Black Hole Spectroscopy: From Fundamental Physics to Precision Science

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Black hole spectroscopy with gravitational waves offers unprecedented access to the strong-gravity regime of general relativity. By studying the characteristic oscillations emitted after binary black hole mergers, we can test key predictions of Einstein's theory, search for possible deviations from the standard black hole paradigm, and probe new physics in extreme gravitational environments. In this talk, I will briefly review the essential theoretical background and the current status of gravitational-wave astronomy before focusing on recent progress and open challenges in black hole spectroscopy. As observations from next-generation detectors reach higher signal-to-noise ratios, theoretical uncertainties and data-analysis systematics will become increasingly important. Are our current theoretical frameworks sufficiently accurate to fully exploit the scientific potential of future detectors, or could systematic biases limit our ability to extract new physics from these observations? I will also discuss complementary directions and synergies with neighboring research areas. These include universal relations in neutron stars, which may provide new insights into the physics of dense matter, and analog gravity systems in quantum platforms, which offer novel ways to investigate foundational aspects of horizons, black holes, and strong-gravity phenomena in controlled laboratory settings.