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Gravitational Wave Paleontology and the Progenitor Uncertainty Challenge

We are on the precipice of the Big Data gravitational wave (GW) era. Pairs of stellar-mass black holes (BHs) or neutron stars (NSs) across our vast Universe occasionally merge, unleashing bursts of gravitational waves that we can observe here on Earth since their first detection in 2015. Over the next few years, the population of detected mergers will rapidly increase from a few hundred to many million detections per year as new GW observing runs (LIGO/Virgo O4; 2023, LIGO/Virgo O5; 2025) and next-generation detectors (Cosmic Explorer; Einstein Telescope, LISA; 2035) provide data with ever-increasing precision and to larger distances, pushing the reach of gravitational-wave astronomy to the edge of the observable Universe; revolutionizing our view of the cosmos. Making the most of these observations and the rapidly increasing landscape of gravitational-wave detections requires comparing the observed properties, such as their rates, BH and NS masses, and BH spins, to theoretical "population synthesis models"simulating their formation pathways. However, at present, this endeavor is limited by the so-called progenitor "Uncertainty Challenge": uncertainties within the theoretical models are so large, and the models so computationally expensive, that learning about the underlying fundamental physical processes in the lives and deaths of massive stars from observations is completely out of reach, especially for rare events. All present-day simulations thus pay a high price by using highly approximate algorithms that treat the physical processes in a simplified way, or by limiting the total number of simulations, restricting the exploration of the impact of the uncertain physical input assumptions beyond a few variations. In this talk I will introduce the problem and lead an interactive discussion with the participants to investigate statistical techniques to tackle the key Uncertainty Challenge bottleneck in two key areas: (i) improving the sampling of rare events (such as GW sources) in simulations by improving techniques such as adaptive importance sampling, Markov Chain Monte Carlo, and nested sampling and (ii) developing effective emulators predicting model outcomes from small parameter explorations by improving upon techniques from deep learning, normalizing flows, uncertainty quantification, and Gaussian process regression.

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