Research Experience

Anirban Bairagi

I am currently a Ph.D. student at the Institut d'Astrophysique de Paris, working with Prof. Benjamin Wandelt. Prior to this, I completed my Bachelor's and Master's degrees at the Indian Institute of Technology Kharagpur, where I began my research career under the mentorship of Prof. Sayan Kar and Prof. Somnath Bharadwaj. During my undergraduate studies, I spent considerable time working on gravitational wave physics. My primary interests lie in Large-Scale Structure and the Primordial Universe, with a strong inclination towards the theoretical and computational aspects of cosmology.

My research experiences during PhD are as follows:

How many simulations do we need for Simulation-based Inference in Cosmology?

(Collaborators: Benjamin Wandelt, Francisco Villaescusa-Navarro)
Link: `https://arxiv.org/pdf/2503.13755?`
Neural networks offer the potential to extract all non-linear information from cosmological density fields. However, achieving optimal "neural summaries" depends critically on the number of simulations available, network architecture, and training efficiency. We demonstrated that the 2,000 Quijote Latin-hypercube simulations are insufficient to to get the optimal neural summaries even for the two-point statistic P(k). We further derived a power-law relation to estimate the number of simulations needed to reach optimal performance.

A hierarchical approach for Field level Inference

(Collaborators: Benjamin Wandelt, Marina Cagliari)
Upcoming surveys like Euclid and DESI will deliver data rich in non-linear, non-Gaussian information, beyond what two- or even higher-order statistics can capture. Full field-level inference is ideal but computationally prohibitive at survey scales. We propose a hierarchical method that combines small-scale information from sub-boxes (patches) with large-scale information from P(k) and B(k), achieving nearly full information recovery while mitigating GPU memory limitations and simulation costs. We have shown this method works for Quijote dark matter and Quijote-PNG halos and currently extending this work for other tracers as well.

Point-set clustering correction using a displacement potential

(Collaborators: Benjamin Wandelt, Deaglan Bartlett)
Fast Particle-Mesh (PM) simulations offer speed but fail to capture small-scale structure. To address this, we developed an analytical displacement potential method that moves particles to match a target P(k). Applied to CHARM halos from fastPM simulations, our method corrects the small-scale clustering, producing power spectra comparable to full N-body results like Quijote, with improvements also observed in the bispectrum.

Simulation-based Inference using Wavelet Scattering Transform

(Collaborators: Ce Sui, Matt Ho)
We trained an ensemble of normalizing flows on wavelet scattering coefficients of fastPM halos and galaxies in redshift space, aiming to constrain cosmological parameters. Validating on Quijote and Abacus simulations, our models achieved parameter inference consistent with self-consistency tests, demonstrating robustness for the Learning the Universe pipeline.

CAMELS Hydrodynamical Primordial Non-Gaussianity Simulations Analysis

(Collaborators: Benjamin Wandelt, Francisco Villaescusa-Navarro, Shy Genel)
I am currently analyzing $50 Mpc/h^3$ CAMELS hydrodynamical simulations to study the impact

of various primordial non-Gaussianities on galaxy properties such as star formation rates, disk kinematics, stellar-to-halo mass relations, metallicity, and black hole accretion across redshifts. This work is particularly relevant for interpreting the unexpected population of massive high-redshift galaxies observed by JWST.

Some of my research experiences during my undergrad are mentioned below:

M.Sc. Thesis: Gravitational Wave Memory effect in Linearised Gravity and General Relativity

(Supervisor: Prof. Sayan Kar)
For my Master's thesis, I studied gravitational wave memory effects within both linearized gravity and exact radiative spacetimes. I calculated displacement and velocity memory for different gravitational wave pulses, first using the Braginsky-Grishchuk formalism and later through Jacobi propagators in exact spacetimes written in Brinkmann coordinates. I analytically derived memory observables for triangular and square pulses and visualized the deformation of a ring of test particles over time. Additionally, I investigated geodesic congruences using the B-tensor formalism, decomposed into expansion, shear, and rotation components. For a rotation-free, constant-volume hypersurface, I obtained exact expressions for expansion and shear, and derived the collision (focusing) time for gravitational wave pulses characterized by their base and slope. Both the geodesic deviation and congruence analyses consistently predicted the same focusing time, reinforcing the results.

LIGO SURF, Caltech: LIGO Laser Beam Tracking

(Supervisor: Prof. Rana Adhikari, Dr. Yehonathan Drori and Dr. Tega Edo)
Link: `https://dcc.ligo.org/LIGO-T2100205/public`
During my 2021 internship at LIGO, I simulated beam spots including mirror micro-roughness and CCD noise effects, and developed a CNN model to predict beam positions from CCD images with sub-pixel accuracy (error $<$ 40 microns). This method helps mitigate systematic errors in gravitational wave data arising from rotational movement of test masses.

Gravitational Waves Detection and Glitch Classification using CNN

Link: `https://ras.ac.uk/poster-contest/anirban-bairagi`
I developed a Convolutional Neural Network (CNN) model from scratch to classify noise artifacts in gravitational wave spectrograms into 22 different classes, achieving 95% accuracy after three hours of training. The model can also accurately identify gravitational wave signals, particularly chirp-like events, within noisy spectrograms. This work demonstrates the potential of machine learning methods for improving gravitational wave data quality and detection sensitivity.

MITACS GRI, Western University: Detection and Parameter Estimation of Continuous Gravitational Wave Signals

(Supervisor: Prof. Sree Ram Valluri)
I modeled continuous gravitational wave signals from non-precessing triaxial neutron stars, incorporating key effects such as Doppler shifts, Roemer delays, and Shapiro time delays. Using these realistic signal models, we performed parameter inference to recover neutron star properties in the presence of noise.

N-body Cosmological Simulation

(Supervisor: Prof. Somnath Bharadwaj)

- Developed a Python wrapper to efficiently run an N-body simulation code written in C.
- I wrote a 1-D Particle-Mesh code from scratch.

Machine Learning Projects

The following capstone projects were done during my undergrad as part of Deep Learning Foundation and Applications course (Grade: A) taken at IIT Kharagpur and Coursera Certification `https://anirbanbairagi.github.io/portfolio/#certifications/`.

Handwritten Digit Recognition

Link: `https://github.com/anirbanbairagi/MNIST`
Implemented and trained LeNet-5 CNN architecture using SGD and Adam optimizers with varying learning rates for handwritten digit recognition on MNIST; evaluated generalization by testing on Bengali Digit Dataset from Kaggle.

Emotion Tracking

Trained a Convolutional Neural Network using Keras that takes pictures from a camera, detects a person and determines if they are happy or not with a 95% accuracy.

Face Recognition

Developed and trained deep learning models using Keras for face verification and face recognition tasks, leveraging Siamese Networks and CNNs for robust identity matching.

Autonomous Driving- Car detection

Developed a car detection system using YOLO and TensorFlow that accurately identifies and localizes multiple car types in images with bounding box coordinates.

COVID-19 Radiology CXR

Link: `https://github.com/anirbanbairagi/COVID19Action-Radiology-CXR`
Implemented a class of CNN-based models to classify COVID-19 infection from chest X-ray images, achieving accurate detection; Conducted hyperparameter tuning and evaluated model performance using precision and F1 score metrics as part of the course project on medical imaging and AI.

Brain Tumor Segmentation

Trained a Brain Tumor Segmentation model for MRI scans using U-Net architecture as part of a Coursera certification.