Cosmology with Gravitational Waves

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Proposed for: [Bachelors/Masters]
Number of Students: ...

1. Introduction

The Cosmic Microwave Background (CMB) provides a snapshot of the universe at recombination, but the epoch preceding it, governed by physics at energies far beyond the reach of terrestrial colliders, remains largely unexplored. The Standard Model of particle physics is incomplete, and its extension via Grand Unified Theories (GUTs) or other high-energy frameworks often predicts a cosmological phase transitions in the early universe. This transition can leave behind observable relics, notably a stochastic background of gravitational waves (GWs) sourced by the topological defects such as cosmic strings and domain walls [1,2]. The recent discovery of a nanohertz GW signal by Pulsar Timing Arrays (PTAs) [3,4] has opened a new observational window, potentially providing the first direct evidence of new physics at the GUT scale. This project aims to theoretically model the cosmological signatures of high-energy physics and connect them to current and future GW experiments.

2. Project Description

The main body of the project will involve the theoretical and computational study of the gravitational wave spectrum generated by early-universe phenomena. The participant will focus on calculating the unique GW signatures produced by the dynamics of topological defects, such as cosmic strings formed after a GUT-scale phase transition, Primordial Black holes and the potential for these signals to be detected by GW observatories.

The research will follow two primary avenues:

Theoretical Modeling: Deriving the GW power spectrum from cosmological sources and studying its dependence on key model parameters.
Data Analysis & Simulation: Using the **PTArcade** package [5] to simulate and analyze PTA data, comparing theoretical models against the latest observational datasets to constrain the properties of the early universe.

The participant will use a combination of analytical methods and computational tools, including Mathematics, Python-based simulations and data analysis pipelines.

3. Prerequisites

- Proficiency in theoretical physics, cosmology, and general relativity.

- Programming skills: **Mathematica, Python**, familiarity with data analysis and scientific computing libraries (e.g., NumPy, SciPy, Matplotlib).
- Basic knowledge of gravitational wave theory and data analysis is a plus.
- English language proficiency.

Recommended Literature

1. http://www.cambridge.org/mw/academic/subjects/physics/theoretical-physics-and-mathematical-physics/cosmic-strings-and-other-topological-defects?format=PB
2. Science with the space-based interferometer eLISA. II: gravitational waves from cosmological phase transitions - IOPscience
3. https://doi.org/10.3847/2041-8213/acdc91
4. https://doi.org/10.3847/2041-8213/acdac6
5. PTArcade