Gravitational Wave modelling

Snowmass White paper

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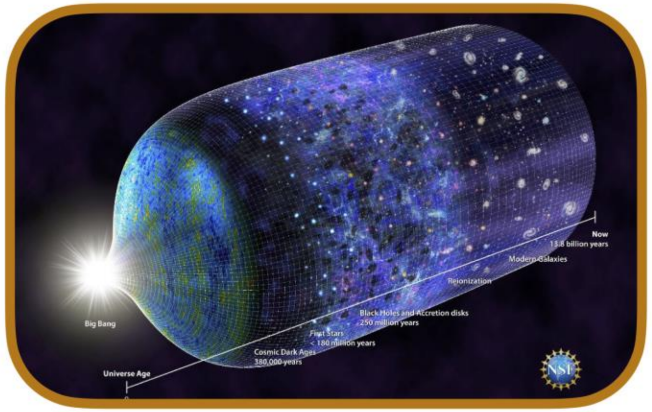
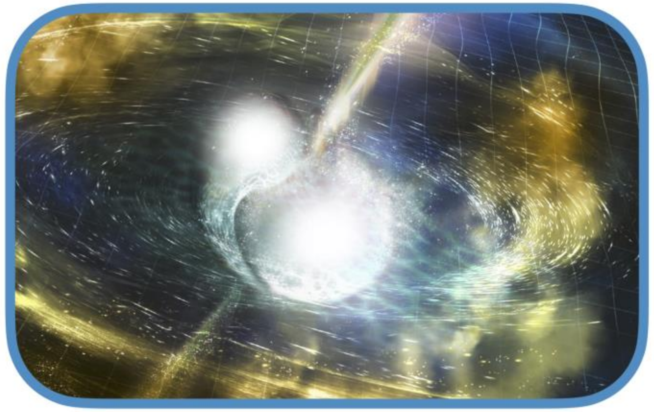
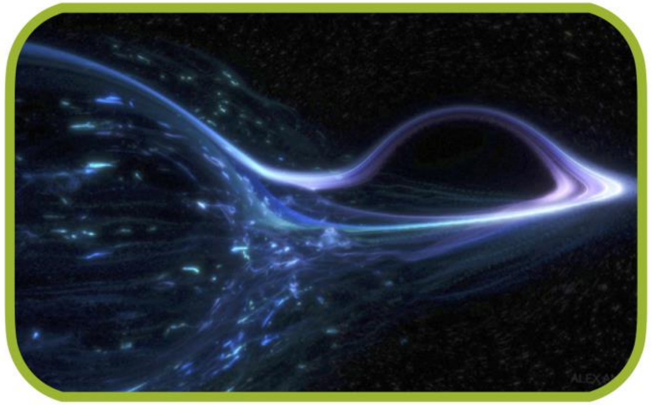
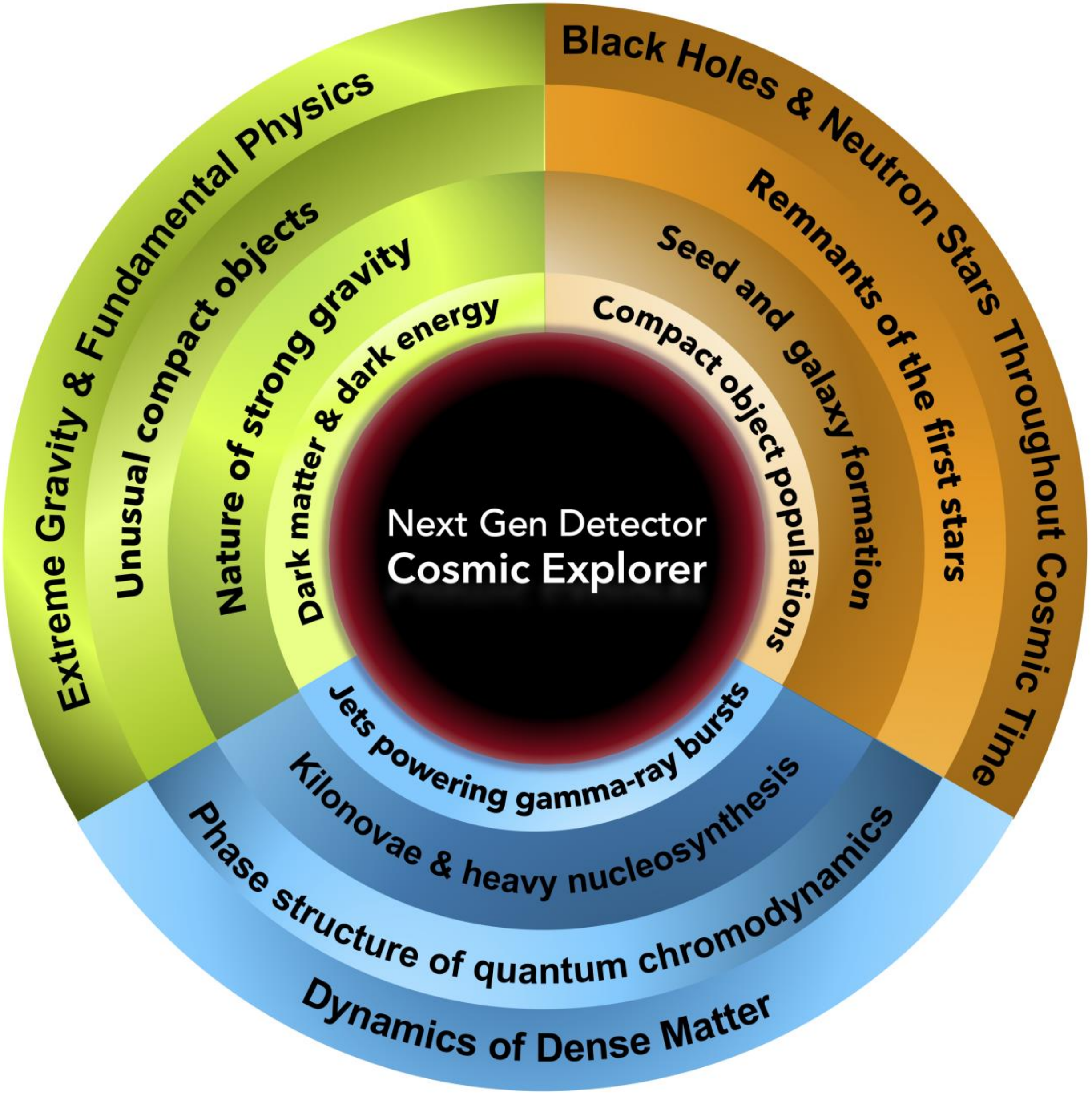
Scientific motivation



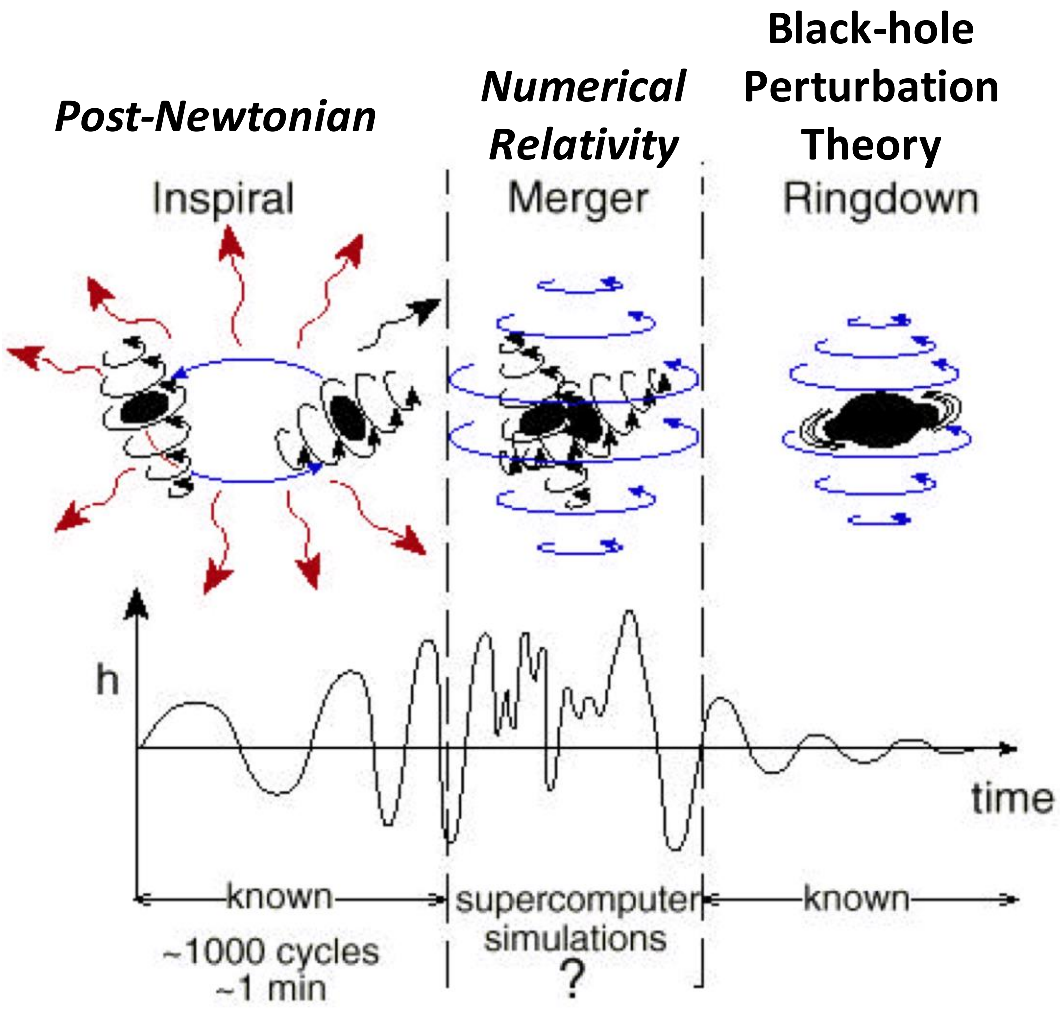




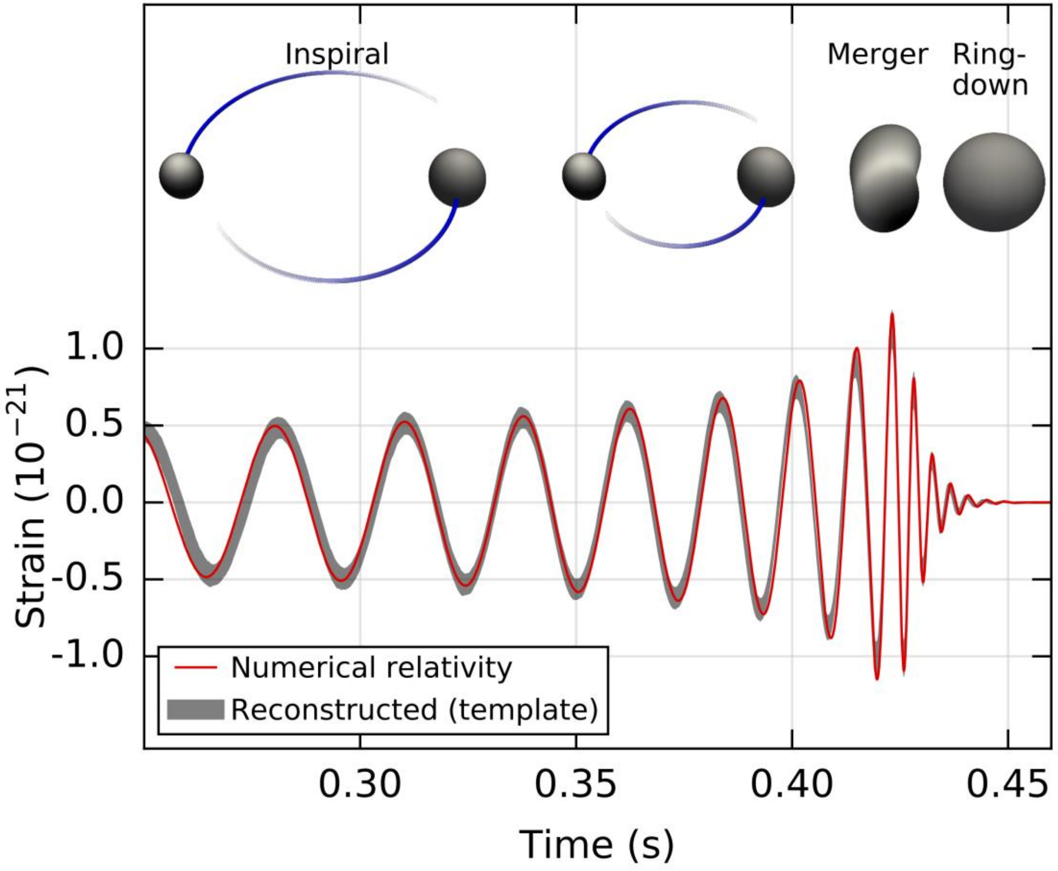


Images courtesy Cosmic Explorer, N. R. Fuller, National Science Foundation, Aurore Simonnet, Sonoma State University, Alex Andrix, independent artist, Virgo/EGO.

Waveform modeling in a nutshell



KS Thorne, in *The Future of Spacetime* *(WW Norton, NY, 2002)*



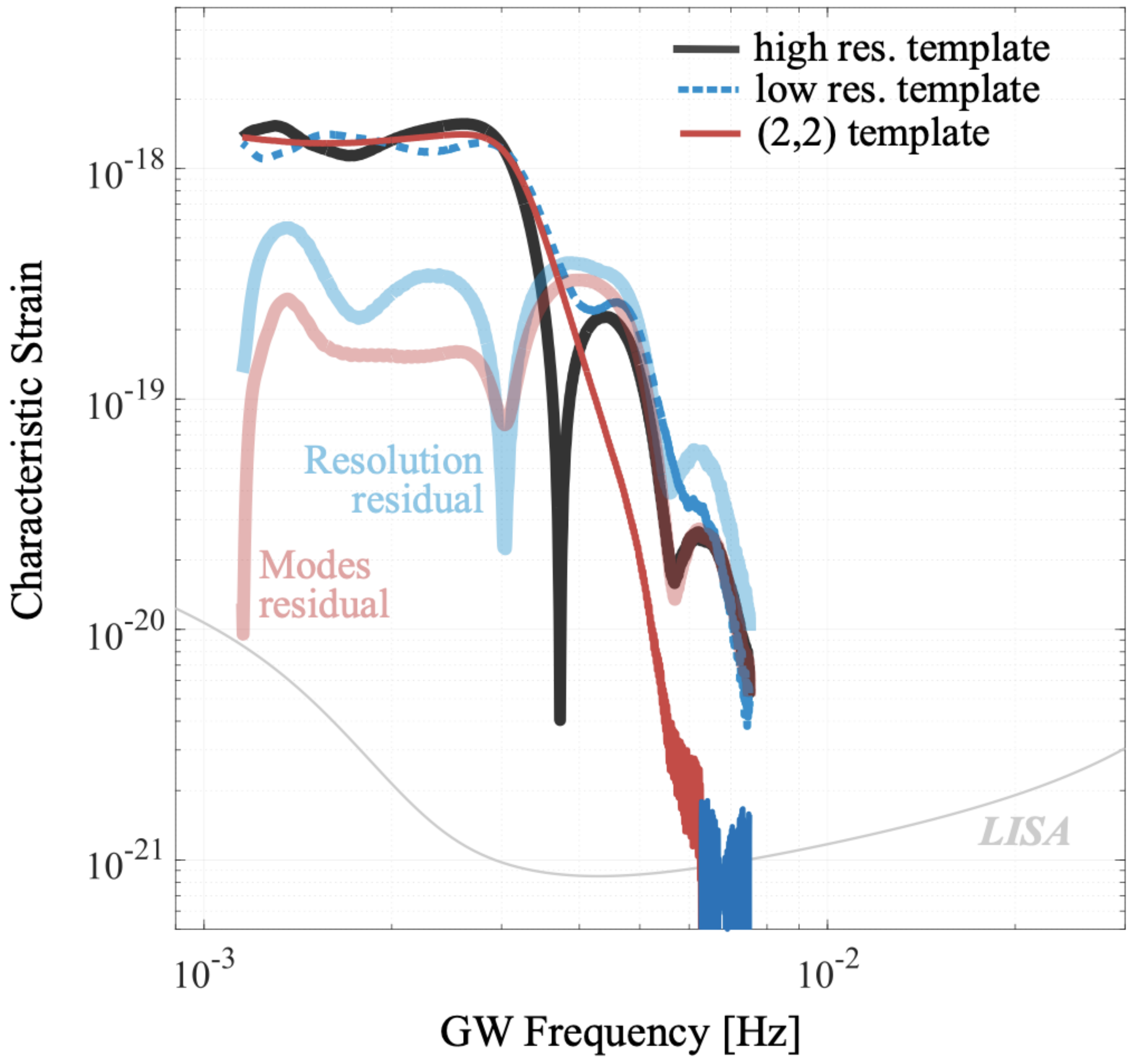
Abbott+, PRL 116, 061102 (2016)

Accuracy of NR & Next Generation Detectors

- Accuracy required of NR simulations increases with detector sensitivity

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

- Next-generation detectors' observations with the highest signal-to-noise-ratios (SNR)
  - SNR $O(10^3)$, vs. SNR 24 (GW150914)
- A new generation of NR software
  - Software that runs at scale on the supercomputers that will be available in the 2030s.
  - Open-source NR codes that produce publicly available catalogs of simulated GWs for merging black holes and neutron stars



Ferguson et al PRD 104, 044037 (2021)

High-precision gravitational-wave observations

- Next generation observatories
  - Cosmic Explorer (CE) & Einstein Telescope (ET)
  - Laster Interferometer Space Antenna (LISA)
- Modeling challenges
  - SNRs in the 1000s
  - Overlapping signals
  - Will need an order of magnitude gain in accuracy to avoid bias in interpreting observations
- Meeting these challenges
  - Pushing existing codes to higher accuracy
  - A new generation of numerical-relativity codes

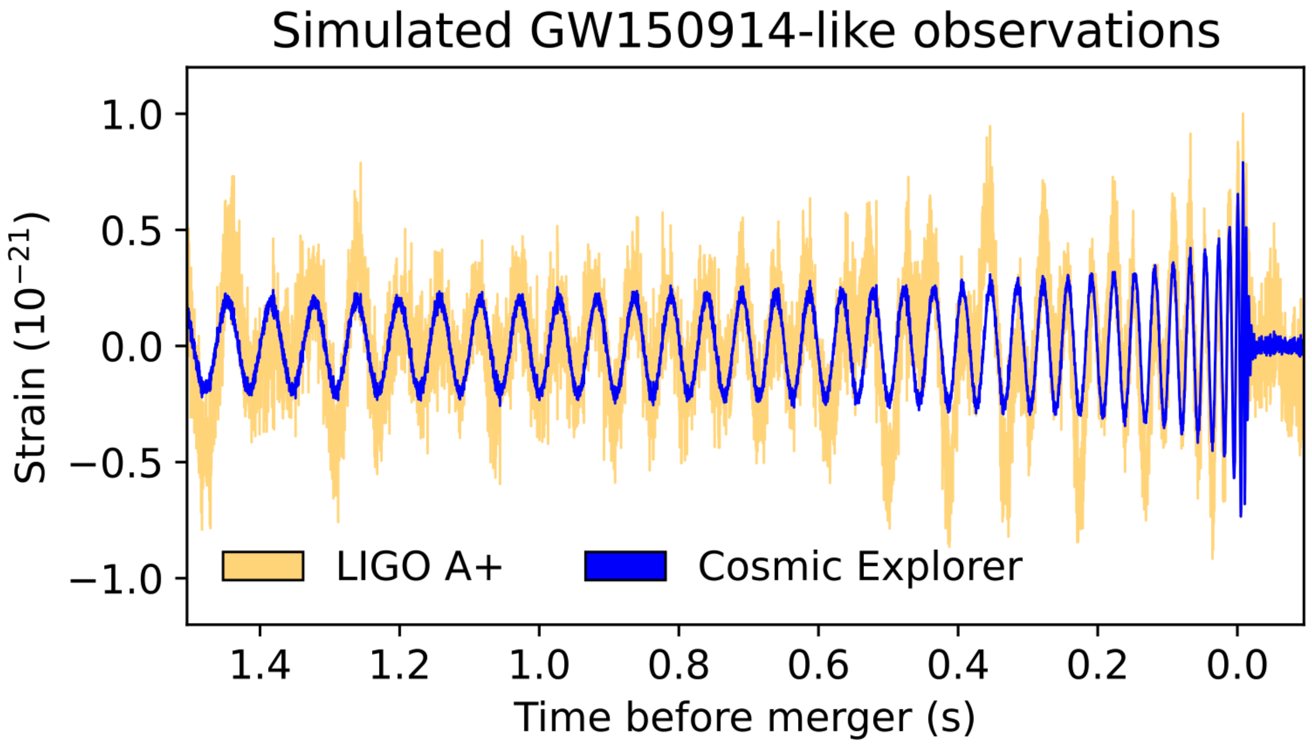
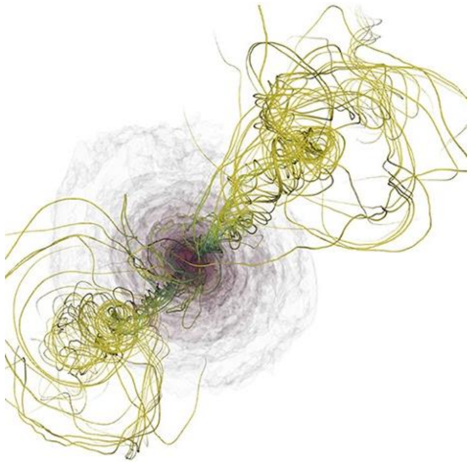
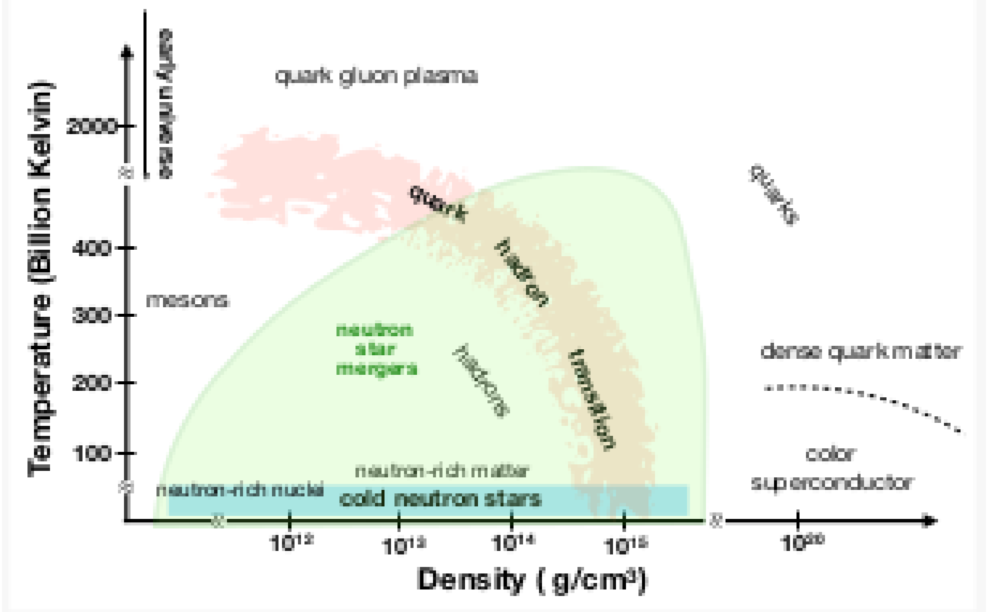


Figure courtesy Cosmic Explorer Horizon Study
https://arxiv.org/pdf/2109.09882.pdf

Binary neutron star modelling

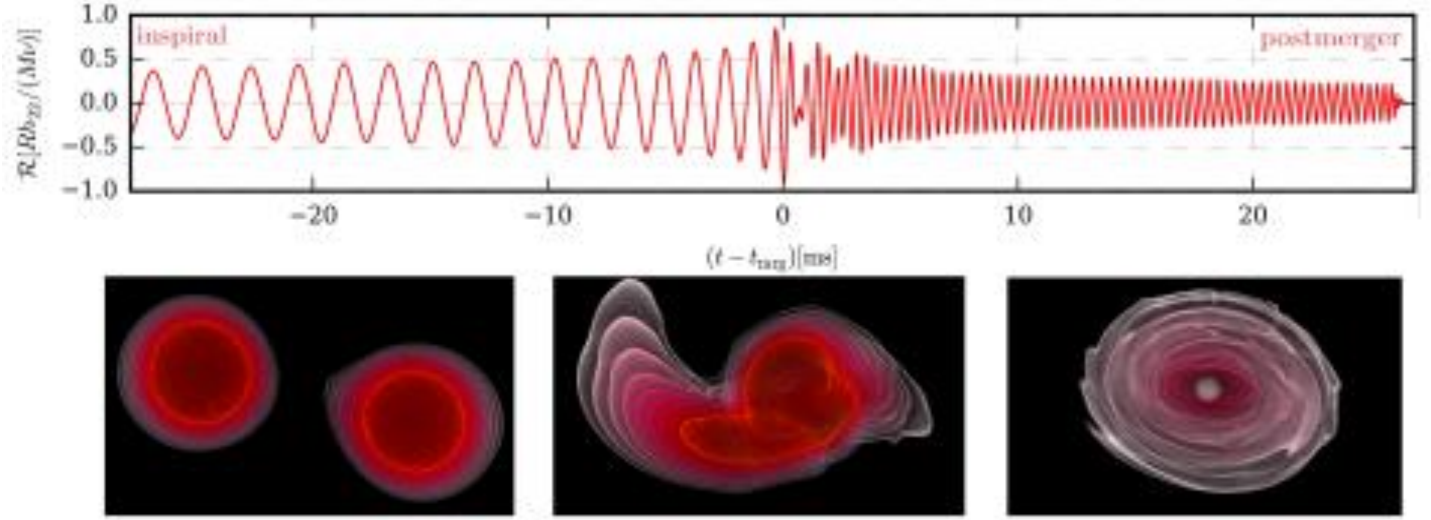




Simulations: predict observable GW and EM emission during merger and post-merger

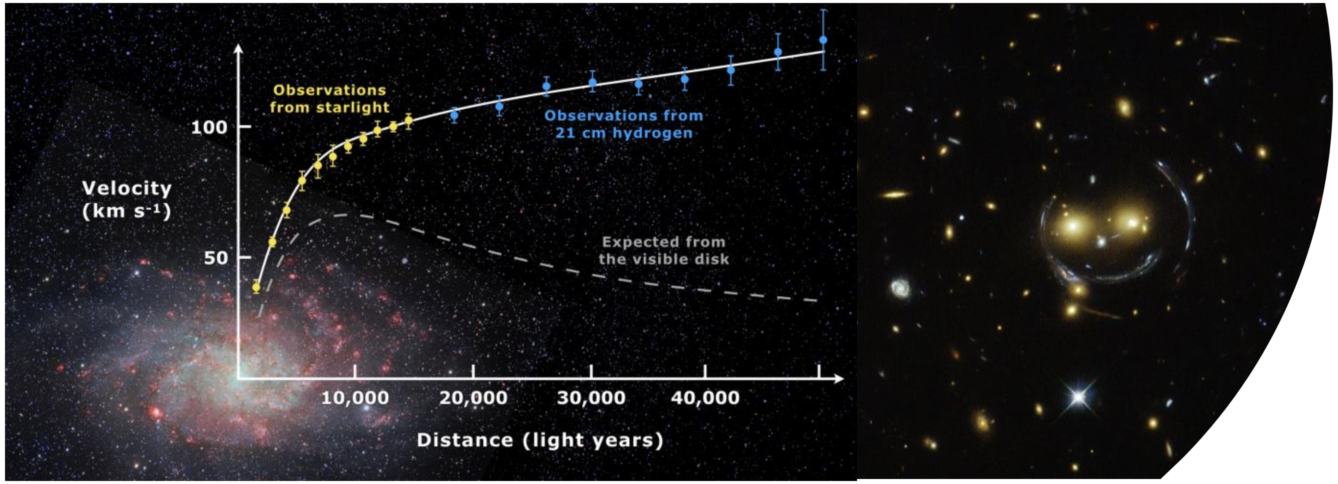
Next challenges:

- Small time & spatial scales in simulations (up to ~ 100 ms and ~ 1000km) compared to those in the sources of astrophysical relevance (≳1 s and ≳105 km).
- implementation of microphysics, radiation transport, magnetic fields, mass ejection mechanisms...



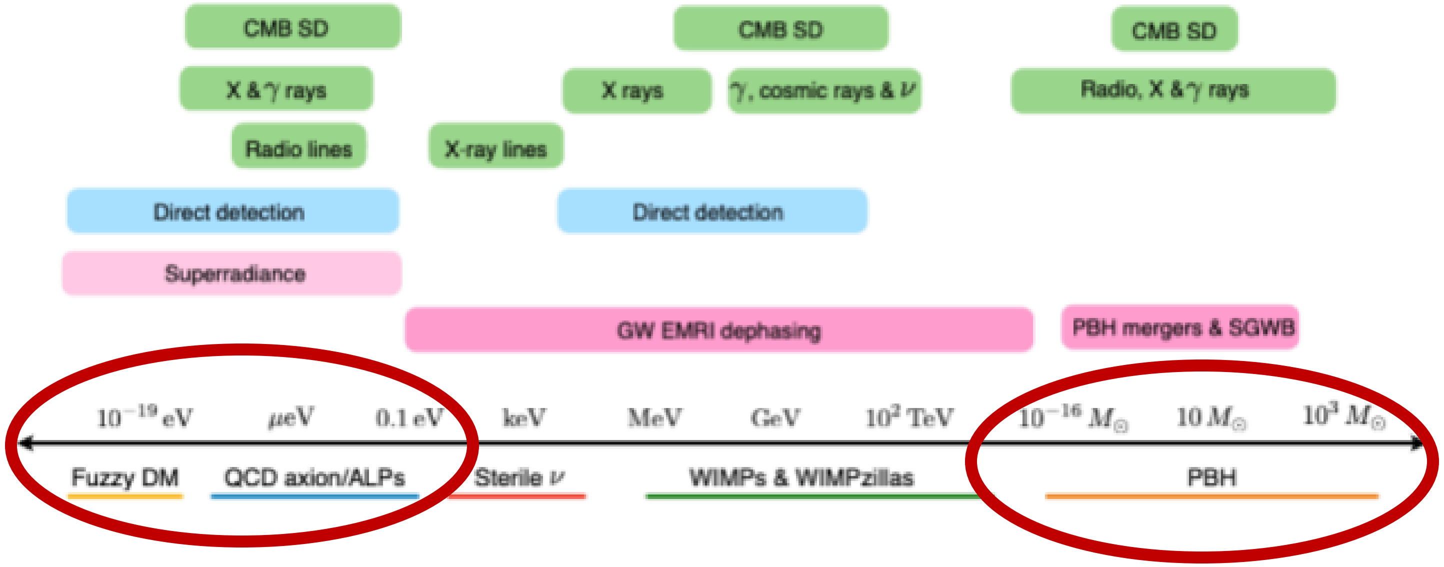
Images: top right: Ciolfi 2020; top left: Next Generation GW Observatories – Science book [https://arxiv.org/pdf/2111.06990.pdf]; bottom: Dietrich et al [https://arxiv.org/pdf/2004.02527.pdf]

Black holes as cosmic particle detectors



What is Dark Matter?

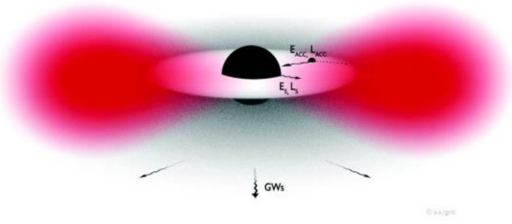
- > 80% of gravitating matter
- Gravitational waves to probe
    - Primordial black holes
    - Axion-like particles
    - Fuzzy dark matter

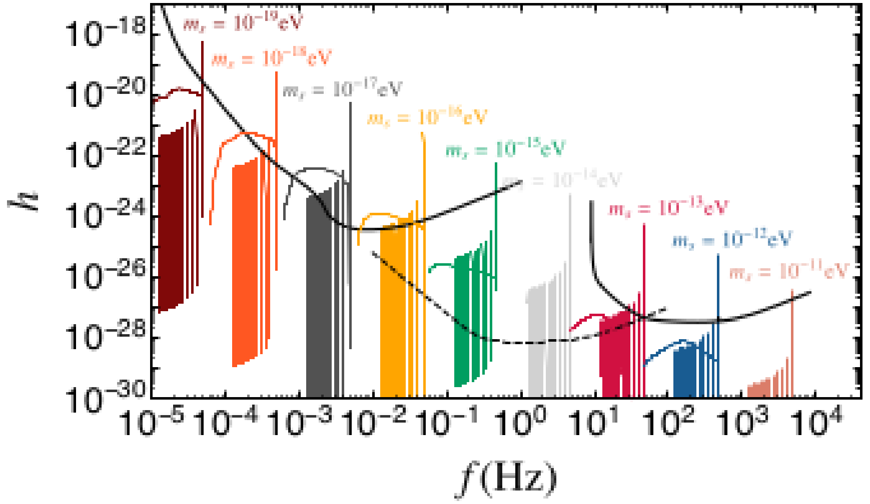


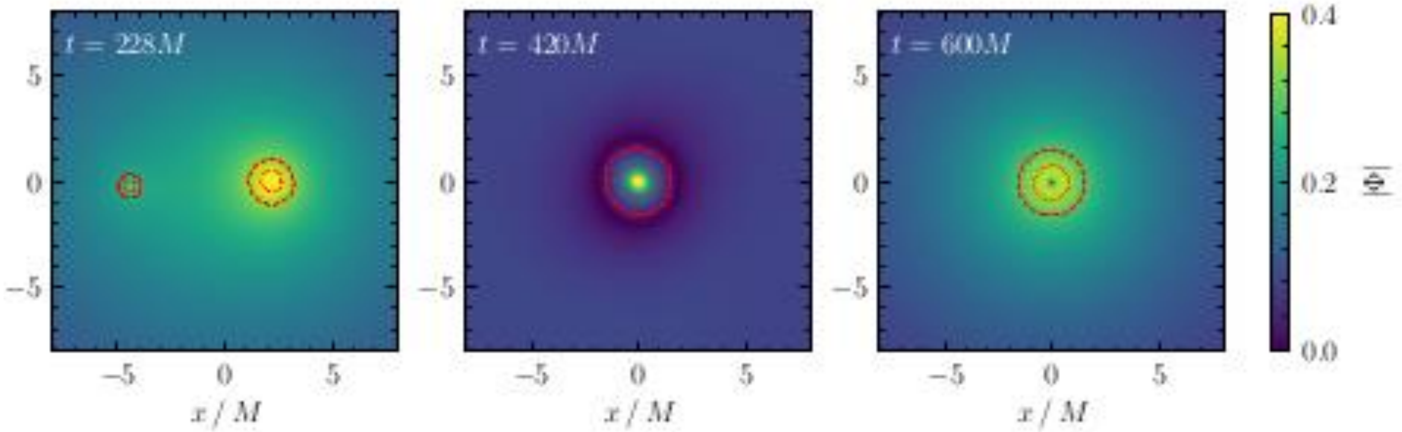
Adapted from EuCAPT White Paper 2021 [https://arxiv.org/pdf/2110.10074.pdf]

Black holes as cosmic particle detectors

- Formation of "gravitational atoms" due to black hole superradiance
  - probe axion-like particles, (hidden sector) vector bosons, gravitons
- Observational signatures:
  - monochromatic gravitational waves
  - Holes in the Regge plane
  - Phase shift in gravitational radiation
- Modelling
  - Mostly single BHs
  - First binaries: perturbative techniques
  - First numerical simulations of binaries

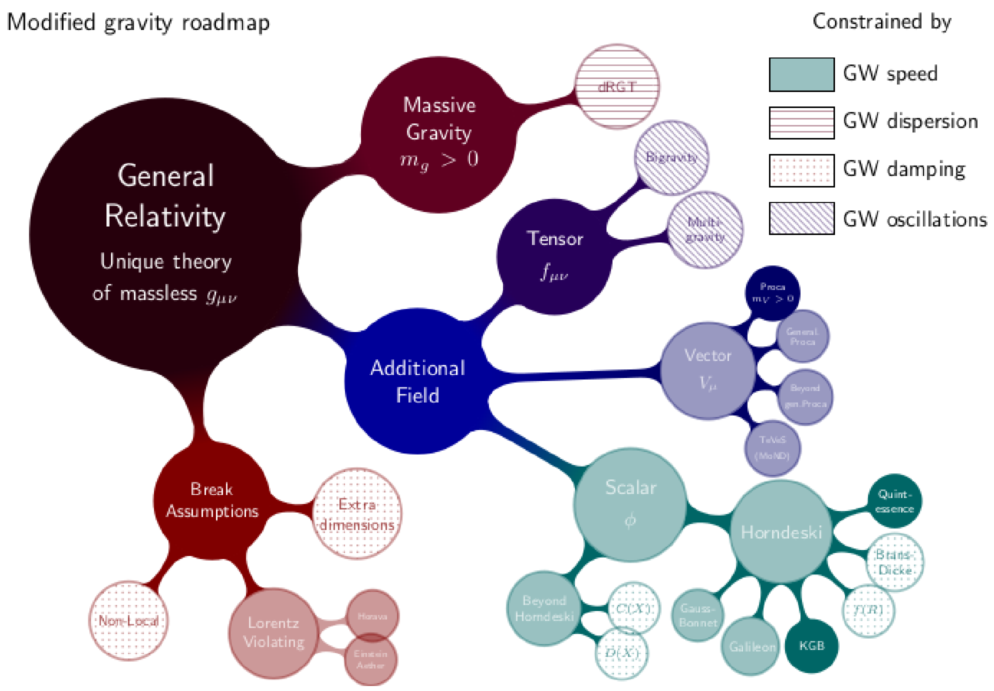






Images: Superradiance '21 [https://arxiv.org/pdf/1501.06570.pdf]; Brito et al [https://arxiv.org/pdf/1706.05097.pdf]; Ficarra et al, in prep. '21

Explore the basic nature of space and time

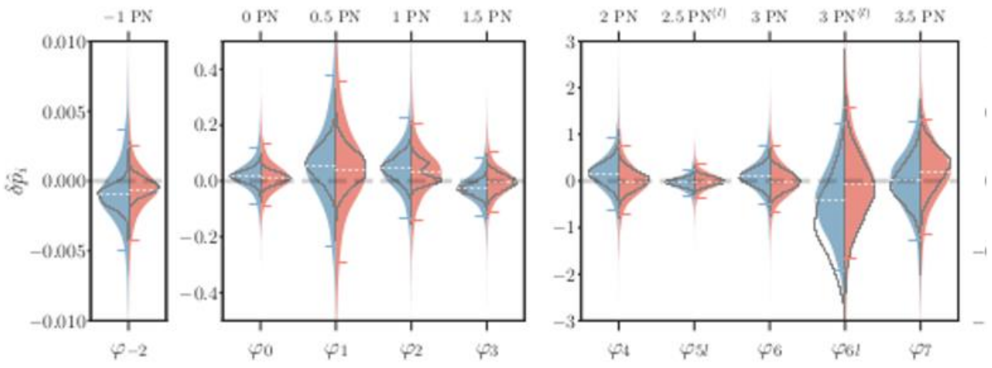


- Dark energy?
- Lorentz invariance?
  - unprobed in gravitational sector
- Higher dimensions?
- Gravity + quantum = quantum gravity?

--> Test gravity in strong-field regime

Current status:

- Null tests against GR
- Consistency checks
- Proof-of-principle predictions beyond GR



Images: Ezquiaga et al [https://arxiv.org/pdf/1807.09241.pdf]; LVKC '20 [https://arxiv.org/pdf/2010.14529.pdf]

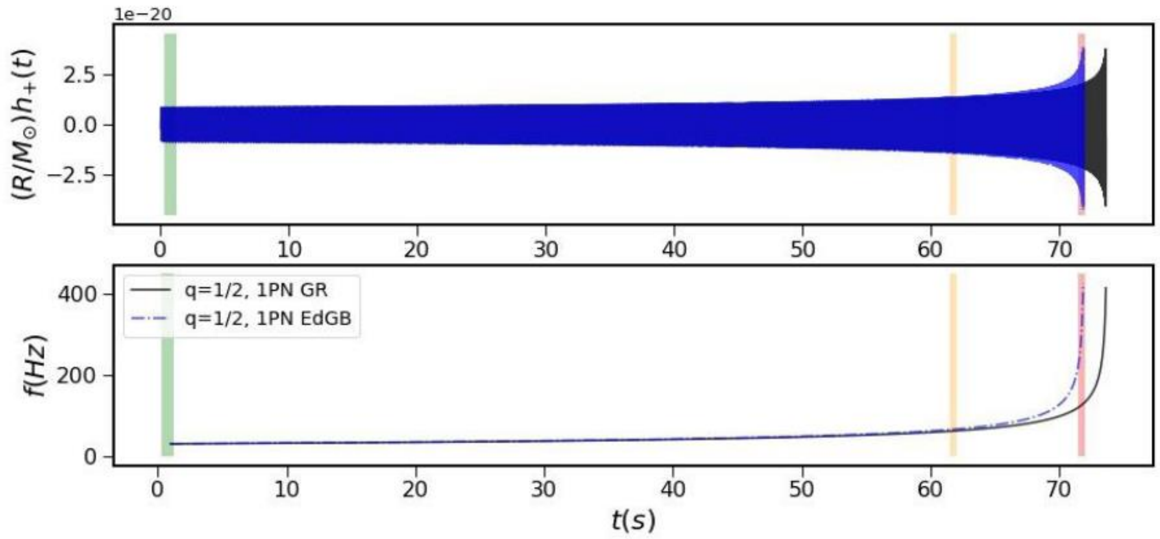
Explore the basic nature of space and time

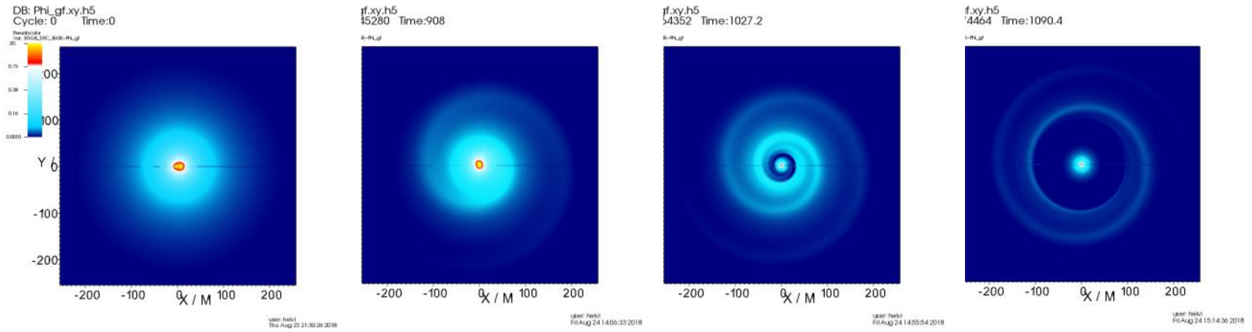
Future developments

- Theory-specific models
  - higher-order PN predictions
  - numerical relativity beyond proof-of-principle
- interface with theory-agnostic models
- waveform catalogs for precision tests of gravity

Observational GW signatures:

- Dephasing of gravitational waves
- Extra polarizations
- New nonlinear effects





Images: Shiralilou et al '21 [https://arxiv.org/pdf/2012.09162.pdf]; Witek et al '19 [https://arxiv.org/pdf/1810.05177.pdf]

Summary

- Enormous discovery potential with gravitational waves
  - Neutron stars as new laboratory for Nuclear Physics
  - Cosmological evolution and H0 resolution
  - Nature of space and time – dark energy to quantum gravity
  - New pathway to dark matter detection
- Gravitational wave modelling is **key** for best science outcome
- We know how to solve new computational and theoretical challenges

White paper "Gravitational Wave Modelling" based on LOIs

- *"Numerical relativity for next-generation gravitational-wave probes of fundamental physics"*
- *"From scattering amplitudes to the relativistic two-body problem"*

Thank you!