Einstein Telescope OSB Division 8: Waveforms

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OSB Kick-Off Workshop
September 21-22, 2021

OSB Div 8: Organisation

Coordinators

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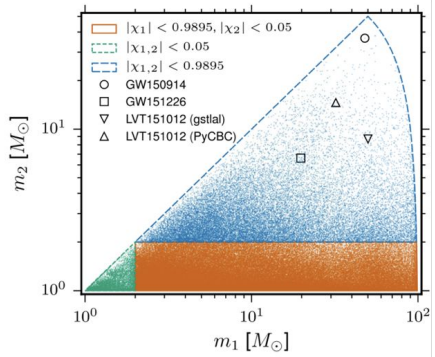
- Patricia Schmidt (University of Birmingham) p.schmidt@bham.ac.uk

Waveforms Mailing list: et-osb-waveforms@ego-gw.it

Waveforms ET Wiki: https://wiki.et-gw.eu/OSB/Waveforms/WebHome

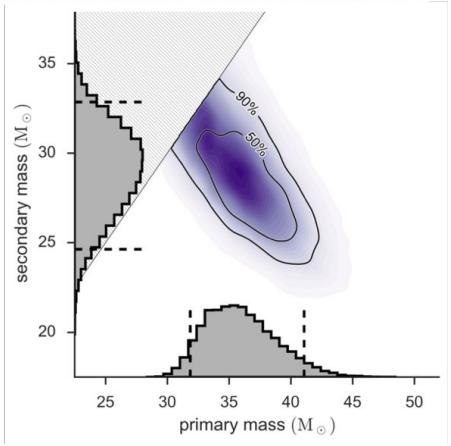
Waveform models essential ingredient to GW astronomy

Detection by matched filtering



LIGO+Virgo, PRX 2016 (1606.04856)

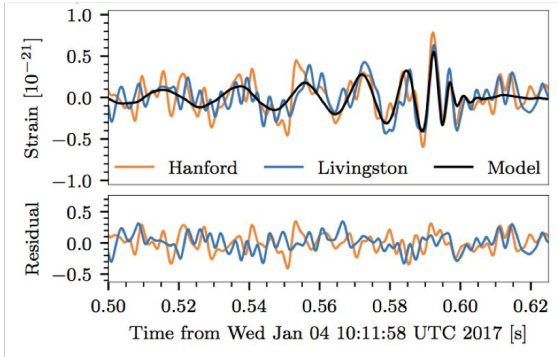
Parameter estimation



"GW150914" Abbott+ PRL 12016

Populations

Testing GR

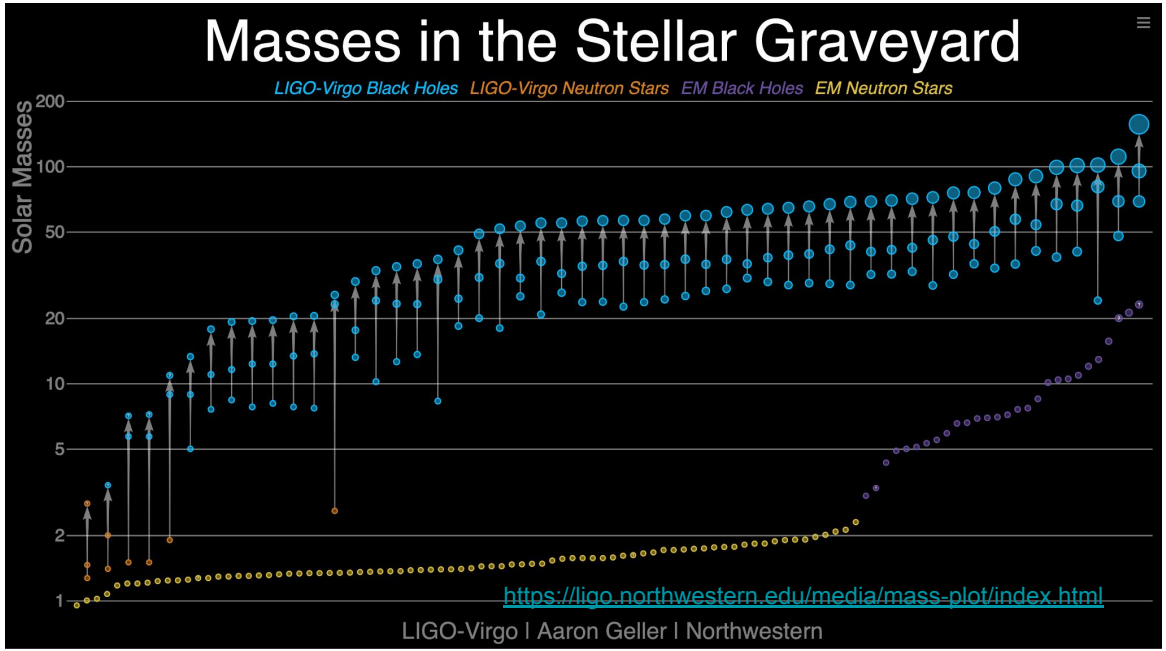


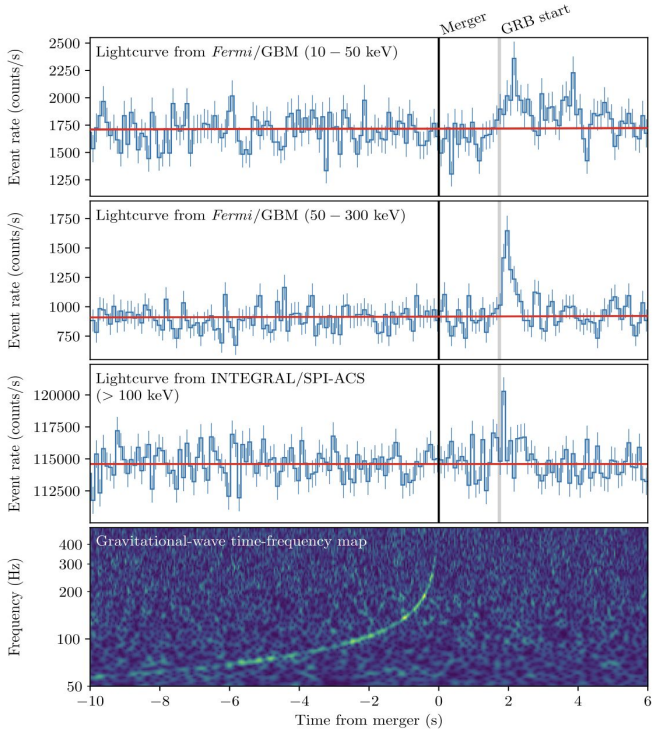
LIGO+Virgo, PRL 2017 (1706.01812)

Goal of Div-8: Facilitate and foster research towards waveform models that enable all ET science goals.

Waveform models in today's GW detectors

- GW astronomy strikingly successful
- Waveform models supported these successes

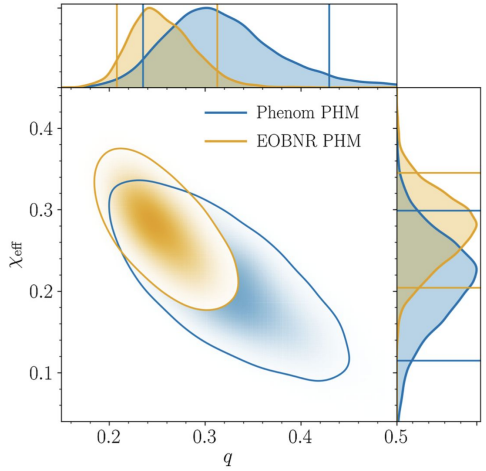




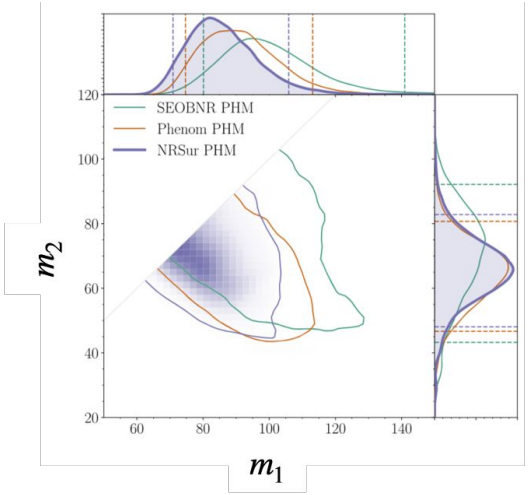
Astrophys. J. Lett. **848**, L13 (2017)

Waveform models in today's GW detectors

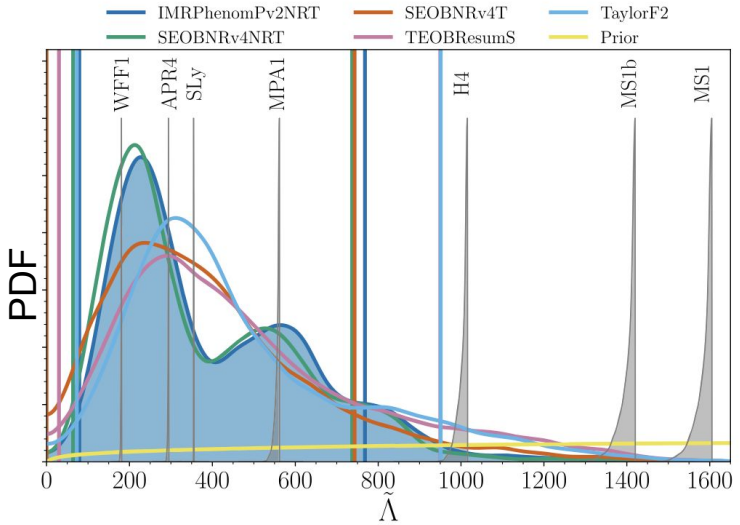
In a small number of events, some waveform short-comings are noticeable even at *current* LIGO/Virgo sensitivities



GW190412
BBH 30+8 Msun, SNR 19
[Abbott et al, PRD 102 043015 (2020)]



GW190521
BBH 85+66 Msun, SNR 15
[Abbott et al, ApJL 900:L13 (2020)]



GW170817
First BNS, SNR 32
[B. P. Abbott et al. Phys. Rev. X **9**, 031040]

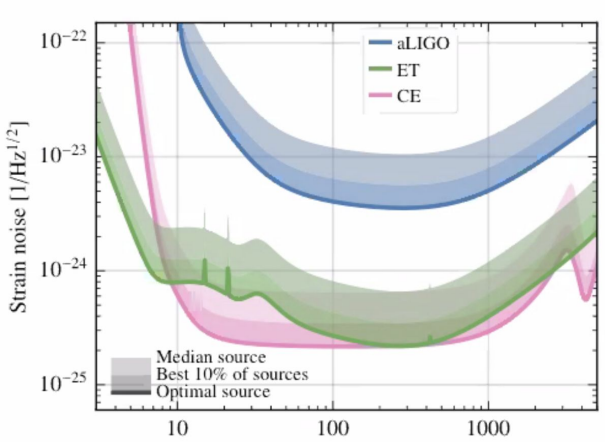
Einstein Telescope: Science Potential = Challenges

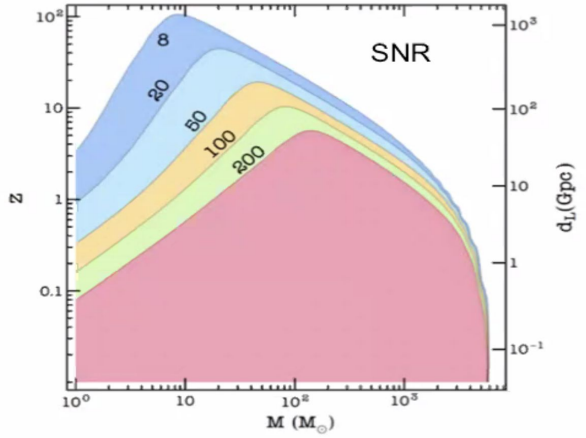
Higher SNR
- more accurate waveforms needed to avoid PE biases
- more physical effects visible (EOS, QNMs, …)

Orders of magnitude more events
- wider parameter space coverage

Broader detector bandwidth
- New cross-frequency physics (BNS inspiral + post-merger)
- each signal in band for many more GW cycles
- preserve accuracy & fast evaluation

Exploitation of ET science requires significant upgrades of all aspects of waveform models





How accurate?

So accurate as not to impact any ET science goal

Types of waveform applications

- Detection *(don't miss events)*
- Single event parameter estimation *(avoid PE biases)*
- Testing GR / search for beyond GR signatures
  (deviation from GR or modeling error?)
- **Analyses that combine many signals** ← ultimate accuracy driver?
  - Rates & population
  - Cosmology
  - Tests of GR / searches for beyond GR signatures

Influence of detector calibration? Overlapping signals?

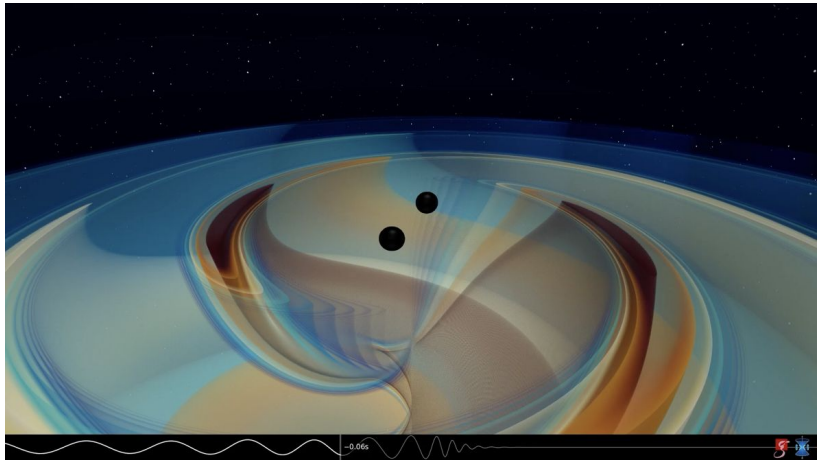
Accuracy requirements needed as targets for development

High-priority goal:
Investigate accuracy requirements

- What is known with relevance to ET?
- Design & initiate new studies
- Improve generically applicable criteria & devise new ones

Major GW sources

Binary black holes



N. Fischer, HP (SXS & AEI)

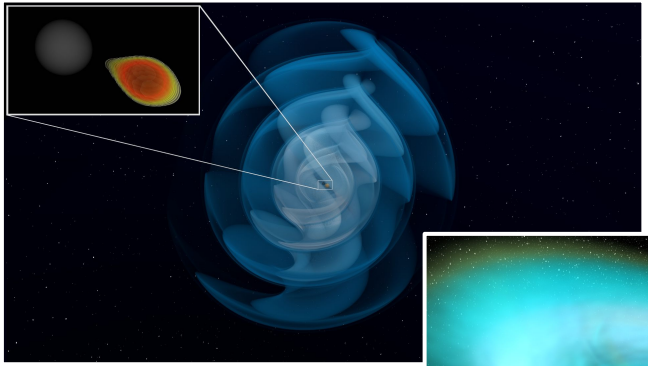
Full Inspiral-Merger-Ringdown models in large parameter space

- Mass ratio reaching into the EMRI regime
- Long inspirals
- Spins to extremal
- Accurate precession in all IMR-stages
- Higher modes
- Accurate ringdown modes
- Orbital eccentricity
- Hyperbolic flybys & captures
- GW memory

Incorporate detailed beyond GR information

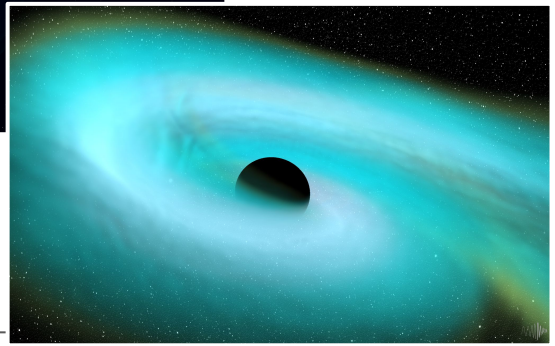
- Theory-agnostic i.e. parameterized deviations from GR
- For concrete alternative theories
- For exotic compact objects

Neutron star - black holes



N. Fischer, HP (SXS, AEI)

D. Ferguson, B. Khamesra, K. Jani
(Austin, GATech, Vanderbilt)

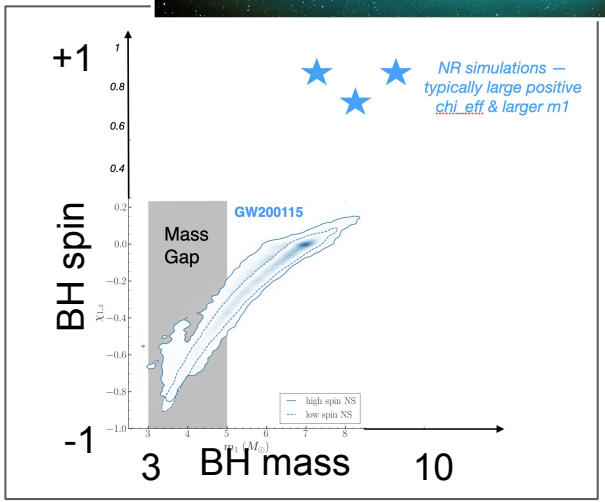


Full Inspiral-Merger-Ringdown models

- Need merger+post-merger part
- Spanning relevant EOS's
- Detailed connection to EM signatures
- Non-linear tidal effects
- And goals shared with BBH:
  - All mass-ratios and spins, higher modes, precession, eccentricity, hyperbolic
  - Long waveforms, accurate, fast evaluation

Beyond standard GR

- Also for exotic compact objects + NS
- Also for BH+NS in alternative theories



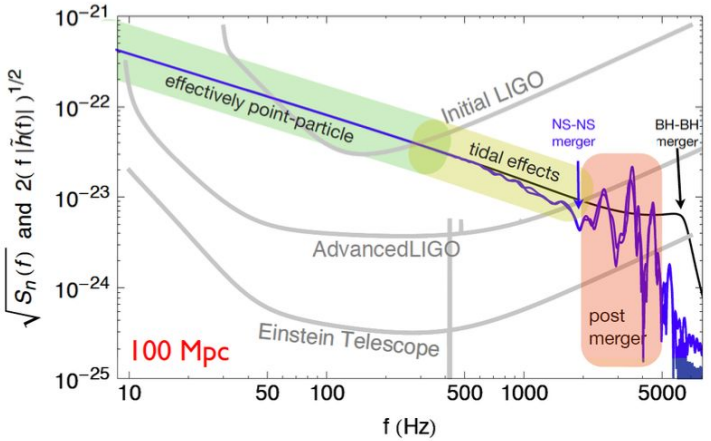
Binary Neutron stars

Inspiral-merger-post-merger models

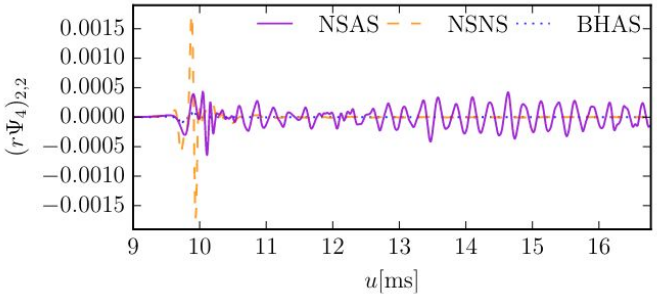
- Need merger + post-merger part
- Spanning relevant EOS's
- Detailed connection to EM signatures
- Non-linear tidal effects
- And goals shared with BBH
  - All mass-ratios and spins, higher modes, precession, eccentricity, hyperbolic
  - Long waveforms, accurate, fast evaluation

Beyond standard GR

- Also for NS+NS in alternative theories
- Also for exotic compact objects
- Explore degeneracies EOS vs. alternative theories



ET Science case (1912.02622)

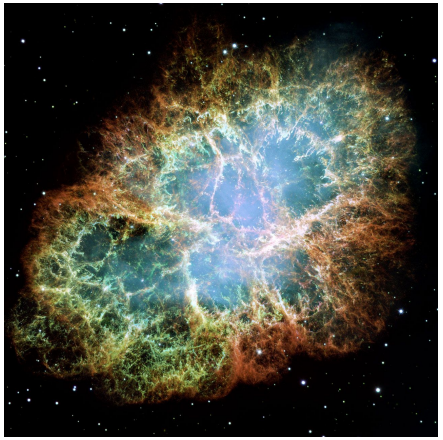


Binaries w/ axion stars (AS) *Dietrich et al. (1808.04746)*

Other sources

Waveforms for any other system ET could conceivably observe, and which are amenable to modeled GW, including

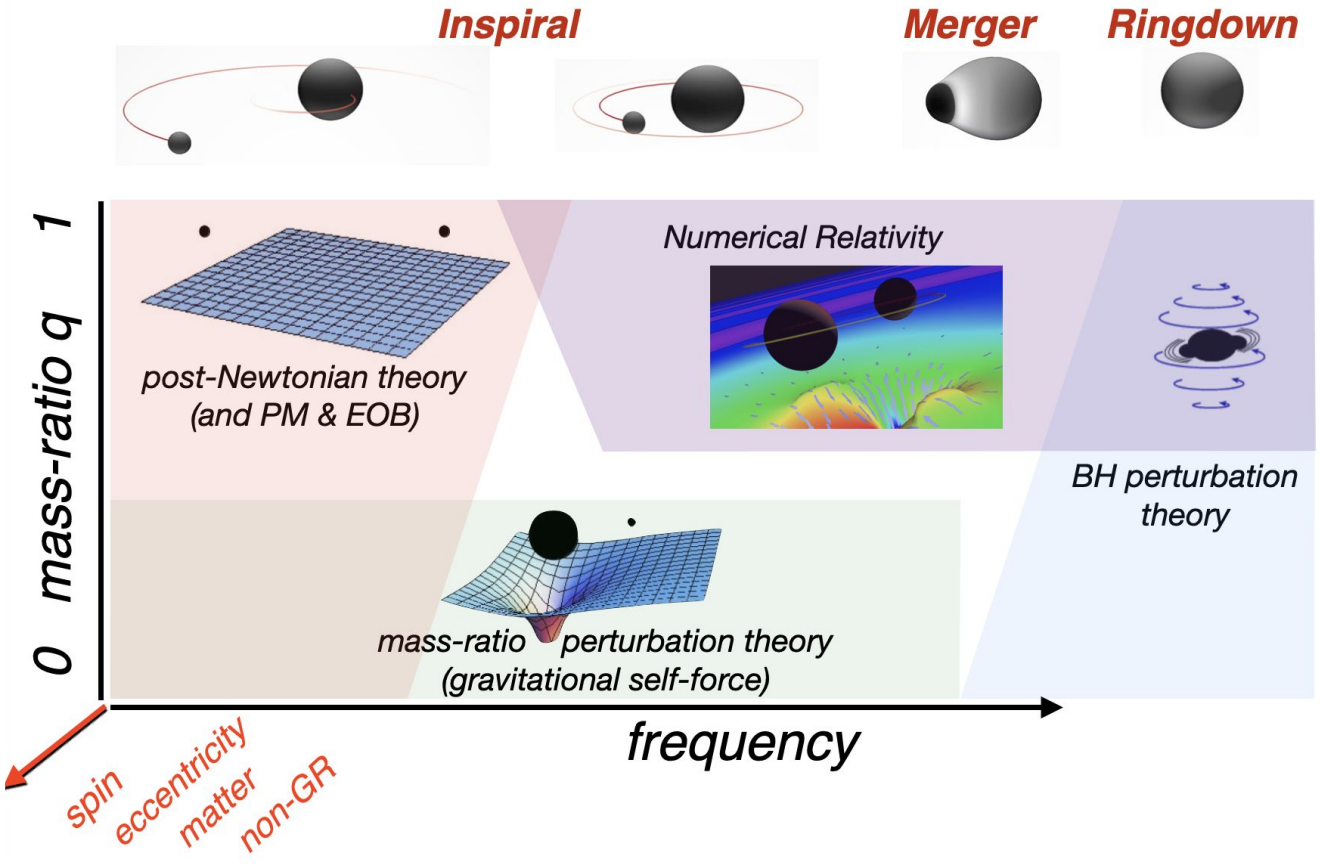
- Core collapse supernovae
- Cosmic strings
- NS oscillations in GR and beyond GR
- BH quasi-normal modes in GR and alternative theories
- Cosmological effects
- Environmental effects
  - e.g. dark matter halos, accretion disks
- multi-body interactions



Hubble

University of Hawaii

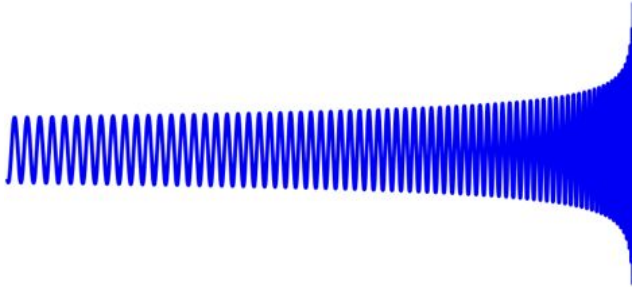
Major Tools


Inspiral
Merger
Ringdown
Numerical Relativity
post-Newtonian theory
(and PM & EOB)
BH perturbation
theory
mass-ratio perturbation theory
(gravitational self-force)
0 mass-ratio q 1
frequency
spin
eccentricity
matter
non-GR

Analytical calculations

Post-Newtonian (multipolar post-Minkowskian-PN, effective field theory, scattering amplitudes)

- Identify the PN order that is needed
- Improve accuracy for spins, eccentricity, tides, precession
- Develop synergies between methods
- Multi-body systems
- BH encounters



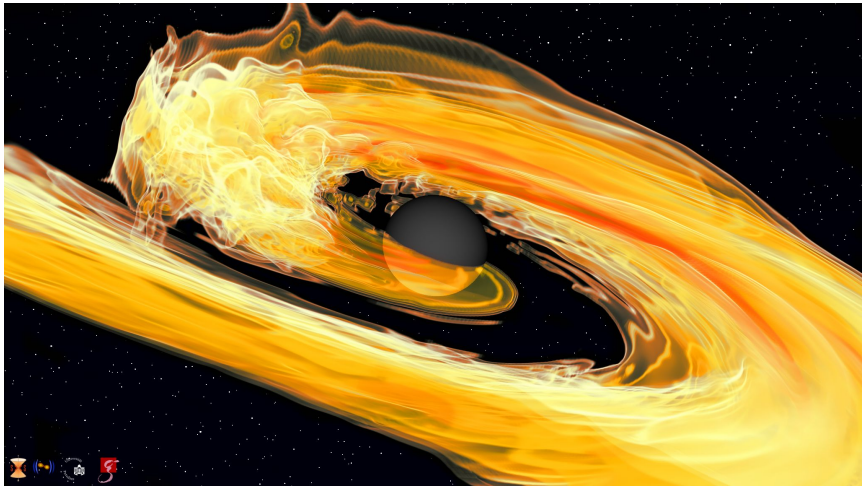
Gravitational self-force

- 2nd order needed for intermediate mass-ratio binaries
- Generic spins & eccentricity
- Perhaps with plunge + merger ?

Beyond GR

- Accurate waveforms for specific modified gravity theories and exotic compact objects
- Agnostic parametrized waveform models (beyond GR)

Numerical relativity

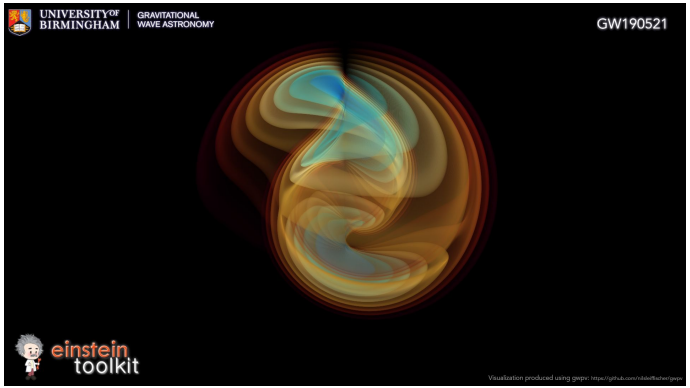


Vacuum GR (i.e. BBH)

- Broader parameter space coverage (q, spins, ecc)
- Better higher modes
- Better QNMs
- Longer
- GW memory

Matter

- GWs from post-merger evolution
- Connection GW -- EM signatures
- Explore parameter space (q, spins, EOS)
- Especially explore BH-NS systems



Beyond GR

- Full IMR studies of exotic compact objects (Boson stars, ...)
- Full IMR studies of alternative theories

… all of this more accurate than today

Inspiral-merger-ringdown modeling - putting it all together

Effective-one-body models, Phenomenological models: Improve...

- Physics
  - validated to high mass-ratios & high spins, eccentricity, higher modes, GW memory (?), hyperbolic flybys+captures
- Matter effects
  - Tides, handling of disruption
- Accuracy
  - Higher order modes, ringdown, precession during merger
- Calibrate / validated against more + better NR
- Evaluation speed

Surrogate models

- Improve validity range across the parameter space
- Reduce evaluation cost

Develop IMR models in alternative theories of gravity

Waveform acceleration

All waveforms must be evaluatable as quickly as needed for ET usage

Parameter estimation needs millions of waveform evaluations

Explore and utilize acceleration techniques, including:

- Reduced-order modelling
- Machine learning/AI techniques
- Multibanding/heterodyning
- Dimensional reduction strategies e.g. effective parameterisations
- ...

We need your help :-)

Please do sign up, If you're interested in...

- waveform modeling,
- any of the tools used for it,
- or the areas of synergies with other OSB divisions
  - Div1 Fundamental Physics
  - Div2 Cosmology
  - Div3 Population studies
  - Div4 Multimessenger
  - Div5 Synergies with other GW observatories
  - Div6 Nuclear Physics
  - Div7 Transient sources
  - Div9 Detector config
  - Div10 Data-analysis