Gravitational Lens Finding for Dark Matter Substructure Pipeline

Google Summer of Code 2023 Project Proposal

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Abstract

The search for a deeper understanding of dark matter has long been one of the great challenges of modern astrophysics, and one promising avenue is through the study of substructures in dark matter. One of the most potent approaches for analyzing dark matter substructure is Gravitational Lensing. Strong Gravitational Lenses can provide a unique view of the distribution of dark matter, allowing us to study the structure of subhalos and other small-scale features. However, identifying and understanding strong lenses is a complex and challenging task, requiring advanced algorithms and computational tools. This project aims to address this challenge by integrating Deep Learning methods with strong lensing simulations based on lenstronomy. We will be implementing various cutting-edge deep learning methods to detect strong lenses from datasets of mock surveys. We will then pass these new found lenses on to the rest of the DeepLense pipeline for detection, classification and interpretation of dark matter substructure.

Background

The quest to uncover the true-identity of dark matter has been a major focus of physicists for decades. The mystery surrounding dark matter persists to confound researchers despite significant advances in the field. However, a few contenders have come to light who might be able to provide the solution to this mystery. Weakly Interacting Massive Particles (WIMPs) and dark matter condensate models, such as Bose-Einstein condensates and Bardeen-Copper-Schrieffer condensates (BCS), are some of these. We now have a rare opportunity to distinguish between several models of dark matter and learn more about its fundamental characteristics. These condensates contain vortices that can produce dark matter halo substructure components.

Gravitational Lensing, the bending of light caused by the gravitational force of massive objects in the universe, provides us with a powerful tool for studying the substructure of dark matter. Strong gravitational lensing has been used successfully in the past to explore and study substructures in dark matter, allowing us to distinguish between different sorts of substructures. We can continue to acquire insights into the properties and structure of dark matter and its substructures by developing and enhancing these techniques.

Motivation

While deep learning methods have shown promising potential in identifying substructures in dark matter using gravitational lensing, there are still several limitations in the existing methodologies. Dealing with the diverse noise and biases included in astronomical imaging data is a huge task. These factors can result in false positives or missing detections, which can have significant consequences for precisely interpreting the substructures in dark matter. To overcome these constraints, new ways that can successfully address these issues are required. One potential solution is to incorporate more advanced deep learning architectures and training techniques capable of dealing with the intricacies of astronomical data. Thus, this project is a crucial step for the rest of the DeepLense pipeline, as the accurate detection and classification of strong lenses will enable further research and analysis of dark matter substructures. The identification of new lenses in mock surveys using new deep learning techniques will also provide a wealth of data to be passed on to other DeepLense projects, contributing to a deeper understanding of the properties and structure of dark matter.

Key Tasks

- Conducting a literature survey on the latest deep learning architectures that will be relevant to our project.
- Developing and implementing new deep learning models that can accurately identify images containing lenses.
- Training and testing the developed models on various datasets to evaluate their performance and improve their accuracy.
- Integrating the developed models with the rest of the DeepLense pipeline for detection, classification, and interpretation of dark matter substructure.
- Documenting all implementation steps, results, and analysis in detail to provide clear and concise information for future reference and potential improvements.

Proposed Program Timeline

- ***May 4 - May 28 (Community Bonding Period)***
    - Focus on getting to know the DeepLense community and their goals for the project.
    - Join relevant communication channels and attend community meetings to introduce myself and learn more about the project's goals and objectives.
    - Spend time familiarizing myself with the project's codebase, setting up the development environment, and going through the existing documentation to gain a better understanding of the current state of the project.
    - Additionally, I will use this time to discuss with my mentor and other community members about the project's technical details and seek feedback on my proposed approach.

- ***May 29 - July 14 (First Half)***

  By the end of first half, I plan to complete the following tasks:

    - Performing a comprehensive literature review to identify the latest and most relevant deep learning architectures for the project. This review will be aimed at gathering insights on the strengths and limitations of existing techniques, and identifying potential areas for improvement or innovation.
    - Familiarize myself with the DeepLense pipeline and explore PyTorch to prepare for the implementation of the selected neural network architectures.
    - Analyze the simulated datasets to identify any class imbalance, biases, or any other predictive modeling issues that might arise during training.
    - Preprocess the dataset as per requirements and develop a general data loader class that can be used to load the simulated data in a suitable format to feed into our neural networks.
    - Implement the selected neural network architectures in PyTorch, and experiment with different hyperparameters to find the optimal architecture for the problem at hand.
    - Discuss with my mentors and other members of the community to finalize the network architecture and set up a version control system to track the progress of the project and ensure that the code is properly documented.

- ***<u>July 14 - August 28 (Second Half)</u>***

  By the end of second half, I plan to complete the following tasks:

  - Developing and refining the code for training and testing the selected neural network architectures, while ensuring that they meet the necessary performance metrics and accuracy requirements.
  - Experimenting with various hyperparameters and training setups to optimize the performance of the neural networks and comparing the results with existing state-of-the-art architectures.
  - Ensuring that the developed architecture is fully compatible with the DeepLense pipeline, and integrating it into the pipeline seamlessly to expand its functionality and capabilities.
  - Creating comprehensive tutorial notebooks and scripts to guide users on how to use the developed code and architecture effectively.
  - Documenting the entire project in detail for future reference and potential integration with other projects.

- ***<u>Post-Program Plans and Contribution to the Community</u>***

  I intend to keep collaborating with the DeepLense community after the program is over to ensure that our developed models are successfully integrated into the pipeline. This would entail resolving any possible problems that emerge during implementation and improving the models in response to user feedback. In order to make the models more available to academics working in the field, I also want to investigate the viability of deploying them on cloud infrastructure. Lastly, I will try to publish the project's findings in a pertinent conference or journal in order to share our findings to a larger audience and promote more study in this field.

Deliverables

- A set of trained models for gravitational lens detection, suitable for use with the DeepLense pipeline.
- Documentation of the models, including detailed descriptions of the architectures used and the hyperparameters tuned, as well as any preprocessing or post processing steps employed.

- Analysis of the performance of the models on a range of test datasets, including both quantitative measures (e.g. precision, recall, F1 score) and qualitative assessments of their ability to correctly identify gravitational lenses.
- Tutorial notebooks/scripts for using the trained models with the DeepLense pipeline, along with detailed instructions for modifying the models or training new ones on other datasets.
- A report summarizing the key findings of the project, including any insights gained into the strengths and limitations of current gravitational lens detection methods, as well as potential avenues for future research.

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).

My Background

As a 3rd Year CSE Undergraduate student at NIT Silchar, Assam, India, I have a good experience in machine learning and deep learning, having worked in this field since my first year of college. I am always looking forward to enhancing my skills and have undertaken several projects in this field. Some of my notable achievements and experiences include:

- Currently working as an AI Research Intern at **Artificial Intelligence Institute at University of South Carolina (AIISC)**, under **Prof. (Dr.) Amitava Das**. Here I am working on improving **Language models** by focusing on the linguistic understanding aspect of the models. Developed a novel language model which enhances traditional distributional models by incorporating more linguistic information to the model to understand the syntactic structures of language. I am currently preparing a **research paper** for publication in a peer-reviewed journal.

- Completed a research internship at the **Machine Intelligence and Bio-Motion Research Lab** under **Dr. Anup Nandy, Assistant Professor, Computer Science and Engineering, NIT-R.** During this internship, I explored 3D Human Gesture Data captured by kinect, extracted features, and developed a high-performing model for **Human Gesture Recognition**.
- Won the **Best Project Award** from the East Zone in Anveshan 2022 - Student Research Convention for my project on **Segmentation of Roads from Satellite Images**.
- **Ranked 2nd in Data Strata** - Annual Data Science Hackathon Nit Silchar.
- An active Moderator of the **Machine Learning Club of NIT Silchar**, where I conducted Machine Learning Classes, took a few workshops, and helped the club grow.

Working as a Research intern has given me first hand experience of working in the field of Machine Learning and Deep Learning. I have acquired the experience of what it's like working under a mentor and developed new skills, be it both technical and soft. During the internship I have read many research papers and successfully implemented those architectures and techniques, which eventually helped me to improve my deep learning skills.

Here is a link to my CV - Krishnav_CV.pdf