

Deep Regression Techniques for Decoding Dark Matter with Strong Gravitational Lensing

Google Summer of Code 2022 Project Proposal

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Proposal Abstract

The study of dark matter substructures has shown promise in addressing the open-ended and long-standing challenge of identifying the true nature of dark matter. Strong gravitational lensing is a potential way to learn more about dark matter's basic nature by probing its substructure. Deep learning approaches can properly recognize images with substructure and distinguish WIMP particle dark matter from other well-motivated models including dark matter condensates, superfluids, and vortex substructure. The DeepLense pipeline combines state-of-the-art deep learning models with strong lensing simulations based on lenstronomy. This project will focus on estimating dark matter characteristics, such as population-level quantities and properties of dark matter particle candidates (e.g. CDM, WDM, axions, SIDM), using deep regression techniques. I shall be implementing and benchmarking the results of different neural network architectures and ensembles on the available DeepLense simulated dataset. To provide a high-level interface for future development, an attempt will be made to incorporate these models with the DeepLense pipeline.

Background

One of the most pressing concerns in physics today is the identity of dark matter. Even though a number of plausible ideas have been offered in recent decades that might reveal dark matter's true identity, the underlying nature of dark matter has remained a mystery. Weakly Interacting Massive Particle (WIMP) is considered to be one of the most promising candidates that could prove insight into this quest. A promising path to identifying the nature of dark matter is to study the substructure in dark matter. A promising path to identifying the nature of dark matter is to study the substructure in dark matter.

To put gravitational lensing simply, when light from distant galaxies passes through large objects in the cosmos, the gravitational attraction from these things can distort or bend the light. Strong gravitational lensing has yielded promising discoveries in the detection of substructure in heavily lensed quasars, high-resolution observations with the Atacama Large Millimeter/submillimeter Array, and extended lensing. With simulated galaxy-galaxy strong lensing pictures, interesting findings have recently been produced using supervised machine learning methods for detecting dark matter substructure features.

Deep learning methods have the potential to accurately identify images containing substructure and differentiate WIMP particle dark matter from other well-motivated models, including vortex substructure of dark matter condensates and superfluids. Taking this as a motivation, in this project, deep regression techniques would be exploited to estimate quantifiable dark matter properties, including population-level quantities and properties of dark matter particle candidates (e.g. CDM, WDM, axions, SIDM).

Key Tasks

- Conducting an extensive literature survey on machine learning applications in this field.
- Experimenting with different pre-trained models
 - Implementing the selected network architectures and ensembles in PyTorch
 - Training, fine-tuning, and testing these networks on the provided dataset(s).
- Incorporation with the DeepLense pipeline.
- Proper documentation and analysis of procedure, observations, and results.

Project Timeline

- **April 4 - April 19 (Application period)**
 - Complete the pre-requisite tests (Common Test I. Multi-Class Classification, Specific Test III. Learning Mass of Dark Matter Halo)
 - Submit the test files and results along with my CV to the organization
 - Wait for an acknowledgment reply from a mentor and submit a proposal.
- **April 19 - May 20 (Acceptance waiting period)**
 - Conduct an extensive literature survey on previous and related works.
 - Study and discover potential pre-trained models.
 - Install all required dependencies and set up a development environment in my system properly.
 - Understand the DeepLens Pipeline and explore the PyAutoLens library on which it is based.

- **May 20 - June 12 (Community Bonding period)**

- Discuss the project and expectations with the mentors.
- Consequently, formulate a to-do list of tasks.
- Discuss with the mentors regarding the simulated dataset(s), the possibility and procedure of data augmentation, and foreseen challenges.
- Make a list of potential pre-trained models.
- Planning the stacking and ensembling methodology in the case of usage of multiple models.

- **June 13 (Coding begins)**

- Comprehensive analysis and visualizations of the provided simulated dataset(s):
 - Identification of biases, noise, or any other predictive modeling issues.
 - Pre-processing the data consequently.
- Create a custom dataset class (in PyTorch) and implement data loaders for the provided data to load the simulated data in a suitable format to feed into the neural network(s).
- Perform mix-up and data augmentation if possible and necessary.
- Train and test the listed potential pre-trained models on the data.
- Try various combinations of model stacking and ensembles to improve predictions.

- **July 25 - July 29 (Phase 1 evaluation)**

- For the first evaluation, I plan to complete and present the following tasks:
 - Results and visualizations and what could be inferred from the extensive analysis of the dataset.
 - Methodology of pre-processing the data.
 - Custom dataset class and data loaders to load the simulated data.
 - Carrying out data augmentation techniques (if possible and required)

- **September 5 - September 12 (Phase 2 evaluations)**

- By the time of the final evaluation, I plan to complete the rest of the tasks:
 - Training, fine-tuning potential pre-trained models on the provided data.
 - Hyperparameter tuning and using different promising techniques (for example, attention mechanism, parameterized activation functions, learning rate schedulers, methods for faster training convergence, etc).
 - Trying different combinations of stacking/ensembling best models to further improve predictions.

- Incorporating the models with the DeepLense pipeline to use the models without training them again and provide a high-level interface for future development.
- Formulating pellucid documentation in parallel.
- **September 20 (Initial results of GSoC 2022 announced)**
 - Further refinement of documentation and presentation of results corresponding to feedback from the mentor.
- **Post GSoC**
 - Work with the community to get all the code and models integrated with the DeepLense Pipeline.

Features and Deliverable Specifications

- High-performing neural network models incorporated with the DeepLense pipeline.
- Weights for the network architectures for future re-use and further fine-tuning.
- Proper documentation and tutorial notebooks for the usage of the model and code.
- Publication-ready graphical material like plots, graphs, tables, etc. to display the benchmarking results on the simulated data.

Summer Availability / Commitment

I am currently in the final semester of my undergraduate studies. My final examination and bachelor's thesis project presentation will be over before the second week of May. I will then have a gap of 3 months between the completion of my undergraduate degree and the inception of my Master's. Hence, I shall be able to completely devote my time and commit to the project.

References

- Alexander, Stephon, Sergei Gleyzer, Hanna Parul, Pranath Reddy, Michael W. Toomey, Emanuele Usai, and Ryker Von Klar. "Decoding dark matter substructure without supervision." *arXiv preprint arXiv:2008.12731* (2020).
- Alexander, Stephon, Sergei Gleyzer, Evan McDonough, Michael W. Toomey, and Emanuele Usai. "Deep learning the morphology of dark matter substructure." *The Astrophysical Journal* 893, no. 1 (2020): 15.
- Alexander, Stephon, Sergei Gleyzer, Pranath Reddy, Marcos Tidball, and Michael W. Toomey. "Domain Adaptation for Simulation-Based Dark Matter Searches Using Strong Gravitational Lensing." *arXiv preprint arXiv:2112.12121* (2021).

About Me

[Link to my CV](#)

[Link to my portfolio website](#)

Relevant Experience

1. Research Intern @ University of Franche-Comté

- Working under Dr. Raphaël Couturier
- Working on Autoencoders and Object Detection algorithms to predict optimal clusters in unlabelled data

2. Research Intern @ Aix-Marseille University in collab. with NIT Silchar

- Worked under the joint guidance of Dr. Benoit Favre and Dr. Partha Pakray
- Formulated novel methods for efficiently evaluating summaries generated by Abstractive Text Summarization systems using Textual Entailment
- Compared summaries generated by a baseline Seq2Seq LSTM model having Attention mechanism with pre-trained BART-based text summarizer using proposed evaluation metric

3. Data Science Intern @ Devopedia

- Performed web scraping using BeautifulSoup and used Feed-forward Neural Networks to automatically identify Title, Author, and Year (of publishing) entities from any webpage
- Constructed an end-to-end system using Python that generates Reference Citation strings in the Chicago Manual Style format from URL inputs

Publications

● “Exploiting Cepstral Coefficients and CNN for Efficient Musical Instrument Classification”

Saranga Kingkor Mahanta, Nihar Jyoti Basisth , Eisha Halder, Abdullah Faiz Ur Rahman Khilji, Partha Pakray

Paper under review at Applied Intelligence

● “Textual Entailment as an Evaluation Metric for Abstractive Text Summarization”

Swagat Shubham Bhuyan, Saranga Kingkor Mahanta, Partha Pakray, Benoit Favre

Paper under review at Journal of Artificial Intelligence Research

● [“COVID-19 Diagnosis from Cough Acoustics using ConvNets and Data Augmentation”](#)

Saranga Kingkor Mahanta, Shubham Jain, Darsh Kaushik, Koushik Guha

Paper presented at IEEE International Conference on Advances in Computing and Future Communication Technologies 2021 - MIET Meerut

- [“Deep Neural Network for Musical Instrument Recognition using MFCCs”](#)
Saranga Kingkor Mahanta, Abdullah Khilji, Partha Pakray
Paper Published in Computación y Sistemas: Vol 25, No 2 (2021)

Vision and Goals

My long-term vision is manifold. I wish to understand the underlying nuances of neural networks and how they automatically extract the essential features from data. Gaining such insights will help in building more robust models that will tackle adversarial examples, which are inputs that are purposefully designed, or adulterated to cause a model's predictions to be incorrect, yet look valid to a human. Immunizing models against adversarial attacks is not only a vital task for security measures, but solving this problem would also shed new light on the model-based optimization problem. This should ultimately result in the creation of novel functions, the outcomes of which would be revolutionary across diverse fields. Another intelligent task that interests me is zero-shot learning, training a model to predict examples from unprecedented classes. This is a trivial and frequently occurring scenario for humans, to encounter newfound objects, yet be able to draw relations about them from pre-acquired knowledge and experience. That is true intelligence.

In a broader sense, I am always looking for exciting areas where Machine Learning and Deep Learning techniques could be applied to produce insightful findings. This project would be one such sophisticated venture that I direly want to take upon.

Technical Strengths

- **Computer Languages:** Python, C, C++, HTML, CSS
 - **Libraries and Frameworks:** PyTorch, TensorFlow, NumPy, Pandas, Flask, Librosa, Scikit-learn
 - **Domain Interests:** Deep Learning, Artificial Intelligence, Computer Vision, NLP, Generative Learning
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