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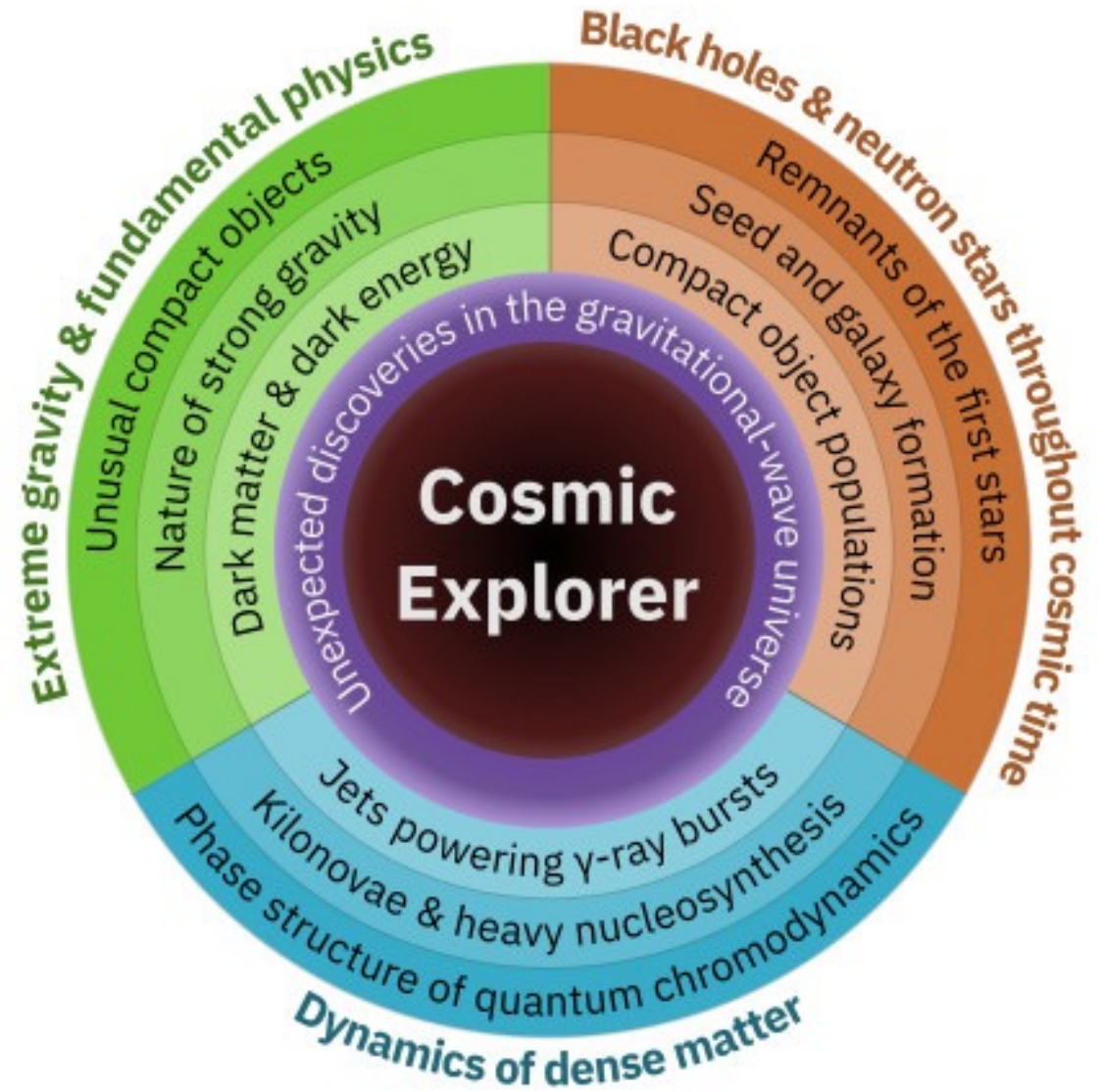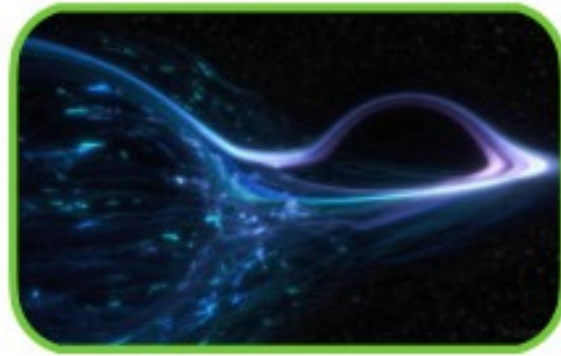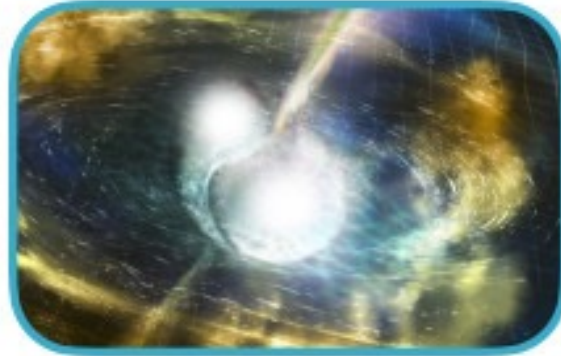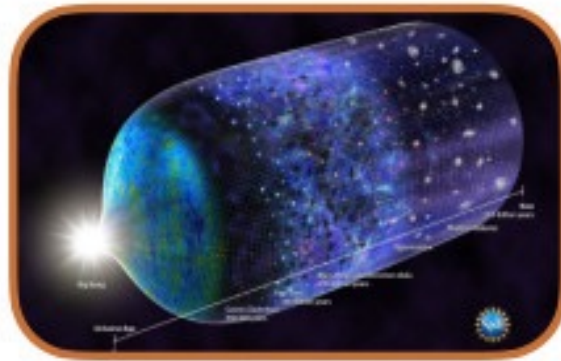
Snowmass White paper

Pablo Laguna (University of Texas – Austin)

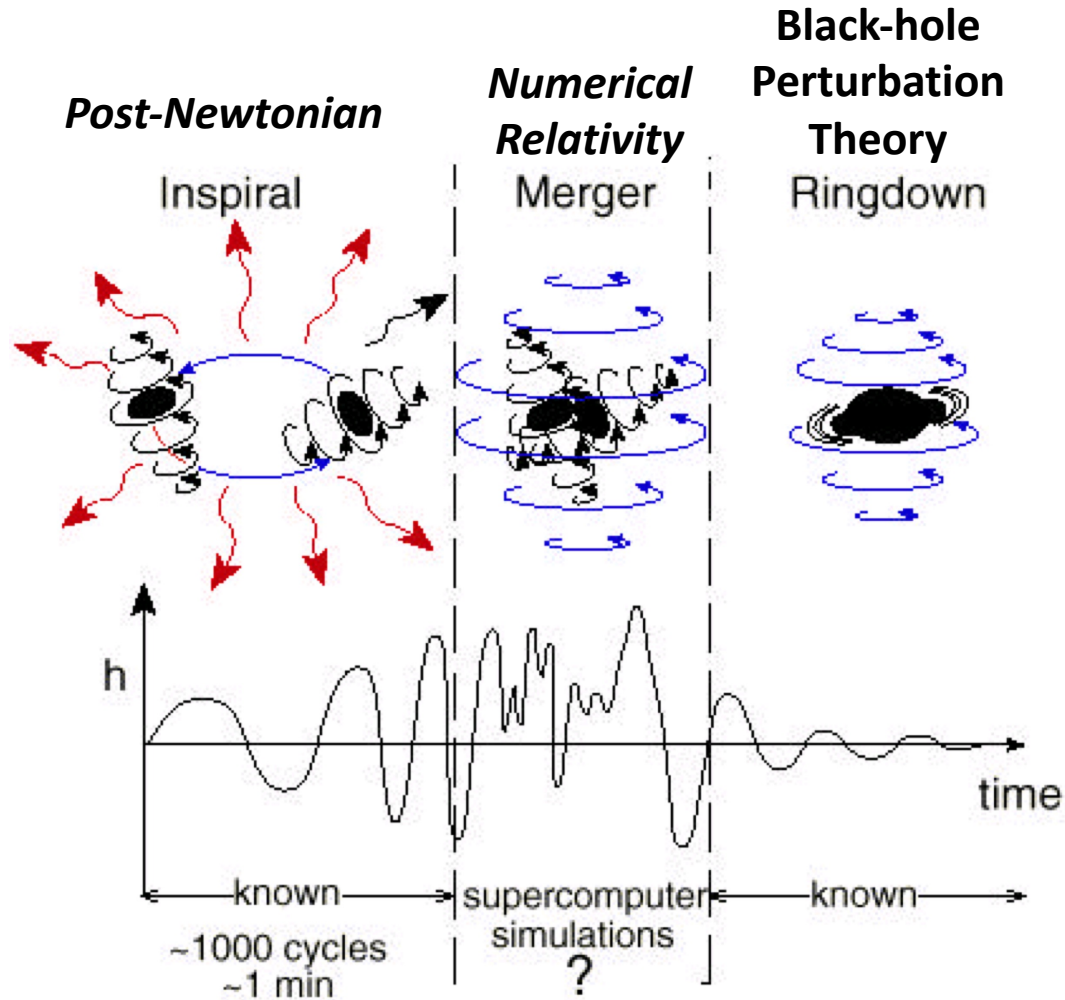Geoffrey Lovelace (California State University –Fullerton)

Helvi Witek (University of Illinois – Urbana-Champaign)

Scientific motivation

Images courtesy Cosmic Explorer Horizon Study, N. R. Fuller, National Science Foundation, Aurore Simonnet, Sonoma State University, Alex Andrix, independent artist, Virgo/EGO.

Waveform modeling in a nutshell

Post-Newtonian — Inspiral

Numerical Relativity — Merger

Black-hole Perturbation Theory — Ringdown

known — ~1000 cycles ~1 min

supercomputer simulations ?

known

KS Thorne, in *The Future of Spacetime* (WW Norton, NY, 2002)
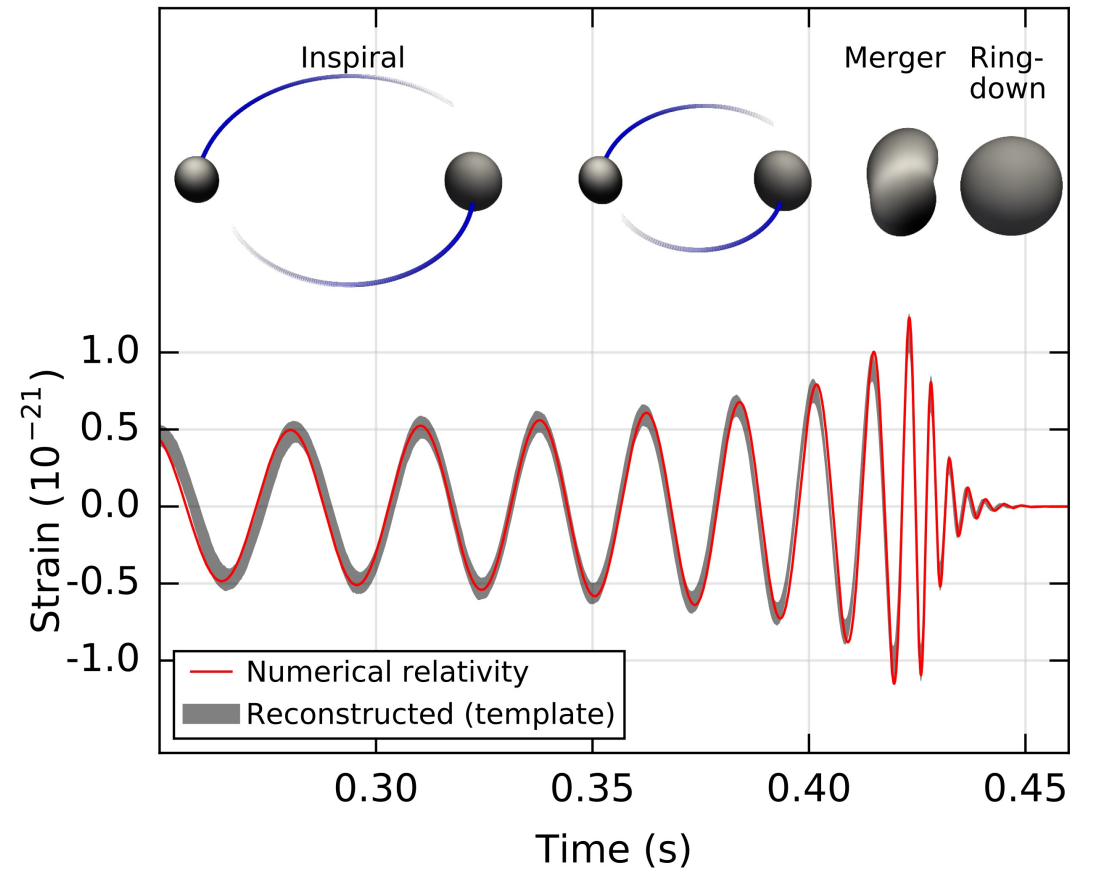
Abbott+, PRL 116, 061102 (2016)

New Challenges

- Accuracy required of NR simulations increases with detector sensitivity

$$\Delta \propto \frac{1}{\text{SNR}^2}$$

- Next-generation detectors' observations with the highest signal-to-noise-ratios (SNR)
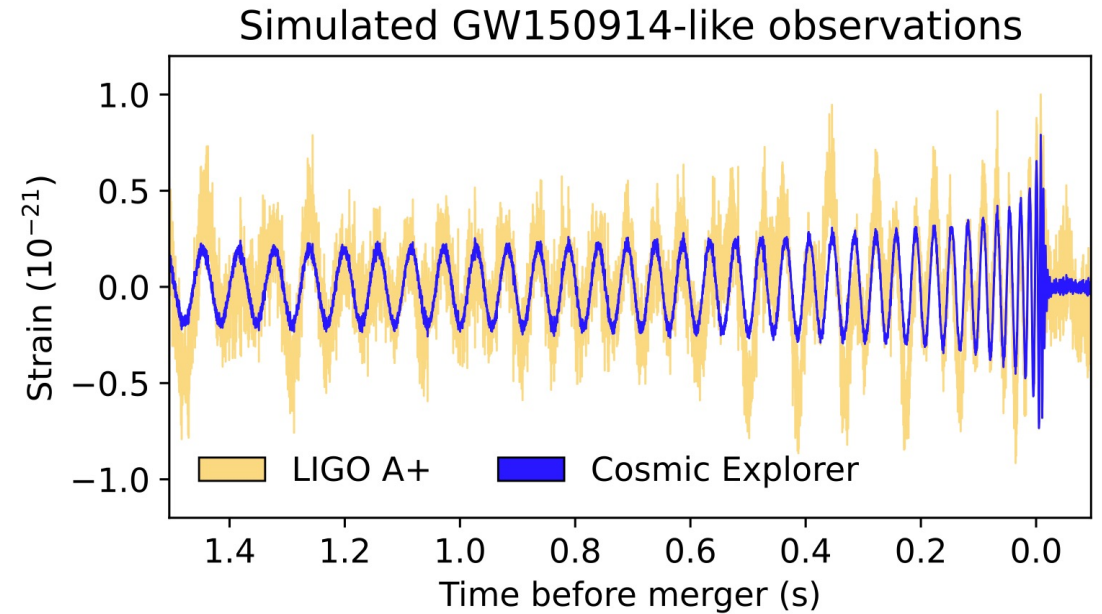 - SNR O(10^3), vs. SNR 24 (GW150914)

- Modeling challenges
  - Increased accuracy for science interpretation
  - Parameter space coverage
  - Overlapping signals
- Waveform model building – NR input crucial for
  - EoBNR, Phenomenological, surrogates

Simulated GW150914-like observations

Figure courtesy Cosmic Explorer Horizon Study
https://arxiv.org/pdf/2109.09882.pdf

What is required to accomplish science goals?

- A new generation of numerical-relativity codes
  - Include new science
  - Increased accuracy
  - Increase performance
  - Open-source software capable to run on exa-scale supercomputing facilities
- Publicly available catalogs of simulated GWs
- Extensive and more accurate waveform catalogs
- (Beyond) Exa-scale computing facilities

Structure of White Paper and Topics

- Authors:

  Laguna (PL), Lovelace (GL), Witek (HW), Foucart (FF), Radice (DR)

- Length: 10-15 pages

- Topics:
  - Motivation and science goals (GL)
  - The A and O of gravitational waveform modelling (HW, PL)
  - Nuclear Physics and neutron stars (FF, DR)
  - High-Precision gravitational wave observations (GL, PL)
  - Testing gravity in the nonlinear regime (HW)
  - Black holes as cosmic particle detectors (HW)
  - Summary and future directions

Status of White Paper

- Go to overleaf document

Plans for completing White Paper

- Additional authors:
  - Neutron star modelling: Francois Foucart, David Radice

- Timeline
  - Bi-weekly meetings of co-authors
  - Planned "final" draft: March 2022
  - Share with NR and gravitational wave community for feedback (e.g., via NR-community mailing list, LISA WavWG, …)
  - Planned final version: July 2022