Project Title: Developing machine learning tools for the analysis of gravitational wave signals

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Project summary

Developing fast and efficient data analysis strategies for **gravitational wave** experiments is a key aspect of achieving the scientific goals of facilities such as **LIGO** and **LISA**. The main aim of this project is to explore how recent developments in **machine learning** (ML) enhanced **simulation-based inference** (SBI) techniques can help solve outstanding problems in this field.

Background

There are a number of steps involved in detecting and analysing a gravitational wave source at a detector such as LIGO. First, possible events must be identified in the data stream using techniques such as matched filtering. Then, more careful Bayesian inference follow up is carried out on these candidate events. This second task is the focus of this project - i.e. how do we obtain accurate, robust, and fast inference on parameters such as the spins, masses, and sky locations of candidate binary black hole and neutron star signals?

Currently, classical approaches such as Markov Chain Monte Carlo (MCMC) or nested sampling are used to explore the parameter space of merging compact objects. Recently, however, there has been a rapid development of ML based alternatives broadly categorised under the term simulation-based inference. These SBI algorithms have been applied across a number of domains, including neuroscience, particle physics, cosmology, and gravitational waves. Broadly, the various techniques (the most common being versions of Neural Posterior Estimation, Neural Ratio Estimation, or Neural Likelihood Estimation) inherit a number of key properties such as statistical robustness, rapid inference/amortisation, and the ability to break up large models into smaller sub-components.

In the context of gravitational waves, SBI techniques could be crucial for solving problems centred around large event volumes at current detectors, or new classes of overlapping gravitational wave signals at future facilities which stretch the limits of classical sampling techniques.

Project details

This project will build on the **peregrine** (https://github.com/PEREGRINE-GW/peregrine) simulation-based inference code. The code currently implements an algorithm called Truncated Marginal Neural Ratio Estimation (TMNRE) and analyses spinning, precessing binary black hole (BBH) mergers. These systems will be modelled using standard waveform models such as IMRPhenomXPHM and SEOBNRv4. The first step will be to implement a normalising-flow based algorithm (such as Neural Posterior Estimation (NPE)) using standard networks in **pytorch**. Direct comparisons will then be made between the current classifier-based approach and normalising flows to assess the relative benefits and difficulties as far as inference time, training time, robustness, accuracy etc. are concerned.

Then, depending on the interest and scope of the project, there are a number of possible extensions including: developing a sequential (zooming in to relevant parts of parameter space) algorithm for the NPE approach; investigating the impact of different summary statistics and compression neural networks on performance and speed; or developing a model comparison approach (computing Bayesian evidences etc.) for efficiently comparing different models of the compact binary mergers.

Skills required

- Basic Python skills
- Interest in gravitational wave astronomy and data analysis
- Willingness to develop knowledge of pytorch and implementation of normalising flow-based architectures
- Basic understanding of Bayesian inference and Bayes' theorem

Useful References (List of important papers/review articles relevant to the project)

- (Bhardwaj et al.) Peregrine: Sequential simulation-based inference for gravitational wave signals https://arxiv.org/pdf/2304.02035
- (Dax et al.) Real-Time Gravitational Wave Science with Neural Posterior Estimation, https://arxiv.org/pdf/2106.12594
- (Papamakarios et al.) Fast ε-free Inference of Simulation Models with Bayesian Conditional Density Estimation https://arxiv.org/pdf/1605.06376

General References (List of papers referred to in the project)

- (Cranmer et al.) The Frontier of Simulation-based Inference https://arxiv.org/pdf/1911.01429
- (LIGO Scientific) Observation of Gravitational Waves from a Binary Black Hole Merger https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.116.061102

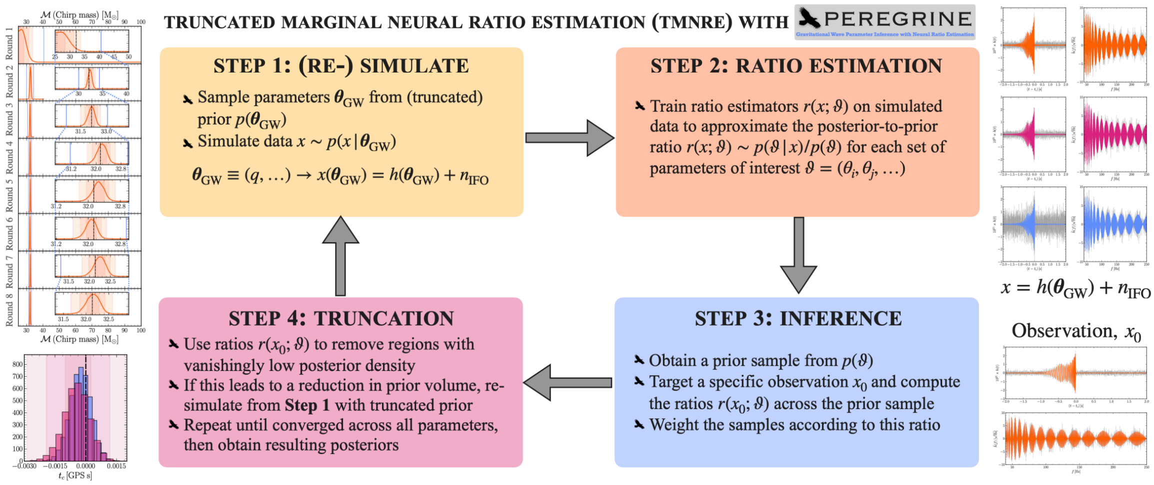

Figure 1: Schematic for the TMNRE algorithm used in the Peregrine code to analyse binary black hole mergers