Proposed Project: Dark Matter Simulation and Detection Using Machine Learning

**Objective:**  
I would like to work on a project that involves simulating the gravitational effects of dark matter in galaxies and using machine learning models to identify dark matter distributions from observational data. The aim is to explore how computational techniques and AI can be used to analyse galaxy rotation curves and detect the presence of dark matter.

**Background & Motivation**

Dark matter remains one of the biggest mysteries in modern astrophysics. It does not emit, absorb, or reflect light, yet its gravitational influence is evident in the motion of galaxies. One of the strongest observational evidences for dark matter comes from galaxy rotation curves, which show that the outer regions of galaxies rotate faster than expected based on visible matter alone.

In this project, I intend to simulate galaxy rotation curves using computational physics methods and train a machine learning model to predict dark matter density in galaxies. By applying numerical simulations and AI techniques, I hope to provide insights into dark matter’s distribution and its effect on galactic structures.

**Project Components**

**1. Computational Physics Aspect**

* Implement an N-body simulation to model the gravitational interactions between visible and dark matter.
* Compute galaxy rotation curves using Newtonian mechanics and compare them to observational data.
* Use numerical methods like Verlet integration or Runge-Kutta to simulate particle motion.
* Solve Poisson’s equation to model the gravitational potential of dark matter.

**2. Machine Learning Aspect**

* Train a regression model to predict dark matter density based on galaxy rotation curves.
* Use unsupervised learning techniques (e.g., clustering) to identify dark matter-dominated regions.
* Explore different machine learning models such as:
  + Random Forest or XGBoost for feature importance in rotation curves.
  + Neural Networks (CNNs or RNNs) for deep learning-based predictions.
  + Clustering techniques (K-Means, DBSCAN) for detecting hidden patterns.

**3. Astronomy Aspect**

* Study the observational evidence for dark matter, particularly from galaxy rotation curves.
* Use real astronomical datasets from sources such as:
  + The Sloan Digital Sky Survey (SDSS)
  + NASA’s Extragalactic Database (NED)
  + ESA’s Gaia mission data
* Compare simulated results with real-world astronomical data.

**Implementation Plan**

1. **Data Collection & Pre-processing:**
   * Gather galaxy rotation curve data from SDSS or NASA archives.
   * Simulate synthetic data for model training.
   * Pre-process data (normalization, noise reduction, feature extraction).
2. **Physics-Based Simulation:**
   * Implement N-body simulations in Python using NumPy and SciPy.
   * Compute and visualize rotation curves for different galaxy models.
   * Compare results with observational data to analyse deviations caused by dark matter.
3. **Machine Learning Model Training:**
   * Train regression and classification models on simulated and real data.
   * Evaluate models using metrics such as Mean Squared Error (MSE) and R² score.
   * Apply clustering methods to detect dark matter-dominated regions.
4. **Visualization & Analysis:**
   * Use Matplotlib and Seaborn for data visualization.
   * Generate heatmaps of dark matter distributions.
   * Compare predictions with astrophysical models.

**Expected Outcomes**

* A simulated model of galaxy rotation curves incorporating dark matter effects.
* A trained machine learning model capable of predicting dark matter density in galaxies.
* Visualizations of dark matter distributions based on real and simulated data.
* Insights into how machine learning can assist in astrophysical research.

**Tools & Technologies**

* **Programming:** Python (NumPy, SciPy, Matplotlib, TensorFlow/PyTorch, Scikit-Learn)
* **Astronomical Data:** SDSS, NASA Extragalactic Database, Gaia Data
* **Simulation Techniques:** N-body simulations, Poisson’s equation solving
* **Visualization:** Matplotlib, Seaborn

**Why This Project?**

This project interests me because it brings together physics, computation, and machine learning to tackle an open problem in astrophysics. By combining numerical simulations with AI-based predictions, I hope to gain deeper insights into the role of dark matter in galaxy dynamics. Additionally, this project aligns well with my interest in computational physics, machine learning, and astronomy, providing valuable research experience that could be applied to future studies or real-world astrophysical problems.