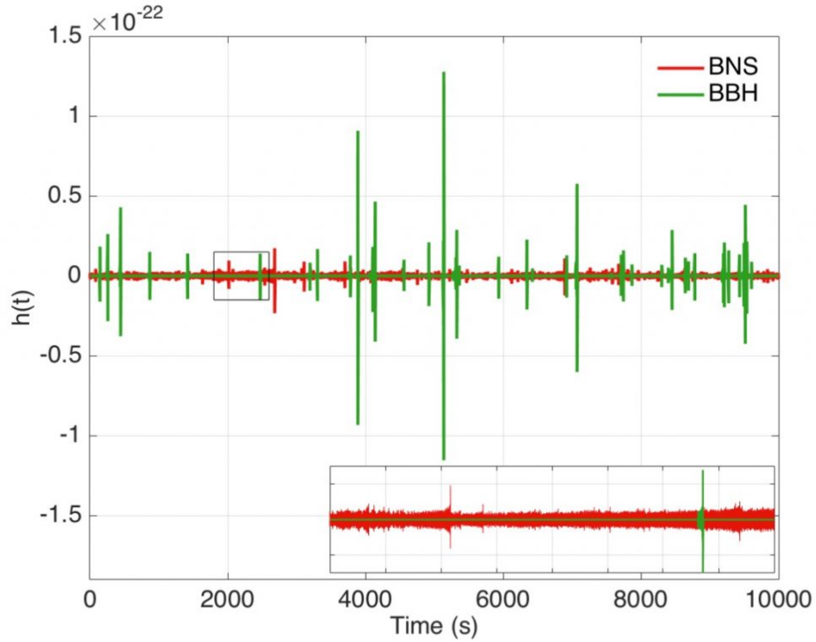

Extreme Gravity: Challenges in data analysis

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Extreme Gravity and Fundamental Physics & Waveform Modeling

I. Science

II. Challenges in waveform modeling

III. Challenges in data analysis

   A. Novel methods to search for GW signals

   B. More efficient methods for parameter estimation

   C. Methods to search for the unknown

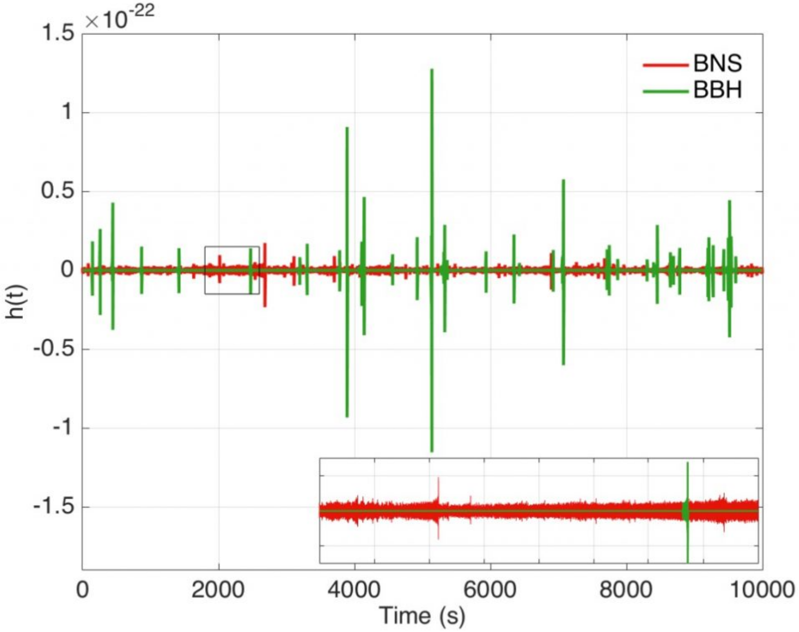
A. Novel methods to search for gravitational wave signals

Compact binary coalescences

- Long and/or overlapping signals
  - Time during which signal in band:

$$\tau \simeq 4.5 \times 10^5\,\mathrm{sec}\left(\frac{1.22\,M_\odot}{\mathcal{M}_c}\right)^{5/3}\left(\frac{1\,\mathrm{Hz}}{f_{\mathrm{low}}}\right)^{8/3}$$

  - Abundance of signals: rate extrapolation from current detections



LIGO+Virgo, PRL **120**, 091101 (2018)

A. Novel methods to search for gravitational wave signals

Compact binary coalescences

- Long and/or overlapping signals
  - Antenna responses change during the time signal in band
  - Standard technique of maximizing SNR over sky position no longer applies
  - Include sky position in the list of parameters over which template bank is constructed
    - Orders of magnitude increase in size of bank
  - Identification/localization of source *before* merger
    - Early warning to EM facilities

A. Novel methods to search for gravitational wave signals

Compact binary coalescences

- Including all relevant physics in the templates
  - Currently at most aligned-spin templates
    - Significant loss of detection efficiency for high mass ratios and large precessing spins
  - Residual eccentricity
  - Intermediate mass ratio inspirals

- This will again lead to significantly larger template banks

- "Semi-coherent" search methods?
  - Analyze data in different frequency bands independently?
  - Hierarchical search strategies?

A. Novel methods to search for gravitational wave signals

Stochastic backgrounds

- Astrophysical backgrounds
  - Most BBH, large fraction of BNS will be *individually* detectable
  - Background of e.g. spinning neutron stars in the galaxy
  - Challenge: detecting small anisotropies from inhomogeneities in matter distribution

- Primordial backgrounds
  - How will the search for these be affected by astrophysical backgrounds?

- Much more sensitive detectors also means more affected by correlated noise between interferometers
  - E.g. Schuman resonances

B. More efficient methods for parameter estimation

- Exploration of the likelihood over parameter space
  - Markov Chain Monte Carlo
  - Nested sampling

- Computational cost:
  - Generation of (long) waveforms
  - Analysis time increases with SNR

- Solutions:
  - Multi-banding of frequency domain waveforms to reduce cost of waveform generation
  - Reduced-order quadratures
    - Currently analysis speed-ups by factors 10 - 300
    - Significant pre-processing cost: construction of reduced basis. Not a problem for 2G, but will this remain feasible in 3G era?
    - Possible middle ground, e.g. separate reduced bases for inspiral, merger, ringdown?

C. Methods to search for the unknown

- Tests of the dynamics of coalescence
- Searching for anomalies in the compact objects themselves
- Searching for anomalies in GW propagation
- Searching for non-GR polarizations

C. Methods to search for the unknown

Tests of the dynamics of coalescence

- Currently:
  - Inspiral-merger-ringdown consistency test
  - Introducing parameterized deformations in IMR waveforms

- Advantages:
  - Can combine information from all detections
  - Ability to find GR violations *even if* they are of a different nature from the chosen parameterized deformations

- However, should GR violation be found, how do we establish its precise nature?
  - If complete waveforms from alternative theories were available, perform hypothesis ranking for a (large) list of theories?

C. Methods to search for the unknown

Searching for anomalies related to the compact objects themselves

- Effect on inspiral due to tidal effects, gravitational drag, …
  - Similar problem as before: how to distinguish scenarios
- Additional information from anomalous ringdown, echoes, …
  - How to optimally utilize this in addressing the above problem?
- No hair tests: how to make optimal use of ability to distinguish individual quasi-normal modes
- Echoes
  - Alongside template-based searches, also morphology-independent searches; there may be exotic objects that are yet to be envisaged
  - Are there features that are robust across echoing objects, and how should they be implemented?
- Testing area increase law
  - Currently done by computing area from masses and spins of initial and final black holes
  - Is there a way to more directly measure area?

C. Methods to search for the unknown

Searching for anomalies in GW propagation

- 3G detectors will see signals over cosmological distances; ideal for propagation effects that accumulate over distance
  - "Leakage" of GW into large extra dimensions
  - Dispersion due to non-zero m_g or local Lorentz violations
- Currently dynamics of the source neglected
  - Probably justified when characteristic length scale expected to be much larger than size of the binary while in band
  - Where not justified, need IMR waveforms from alternative theories

C. Methods to search for the unknown

Searching for non-GR polarizations

- Methods:
  - Bayesian hypothesis ranking
  - If sky position (approximately) known: null streams

- In both cases, science is limited by number of detectors
  - E.g. with 3 interferometers and known sky position, can establish the presence of additional polarizations but not their type
  - Example of how design choices of 3G observatories (e.g. how many interferometers in ET) will affect the science that can be done