting useful AI tools in understanding dark energy; however, there were two major strides that came as a result of the culminated efforts. First, I managed to structure the DeepSphere GCNN model, and train it, in a way that it could predict the average redshift of a given section of the sky. Second, I applied what I learned from completing the first task to train DeepSphere to derive seven cosmological parameters (Ω_{m}, σ_8, w, h, n_{s}, m_ν, and Ω_{b}) given a section of the sky. Before delving into the results, below is a depiction of the general structure of DeepSphere.



The structure of DeepSphere is one that performs two or more successive convolutions (depending on the desired setup) followed by a system of fully connected (dense) layers. At each layer the data is being “shrunk” in size, or encoded, via convolution and pooling, and the most significant features (which are learned through training) of the input are passed on to the next layer. By the time the information reaches the fully connected layer, it has been significantly reduced in size and, in the case of my model’s setup, flattened into a single large array of data. I input a section of a full-sky galaxy density map, and the network encodes it down to just a few outputs. Most of the struggle came from finding clever and efficient ways to deal with the enormous amounts of data (the data was provided by the Gower St. Simulations, which were full sky galaxy simulations for a wide range of cosmologies). Thanks to some earlier work by my team (who used the same simulations for void and ISW measurements) I could simplify some steps in my work, and ultimately, I was able to keep the data prep and training all within my computer’s memory budget. Below are some graphs showing the predictions DeepSphere was able to make after the first and second major tasks this semester.





The first graph, without the detailed title, shows the first training of DeepSphere, in which it learned to predict the average redshift of a section of the sky. The rest of the graphs show in their title which cosmological parameter the machine was predicting based on a given section of the sky. All seven of the cosmological parameters were predicted simultaneously by the model. Due to some of the predictions showing significantly more success than others, some next steps I will take will be splitting up the predictions across several dedicated models, and tinkering with the structures of these models to try to fine-tune them to each specific parameter. Beyond this, the next big step moving forward will be determining how to connect the use of AI to ISW, constraining cosmological parameters, or further exploration of dark energy.

Conclusion

Progress on my research this second semester has included the continual expansion of my own skills and knowledge, deeper exploration of GCNNs and (in particular) DeepSphere, and the explicit curation of data and training of AI for the purpose of being a tool in dark energy exploration. For the next semester this will, in general, continue; however, additionally, I will split up the training of DeepSphere to be more specialized, and I will start exploring specific connections that can be made between this tool's capabilities and the probing of dark energy.