Gravitational wave production using Simulation Based Inference

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1 Introduction

Magnetohydrodynamic (MHD) turbulence in the early Universe, whether stirred by a first-order phase transition or by primordial magnetic fields, sources a stochastic gravitational wave (GW) background that can be potentially observable by current and future GW experiments like LISA and Pulsar Timing Arrays. Its signal is set by the unequal-time correlator (UETC) of the anisotropic stress, $E_\Pi(k, \tau_1, \tau_2)$, which encodes all the information required for a robust predicition of the GW spectrum. The UETC depends on the non-linear dynamics of the source of GWs and, therefore, it requires to conduct high-resolution numerical simulations of the sourcing process to make an accurate estimate. Furthermore, computing the UETC is computationally costly and most simulations usually just compute the resulting GW background by solving the GW equation numerically, which is more efficient than computing UETCs of the sourcing fields (e.g., velocity or magnetic fields in sources of GWs due to the development of MHD turbulence in the early Universe). On the other hand, knowledge of the UETC would allow us to develop theoretical models that can be applied for a range of parameters that characterize the source of GWs, avoiding running expensive simulations for each input parameter of interest.

The objective of the propject is to use simulation-based inference to use the results of numerical simulations that provide the GW spectrum from MHD turbulent processes to train neural networks that allow to develop templates for the GW spectrum and for the UETC of the source. While the former is already enough to make predictions and parameter reconstruction given the observation, the latter modeling can provide us with a more thorough theoretical understanding of the sourcing process, making the results more trustable, falsifiable, and more directly applicable to a broader range of the input parameters.

Due to the humongous number of sources that we expect at the LISA band, the LISA Global Fit combining all the different possible sources, both transient and stochastic, as well as reconstruction of the different sources of noise, makes the problem of reconstructing a stochastic GW background originating from early Universe sources extremelly challenging. Therefore, accurate but

fast reconstruction of the GW background from the parameters that characterize the early Universe process leading to the GWs as, for example, a first-order phase transition around the electroweak scale, will become indispensable for a potential study of these signals from an observed GW background. Hence, these results could be key for studying different beyond the Standard Model physics that lead to a first-order phase transition, potentially providing an explanation to other fundamental open problems like the origin of baryons over antibaryons.y

We propose an MHD-only program that makes UETCs fast while building in the physics. We will learn the space–time spectrum $\tilde{E}_\Pi(k, \omega; T)$ of kinetic, magnetic and cross stresses directly. Positivity of the GW spectrum then holds by construction, and the signal follows from this spectrum on the light cone, $\omega = k$, where Alfvénic resonances and nonlinear decorrelation separate cleanly. We will (i) build streaming UETC diagnostics for MHD lattice codes; (ii) learn reduced stochastic dynamics that extrapolate to late times and high Reynolds numbers; (iii) quantify non-Gaussian corrections from intermittent magnetic fields; and (iv) build differentiable emulators in a compact, source-agnostic parameter space, including GW polarization from helical turbulence.

These emulators make simulation-based inference (SBI) possible. Our SBI pipeline will treat turbulence efficiency and UETC model uncertainty as nuisance parameters, so posteriors honestly include theory error. It will combine our turbulence emulator with existing sound-wave models, handle realistic foregrounds, and allow joint inference with intergalactic magnetic-field constraints.

The outcome will be validated MHD UETC models, a public correlator dataset, millisecond emulators, and an inference pipeline that links GW observations to early-universe turbulence and primordial magnetism with quantified uncertainty.