Snowmass2021 - Letter of Interest

Numerical relativity for next-generation gravitational-wave probes of fundamental physics

Thematic Areas: (check all that apply ☐/■)

☐ (CompF1) Experimental Algorithm Parallelization
■ (CompF2) Theoretical Calculations and Simulation
☐ (CompF3) Machine Learning
☐ (CompF4) Storage and processing resource access (Facility and Infrastructure R&D)
☐ (CompF5) End user analysis
☐ (CompF6) Quantum computing
■ (CompF7) Reinterpretation and long-term preservation of data and code
■ (Other) (CF7) Cosmic Probes of Fundamental Physics

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Abstract: (maximum 200 words)

The next generation of gravitational-wave detectors, conceived to begin operation in the 2030s, will probe fundamental physics with unprecedented sensitivity. These observations will measure the equation of state of dense nuclear matter in the most extreme environments in the universe, reveal with exquisite fidelity the nonlinear dynamics of warped spacetime, put general relativity to the strictest test in the most extreme conditions, and perhaps use black holes as cosmic particle detectors. Achieving each of these goals will require a new generation of numerical relativity simulations that will run at scale on the supercomputers of the 2030s to achieve the necessary accuracy, which far exceeds the capabilities of numerical relativity today.

Motivation. The next generation of gravitational-wave detectors (proposed detectors include LIGO Voyager [1], Cosmic Explorer [2], and Einstein Telescope [3], each with expected operations beginning in the 2030s) will use gravitational waves from sources throughout the cosmos to probe fundamental physics with unprecedented sensitivity. Their observations of coalescing binary neutron stars and black-hole/neutron-star binaries will measure the equation of state of dense nuclear matter in the most extreme environments in the universe, and their observations of gravitational waves from merging stellar-mass black holes which contain the strongest spacetime curvature in the universe will put general relativity to the strictest tests.

Accurate theoretical models of gravitational waves are critical for inferring the properties and behaviors of the waves' sources. Near the time of coalescence, when the spacetime curvature and (if present) neutron-star matter are the most nonlinear and dynamic, all analytic approximations break down; then, the emitted gravitational waves can only be calculated with numerical relativity, that is, by numerically solving the equations of general relativity or, for simulations involving neutron stars, general relativistic magnetohydrodynamics (e.g., [4–8] and the references therein). These simulations are technically challenging, in part because the equations are strongly nonlinear and (if neutron-star matter is present) because the solutions contain shocks. They are also computationally expensive, requiring high-performance computing to achieve the necessary accuracy for applications to today's observations.

The accuracy required of numerical-relativity simulations increases with detector sensitivity. Achieving accuracy sufficient for next-generation detectors' observations with the highest signal-to-noise-ratios (SNR)—i.e. the observations with the most potential to reveal new fundamental physics—will require a new generation of numerical-relativity software, designed to run at scale on the supercomputers that will be available in the 2030s. Meeting this goal will include developing new, open-source numerical-relativity codes that will produce publicly available catalogs of simulated gravitational waveforms for coalescing compact binaries (i.e., binary black holes, binary neutron stars, and black-hole/neutron-star binaries).

Key applications of numerical relativity for probing fundamental physics include the following.

Nuclear physics and neutron stars When two neutron stars, or a black hole and a neutron star, coalesce, they emit gravitational waves that encode the behavior of the densest matter in the universe. But recovering this information from gravitational-wave observations requires an accurate theoretical understanding of the emitted waves, which requires numerical relativity simulations.

These simulations are challenging and expensive, yet they must be sufficiently accurate to avoid introducing systematic bias into the interpretation of gravitational-wave observations. The accuracy required increases with the square of the observation's signal-to-noise ratio [9]. The first (and loudest) gravitational wave observation from coalescing binary neutron stars, GW170817 [10], had a signal-to-noise ratio (SNR) ~ 30. Recent studies [11, 12] find that systematic uncertainties from inaccurate waveform models would be substantial at SNRs ~ 90, which could be achieved if a signal as loud as GW170817 were observed in current-generation detectors when they achieve their design sensitivities. The tremendous sensitivity gains that future gravitational-wave detector concepts [1–3] would achieve means that they would observe a GW170817-like signal with an SNR in the thousands [13], requiring vastly more accurate theoretical waveform models.

Meeting this challenge will require a new generation of numerical-relativity software employing novel methods that will enable high accuracy and performance on the supercomputers that will be available in the next decade. Several such codes are currently in development (e.g. [14, 15]), but none of them have yet matured to the point where they can calculate gravitational waves from merging neutron-star binaries.

High-precision gravitational-wave observations The next generation of gravitational-wave detectors–and also the LISA mission in space [16]—will yield some observations of coalescing binary black holes with SNR in the thousands, enabling high-fidelity observation of the behavior of the curved spacetime near stellar-mass black-hole horizons, the most strongly curved spacetime known. Gravitational wave signals will be so plentiful they will sometimes overlap.

As they have for current observations [10, 17, 18], numerical-relativity simulations will play crucial roles in the detection and interpretation of gravitational waves from merging black holes and neutron stars. In particular, waveforms from these simulations have been used to construct and validate approximate, phenomenological models necessary for interpreting observations (since numerical relativity is too costly to produce every model waveform needed) [17, 19–23], have featured in direct analysis of observations [24], and have helped validate our methods for detecting faint gravitational waves in detector data [25].

But when next-generation detectors are operating, future studies will need to determine how the challenges of extremely high SNR and overlapping signals will impact the accuracy required to prevent numerical-relativity simulations from biasing the interpretation of next-generation gravitational-wave observations [26]. These requirements will be critical for ensuring that our numerical and approximate, analytic waveform models do not bias our interpretation of observations.

Testing gravity in the nonlinear regime A consistent theory of quantum gravity is a major goal of modern physics. General relativity (GR) itself is not consistent with quantum mechanics, because it breaks down at high-energy scales: it is non-renormalizable and exhibits physical singularities, such as those inside black holes and at the big bang. Candidate quantum-gravity theories include well-motivated extensions of GR, typically involving additional fields, higher curvature corrections, or symmetry breaking [27–29].

The nonlinear regime of gravity that unfolds during the collision of compact objects is a particularly promising target to probe for extensions of GR both because new phenomena are expected to be most prominent in that case and because candidate theories can be confronted with gravitational-wave observations [30–33]. However, current tests of gravity have either been limited to the weak-field regime or to null-tests against GR, because complete model waveforms that capture these truly nonlinear beyond-GR effects are lacking. Numerical Relativity beyond GR has produced first proof-of-principle simulations [34–42]. Enabling high precision tests of gravity and searches for signatures of new physics will require innovative theoretical avenues to devise well-posed formulations of beyond-GR theories, and their application to creating high-precision catalogs of simulated waveforms.

Black holes as cosmic particle detectors Although dark matter makes up more than 80% of all matter in the universe, its nature, composition and properties have remained elusive. Black holes might shed light on the dark matter question and also ultralight beyond-standard model particles in general. Massive bosonic fields scattering off rotating black holes may form condensates around them if the fields' Compton wavelength is comparable to the black holes' size [43, 44]. That is, astrophysical black holes in the mass range $5M_\odot \dots 10^{10}M_\odot$ are sensitive to ultralight particles in the mass range $10^{-21}\mathrm{eV} \dots 10^{-8}\mathrm{eV}$ [43, 45, 46]. This range includes popular dark matter candidates [47], the QCD axion [48] and axion-like particles of the string axiverse [49]. Because the underlying phenomenon of black hole superradiance only relies on gravitational interactions, it facilitates searches for new particles independently from their specific coupling to the standard model and thus complements traditional collider physics or direct detection experiments. The single black hole scenario has been studied extensively, and there are first computations of binary black-hole systems in the weak-field [50, 51] or extreme mass ratio regime [52, 53]. How these light fields impact the nonlinear dynamics of the late inspiral and coalescence of black-hole binaries endowed with scalar condensates and what its observational signatures are remain open questions. Addressing them will enable gravitational-wave based searches for new particles but will require significant advances in numerical relativity.

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