Deep Regression Techniques for Decoding Dark Matter with Strong Gravitational Lensing

Tests done - 1&3
Link-Tasks

Abstract

Deep learning has been successful in identifying various substructures of dark matter halos. The mass density of the vortex substructure of dark matter condensates on simulated strong lensing images was estimated using deep learning. Along with this, during the classification of substructure, it was observed that the error map produced by the MSE loss function on the image contained enough information to produce a distribution of substructure mass on the lensing plane. I plan to explore this concept and build models that produce comparable or even better results than the ones built on the lensing images.

1. Motivation

Deep learning has been shown to solve problems in various domains with almost unparalleled results. Gravitational lensing is a phenomenon that can occur when a huge amount of matter creates a gravitational field that distorts and magnifies the light from distant galaxies that are behind it but in the same line of sight. Such lenses can be produced due to the presence of dark matter. Using such images, classification of substructures is possible with the help of deep learning. Such classification has been done with promising results. Taking inspiration from this, regression models were built to estimate the mass density of the vortex substructure of dark matter condensates. For this, two types of dark matter - subhalos of CDM and vortices of superfluid dark matter using the PyAutoLens package, were used. Currently, xResNetHybrid model is used to predict the mass densities from the lensing images. Another approach that gives comparable results involves binary classifiers trained on error map data. The error maps are given by the MSE loss for the classification data and it encodes information on the location of the substructure. I plan to build on this semi-supervised method.

FIG. 7. MSE loss for identical simulated images (save substructure) with no substructure (left), vortex substructure (middle), and vortex substructure with labeled vortex position (right).

Source - Paper 1: https://arxiv.org/pdf/2008.12731.pdf

2. Proposal

Use error maps obtained from classification tasks to estimate the mass density of vortex substructure of dark matter condensates on simulated strong lensing images. The previous experiment used AAE and then passed the error maps through ResNet to perform binary classification. They trained three ResNet architectures as binary classifiers between vortex, subhalo, and no substructure classes. The AUC between no substructure and subhalos was 0.95939, no substructure and vortices 0.99690, and between no substructure and both types of substructure 0.98361. The classification scores were comparable to the scores when lenses were used directly. For estimating mass densities, we can compare the results to last year's project, where MAE was used as the metric. The deliverables will be a semi-supervised regression model that estimates the mass densities. With this, the unsupervised part can again be used with binary classifiers to improve on the previous semi-supervised model. An Equivariant Neural network can also be explored for the supervised classifier.

3. Project Timeline

Week	Task
1	Discuss
2-5	Explore and build initial model
6	Compare models and choose
Phase 1 Submission	
7-8	Optimize the model
9-11	Test
12	Patch up and push
Submission	

Discuss
Prepare data and environment. Discuss and decide on what methods to explore and reproduce the previous results as a benchmark. Decide on the metric.

Explore and build initial model
Implement the methods discussed in the 1st week, try out different unsupervised models to get the feature space, and apply vanilla ResNet for classification. Explore both binary and multi-class classification methods.

Compare models and choose
Compile the results, compare them, verify the implementation and discuss strategies for optimization.

Optimize the model
Optimis the supervised classifier. Experiment with different models, like ResNet, AlexNet, and VGG. Explore augmentation techniques and test out different activation functions and optimizers.

Test

Try out the strategies used in other projects to improve the regressor. Use an Equivariant neural network for binary classification and then compare.

Patching up

Compile all the results, add relevant documentation if missing. Look for bugs and get feedback, then upload to Github.

4. References

Paper-1

Stephon Alexander, Sergei Gleyzer, Hanna Parul, Pranath Reddy, Michael W. Toomey, Emanuele Usai, Ryker Von Klar "Decoding Dark Matter Substructure without Supervision," [2008.12731] Decoding Dark Matter Substructure without Supervision, 2021.

Paper-3

Stephon Alexander, Sergei Gleyzer, Pranath Reddy, Marcos Tidball, Michael W. Toomey, "Domain Adaptation for Simulation-Based Dark Matter Searches Using Strong Gravitational Lensing," [2112.12121] Domain Adaptation for Simulation-Based Dark Matter Searches Using Strong Gravitational Lensing, 2021.

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