USING NUMERICAL RELATIVITY WAVEFORMS FOR GRAVITATIONAL-WAVE OBSERVATION

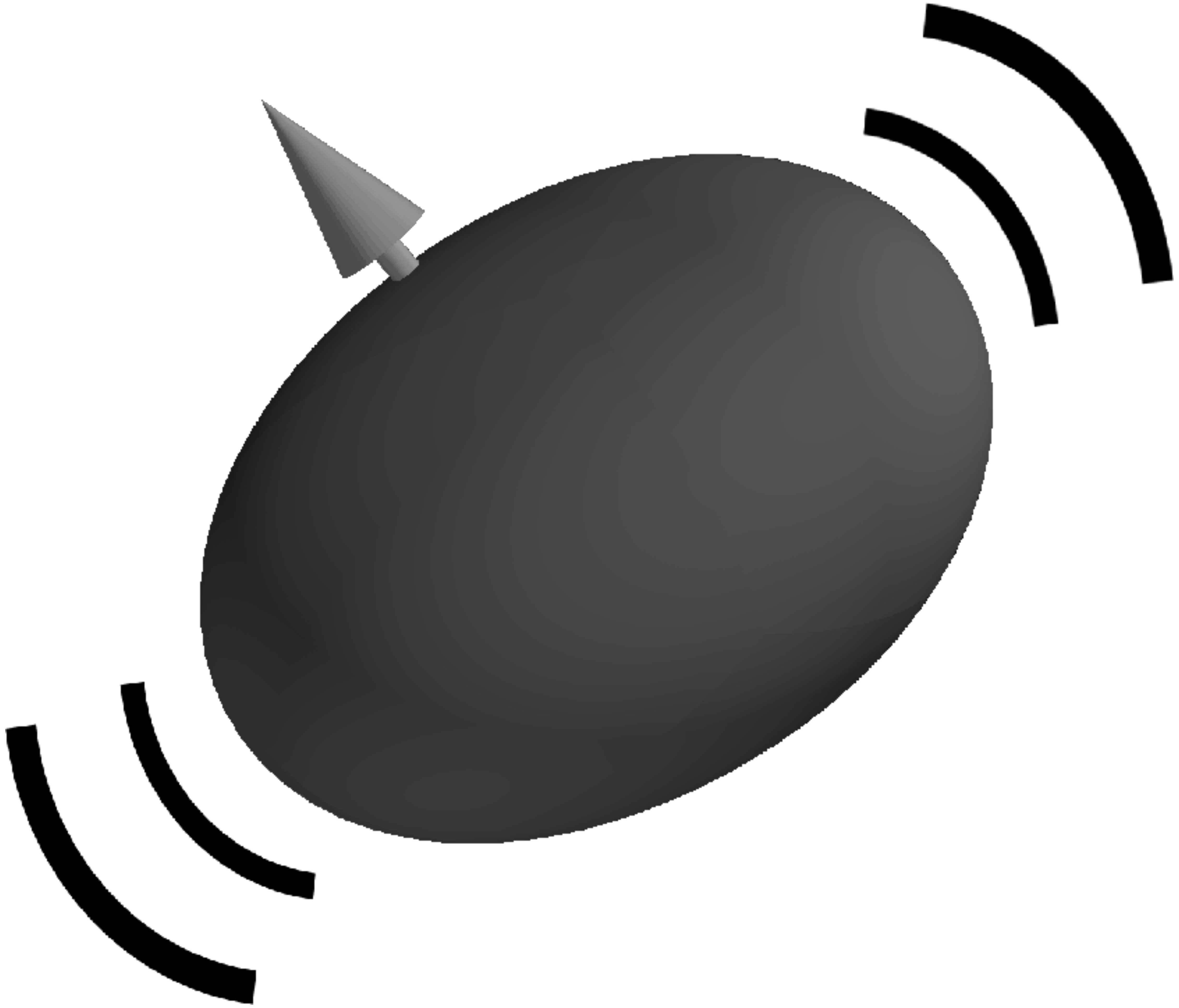
Deborah Ferguson

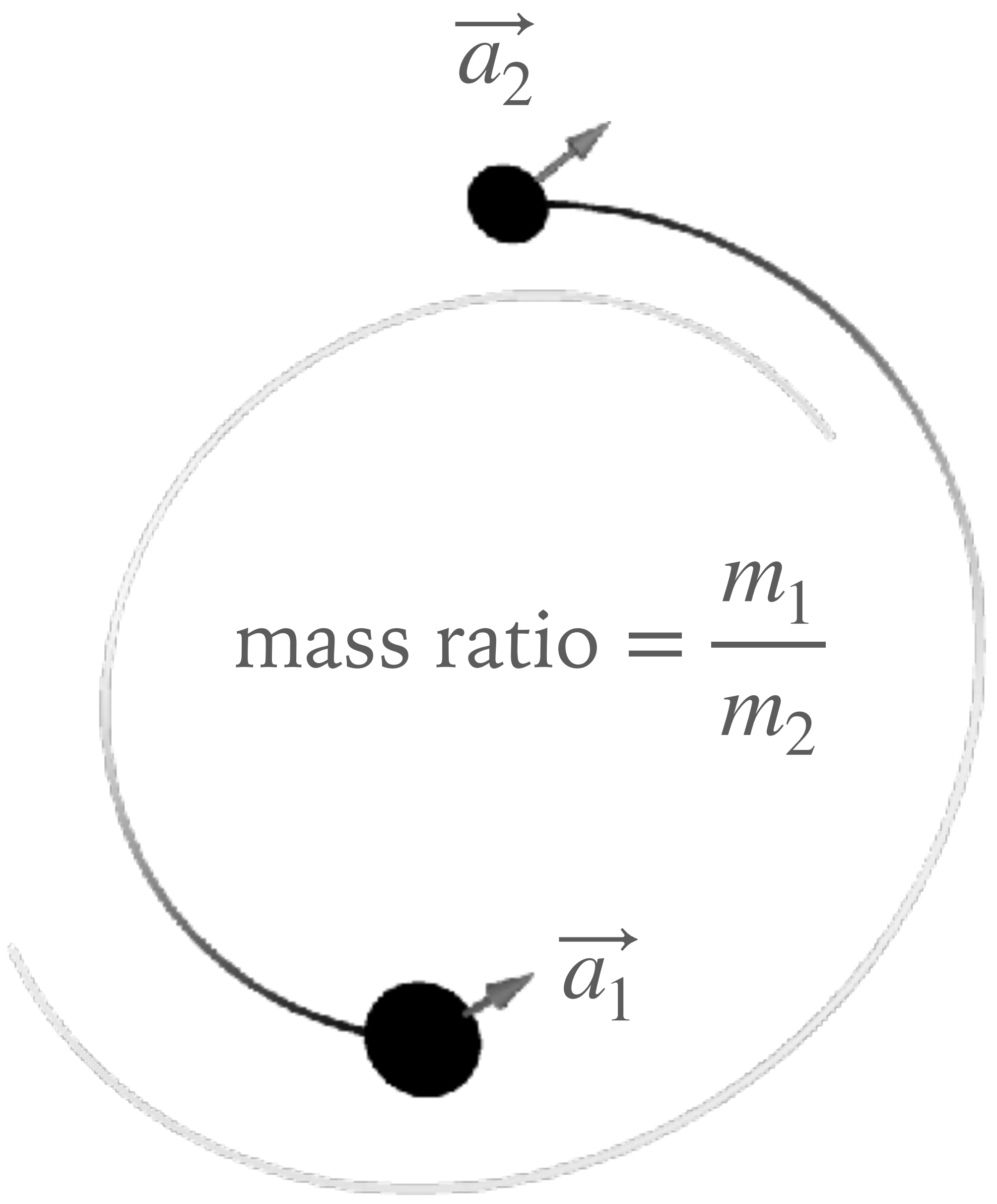
Einstein Toolkit Workshop 2024

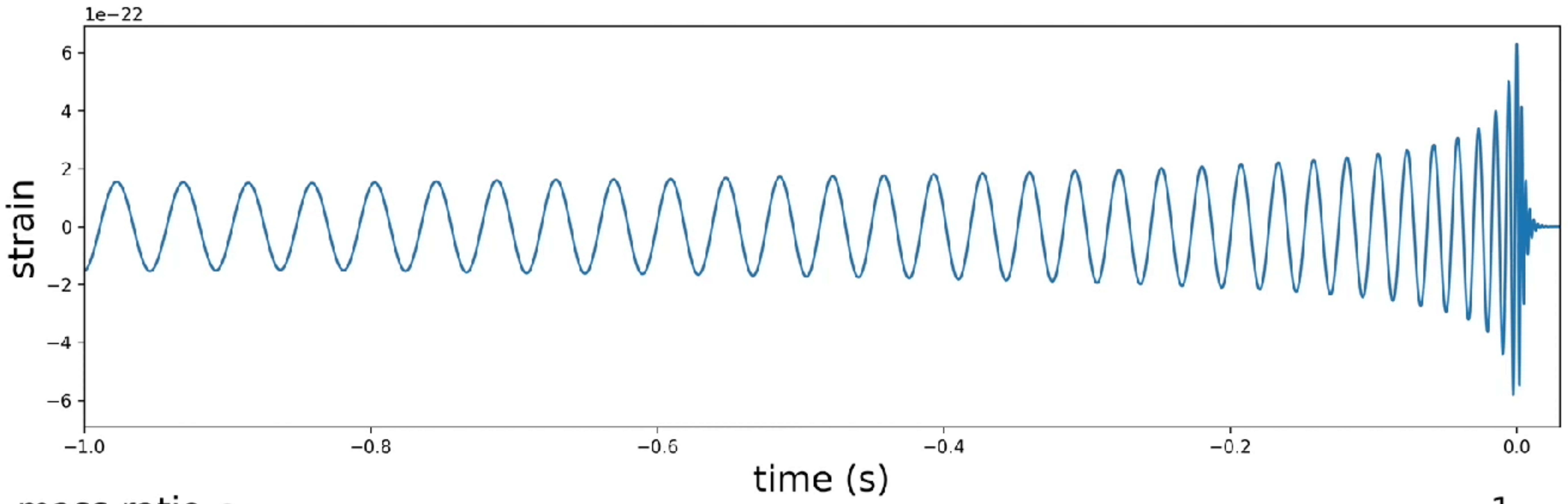
THE DENSEST OBJECTS IN THE UNIVERSE

Mass (m)

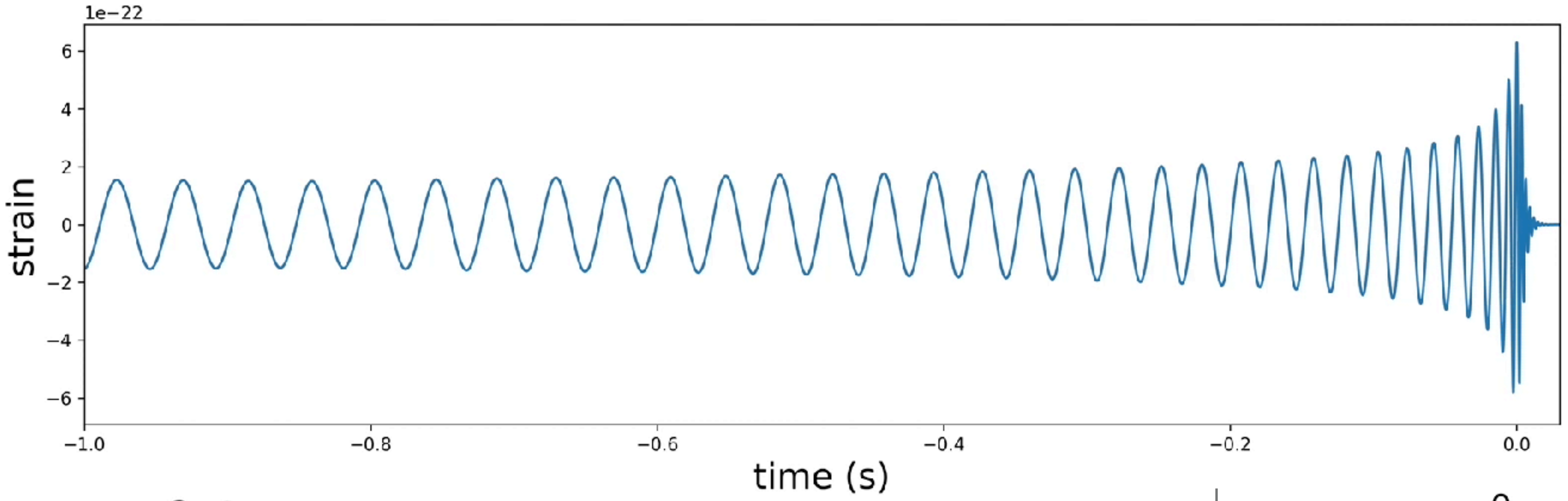
Spin ($\vec{a}$)







mass ratio 1



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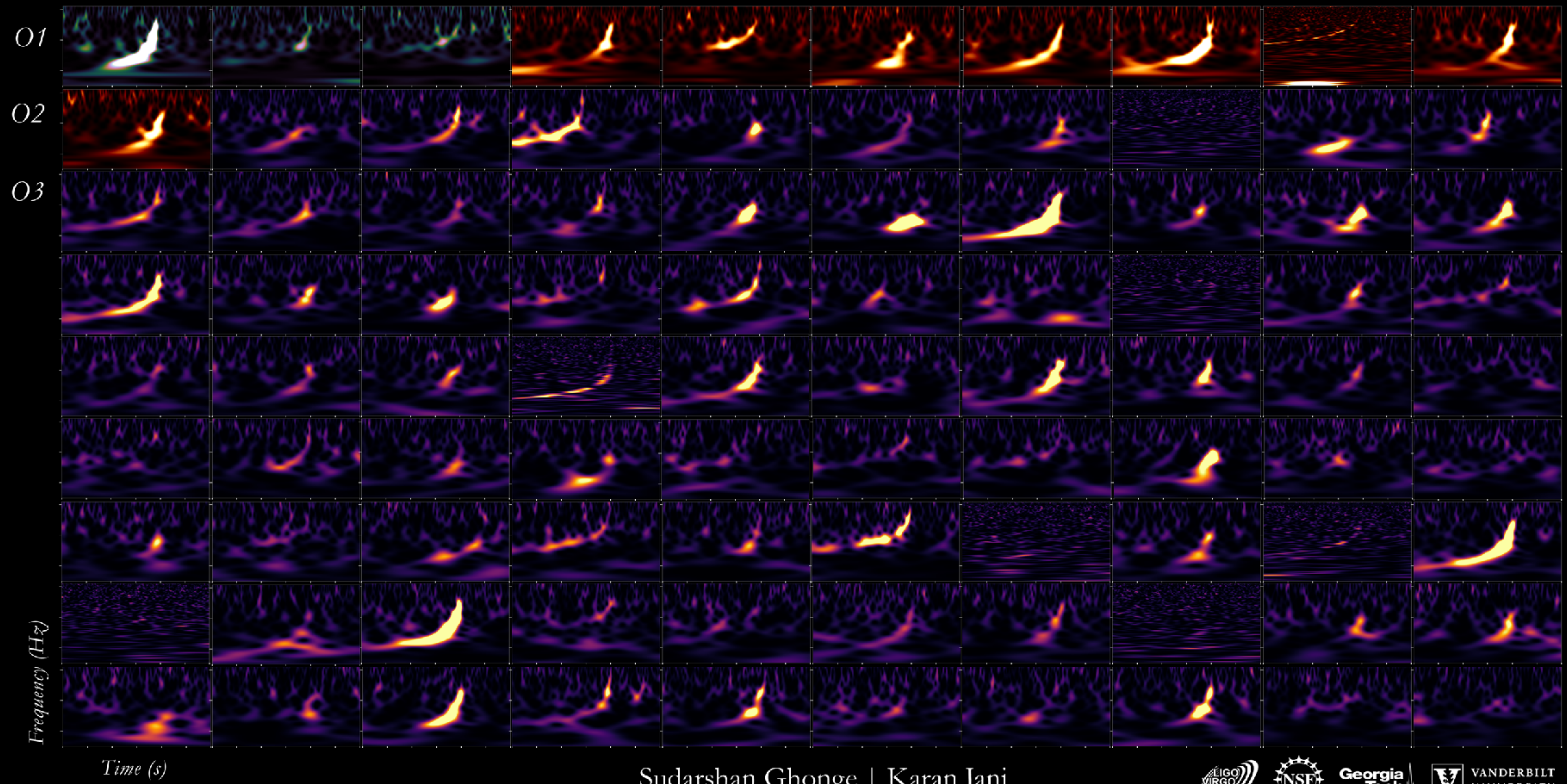
T. Pyle, Caltech/MIT/LIGO Lab


Gravitational Wave Observatories
LIGO Hanford
LIGO Livingston
GEO600
Virgo
KAGRA
LIGO India
Operational
Planned
3 km

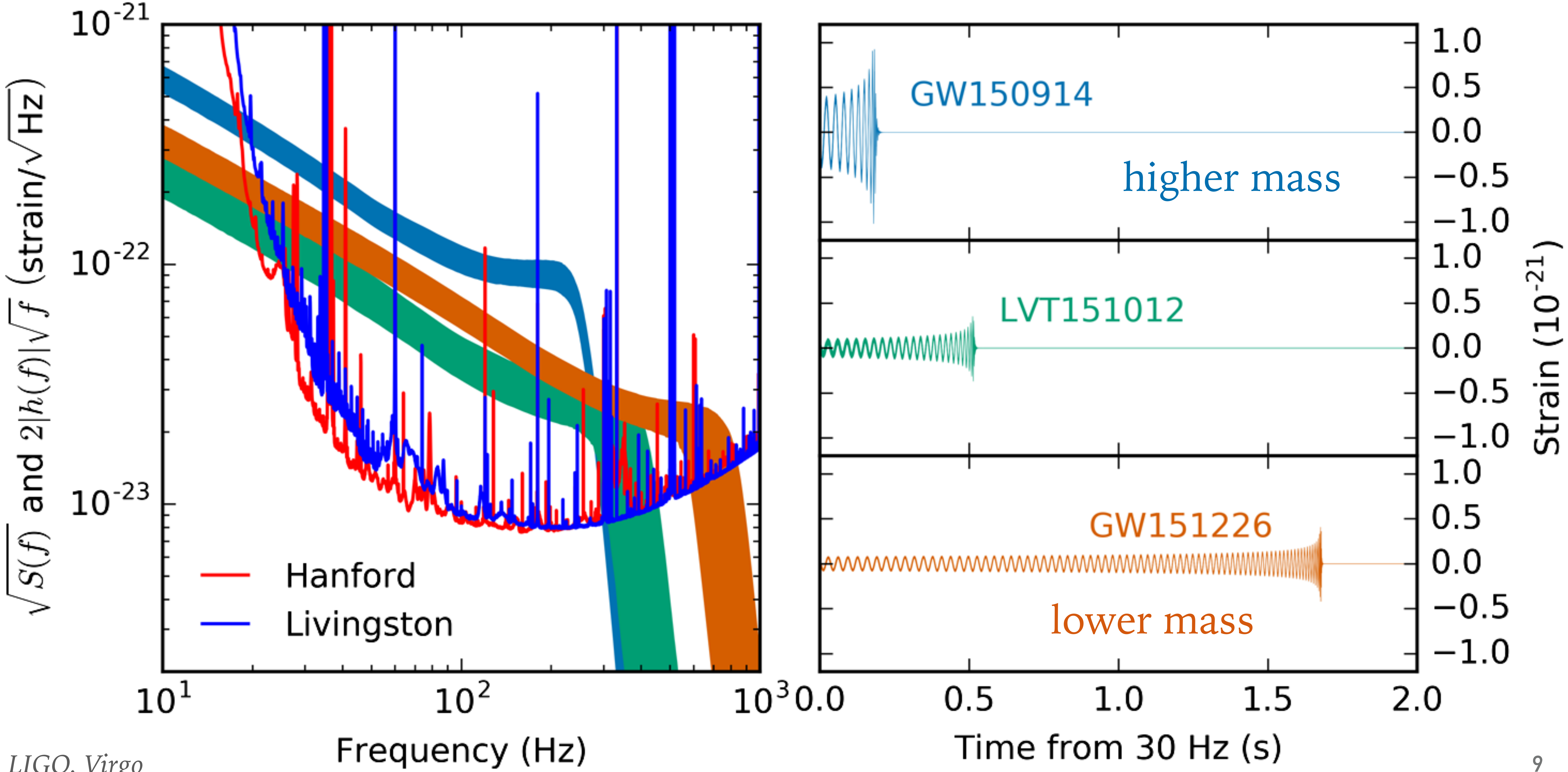
Gravitational-Wave Transient Catalog

Detections from 2015-2020 of compact binaries with black holes & neutron stars



Sudarshan Ghonge | Karan Jani

GRAVITATIONAL WAVES IN TIME AND FREQUENCY DOMAIN

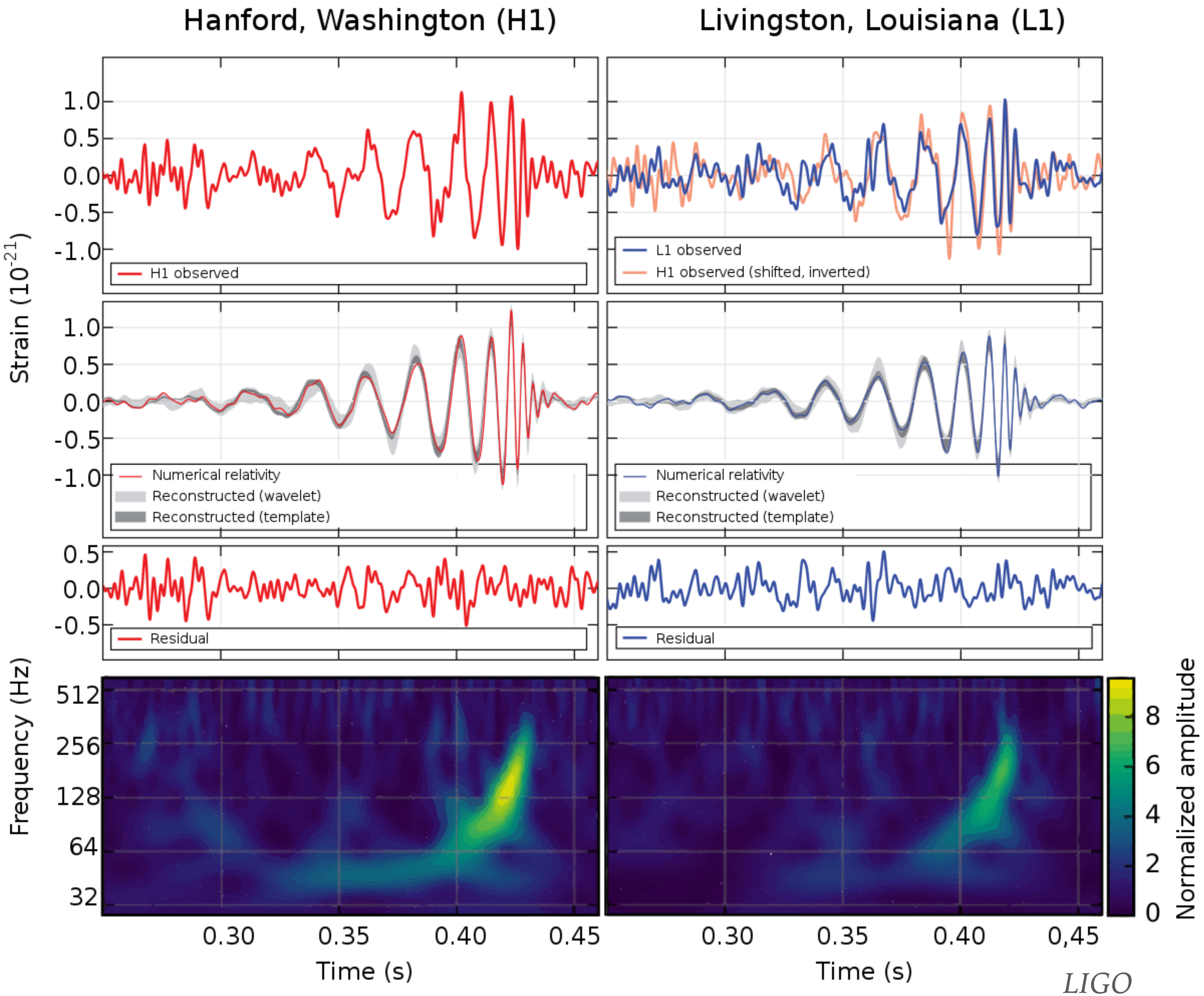


LIGO, Virgo

SEARCH AND PARAMETER ESTIMATION PIPELINES

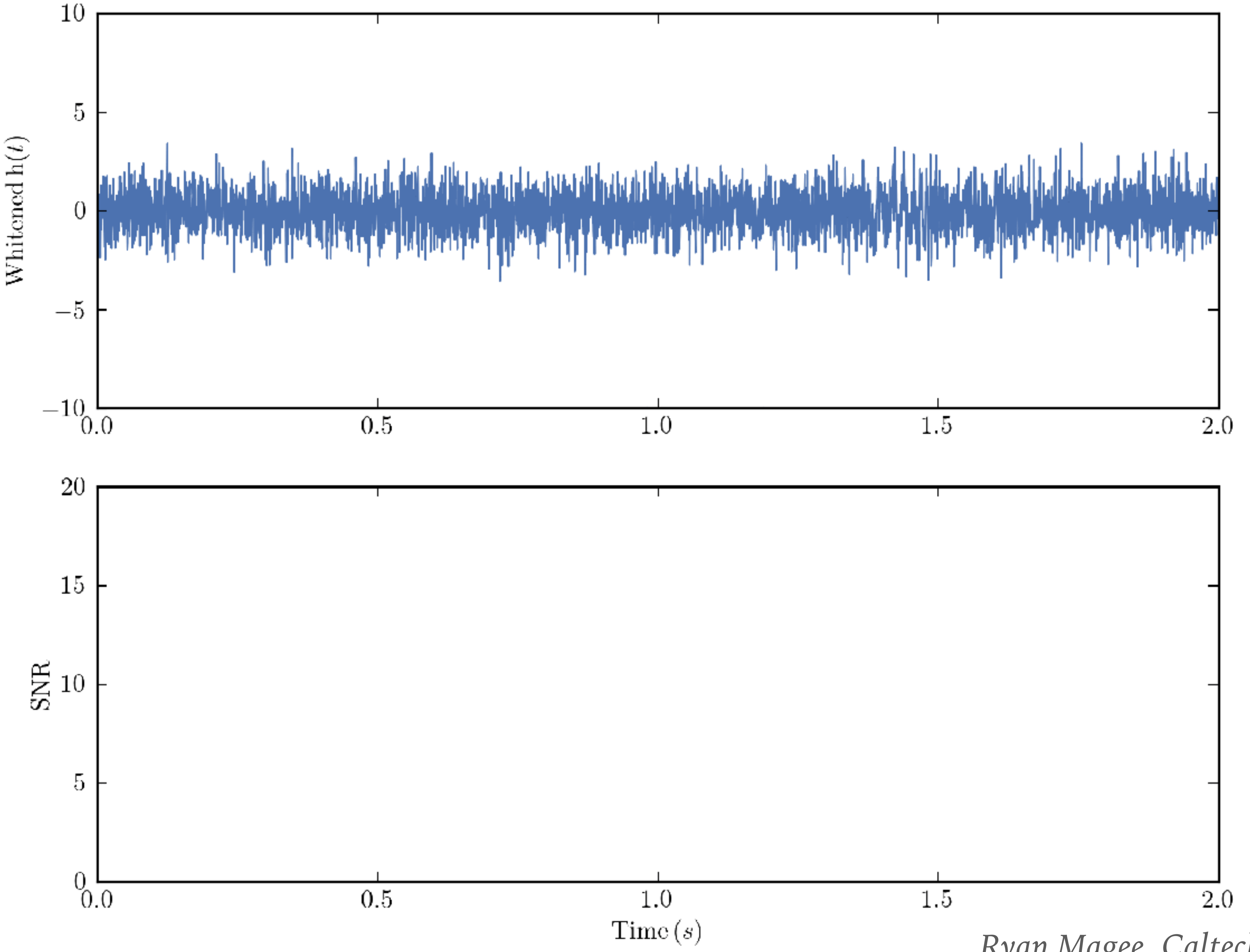
- Modeled Searches
  - Take a template bank of waveforms and search for them in the data by comparing the template to the data
  - Good for expected and well modeled sources such as BBHs, NSBHs, BNSs
  - PyCBC, GstLAL, RIFT
- Unmodeled Searches
  - Search for coincident excess power
  - Able to search for unexpected and unmodeled sources
  - cWB, oLIB, BayesWave

Extracting the waveform from the first detection (GW150914)



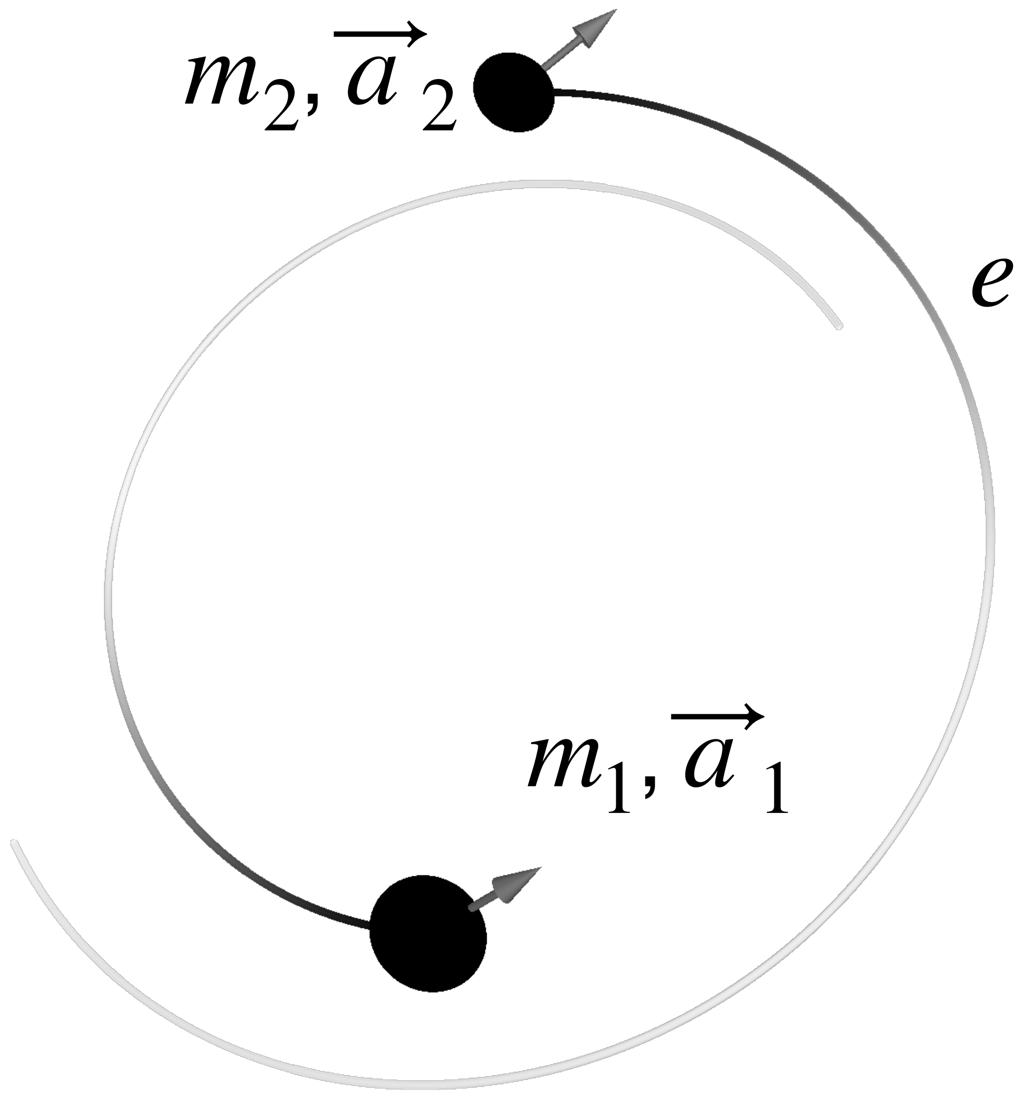
LIGO

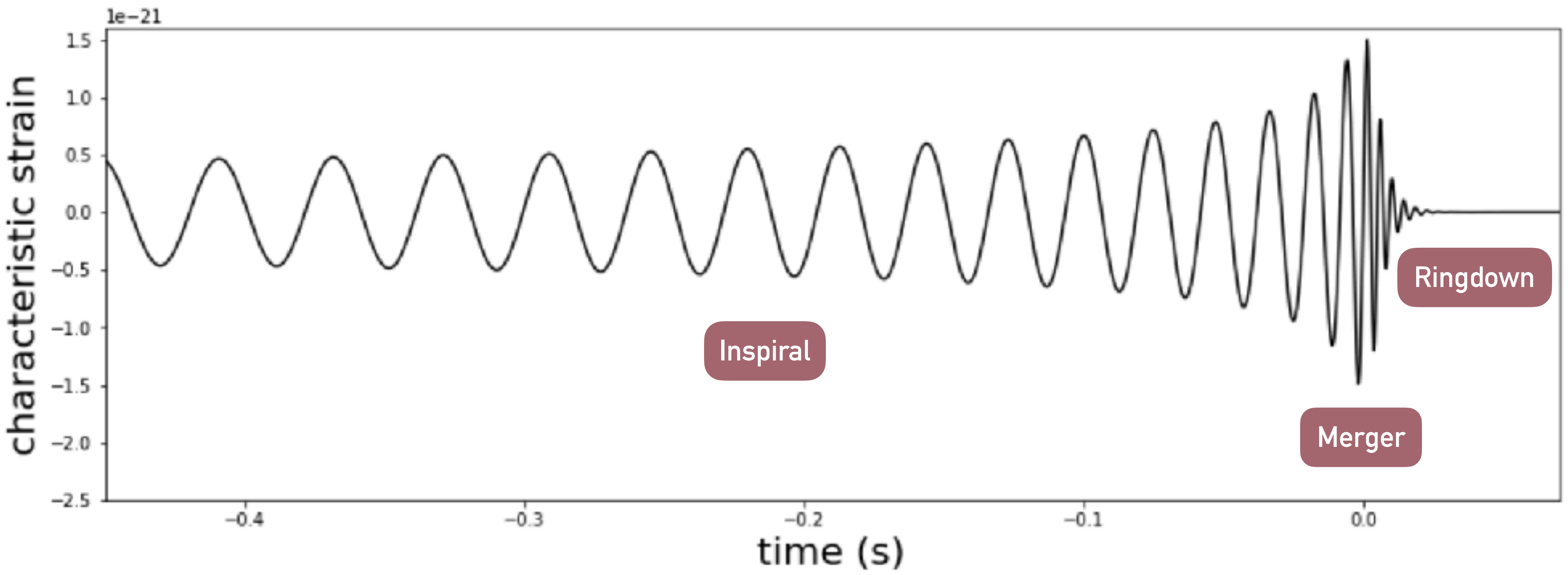
MODELED SEARCHES USING MATCHED FILTERING



TESTS OF GENERAL RELATIVITY RELY ON WAVEFORM TEMPLATES

- Residual tests
  - Subtract the max likelihood template waveform from the data and check if residual is consistent with noise
- Inspiral-merger-ringdown consistency tests
  - Estimate mass and spin of remnant black hole using different parts of the signal
  - Mass and spin are estimated from the ringdown using NR-calibrated fits
- Generic modifications
  - Add parametrized modifications to phase evolution
- For more information see "Tests of General Relativity with GWTC-3" (arXiv:2112.06861)



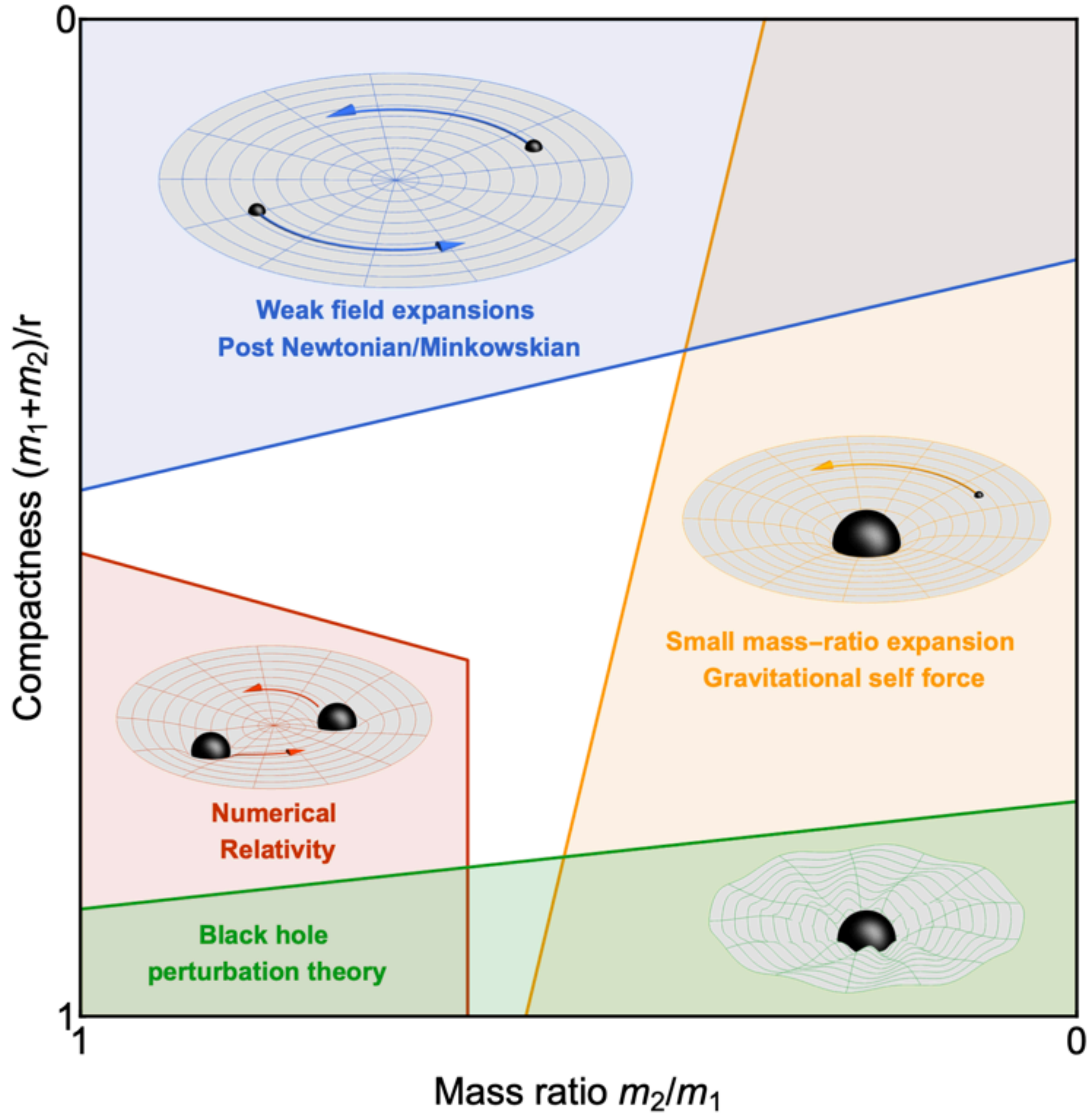


9 dimensional parameter space that needs to be filled to generate template banks for analysis with current and future detectors

HOW DO WE CREATE THESE TEMPLATE WAVEFORMS?

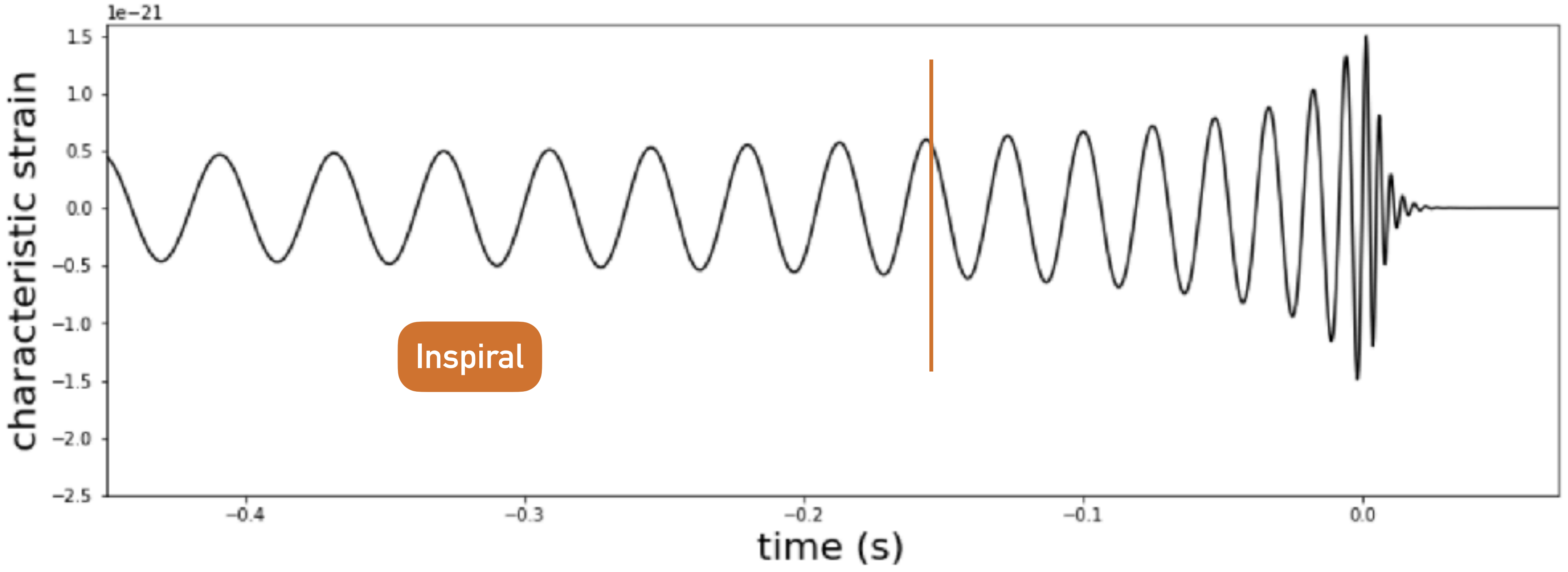
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

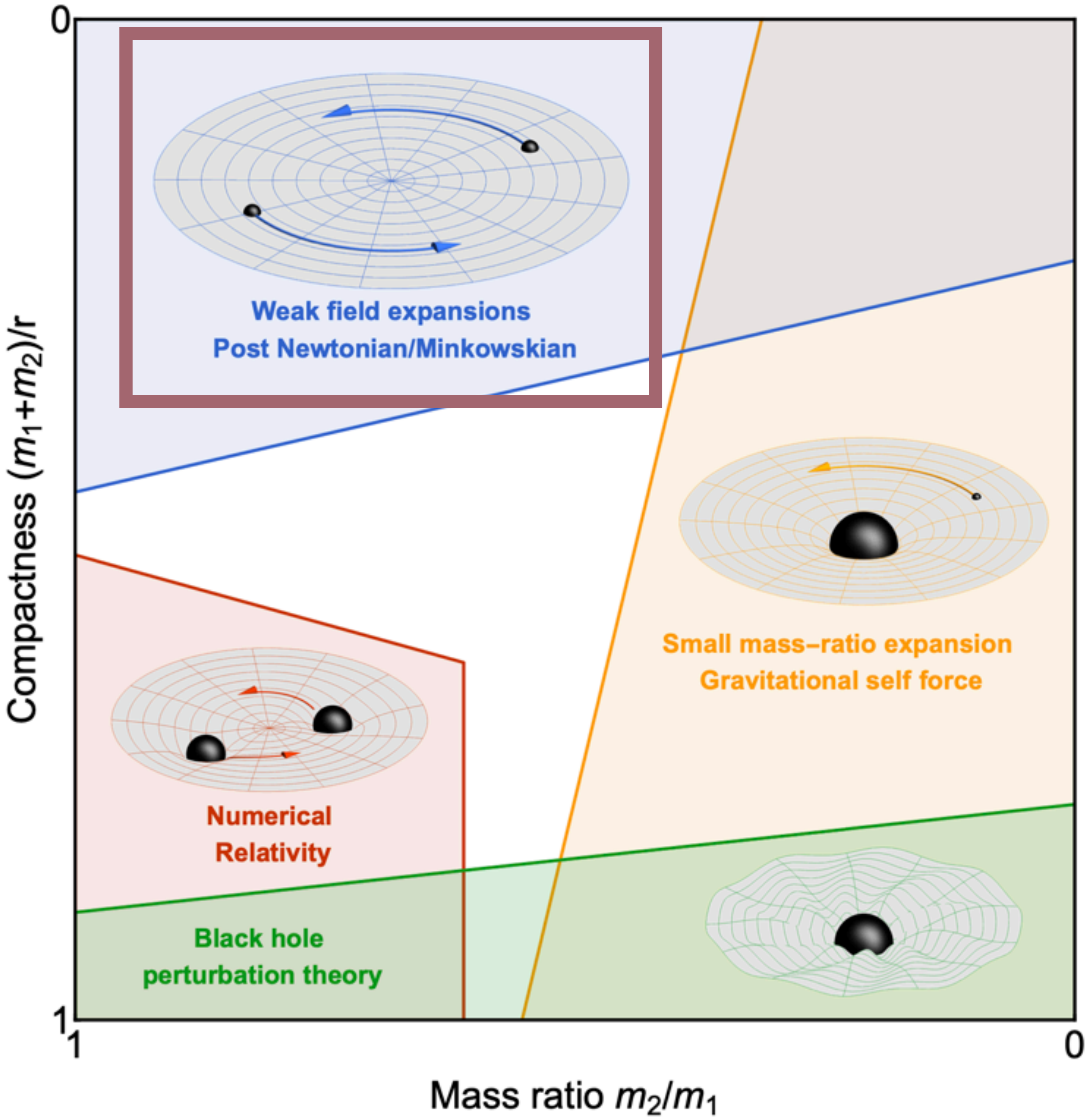
- Set of nonlinear coupled partial differential equations
- No analytic solution to the two-body problem



WEAK-FIELD APPROXIMATIONS

- Post-Newtonian and post-Minkowskian
- Orbital velocities small compared to the speed of light
- Great for modeling inspiral
- See section 4.2 of "Waveform Modelling for the Laser Interferometer Space Antenna" for more information and references





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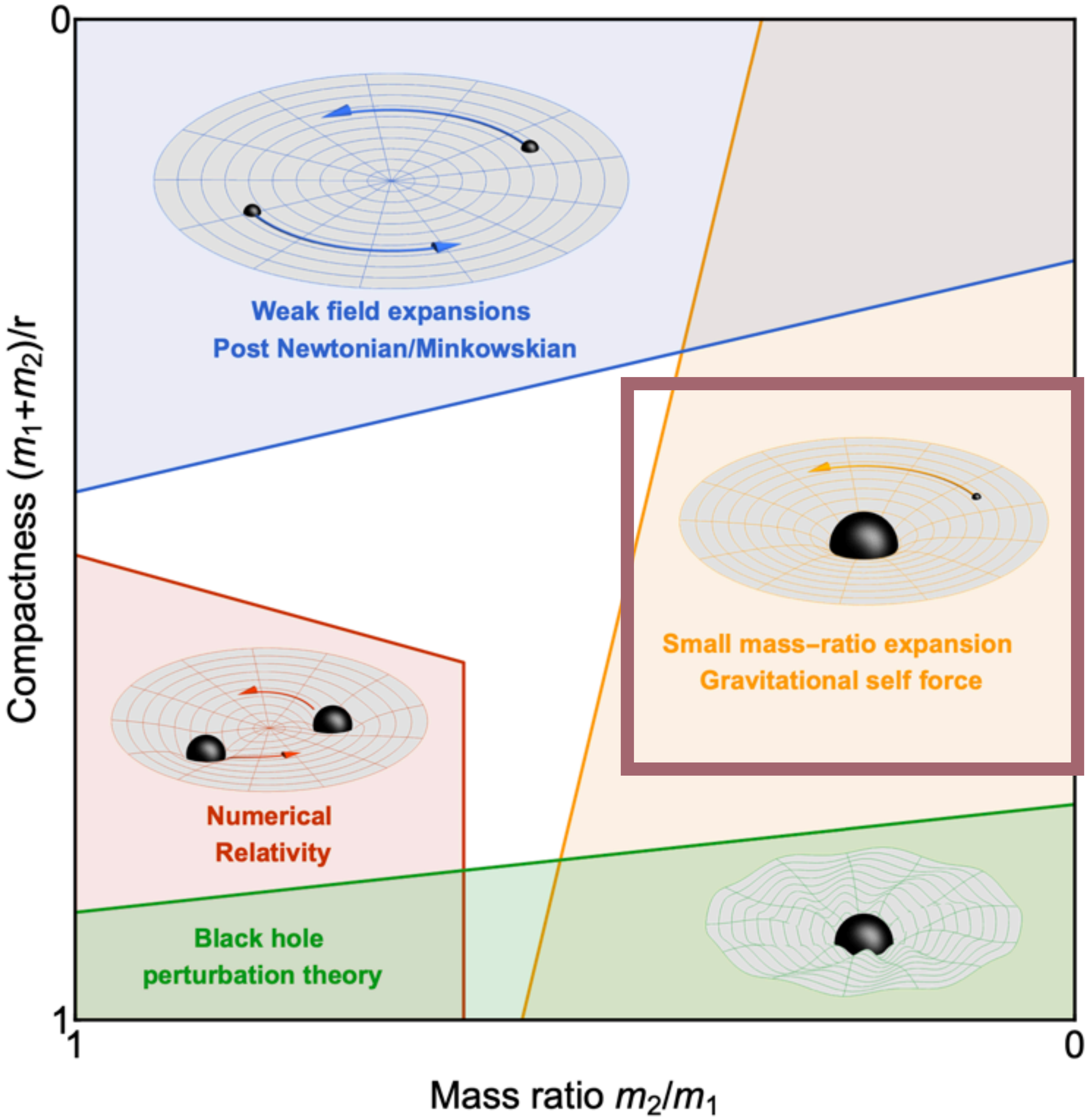
SMALL MASS-RATIO APPROXIMATION

- Applicable when the secondary object is much smaller than the primary object
- Treat the secondary mass as a perturbation to the background metric of the primary object
- Has made huge strides in recent years pushing towards equal mass ratios for nonspinning systems
- See section 4.3 of "Waveform Modelling for the Laser Interferometer Space Antenna" for more information and references



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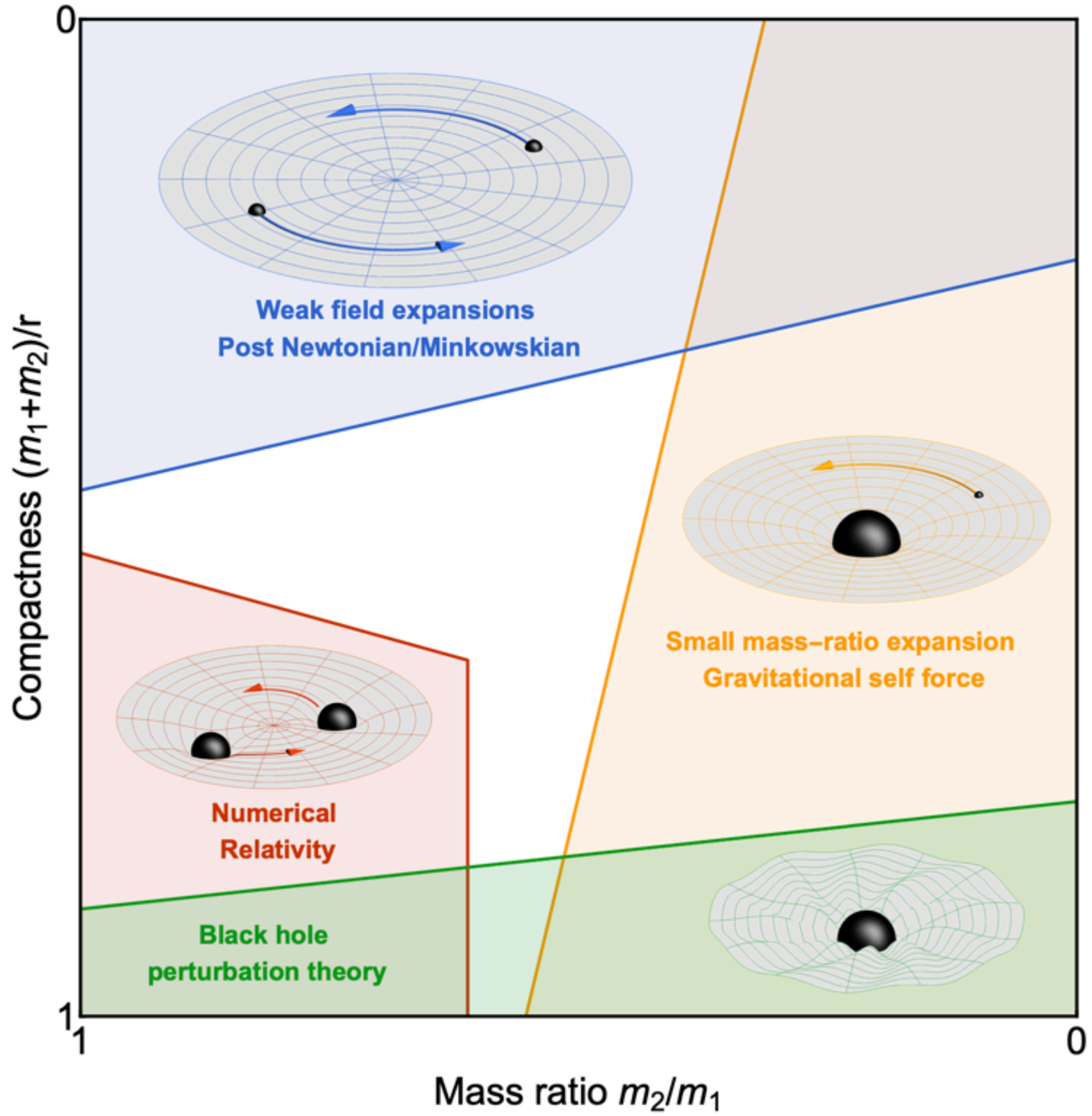
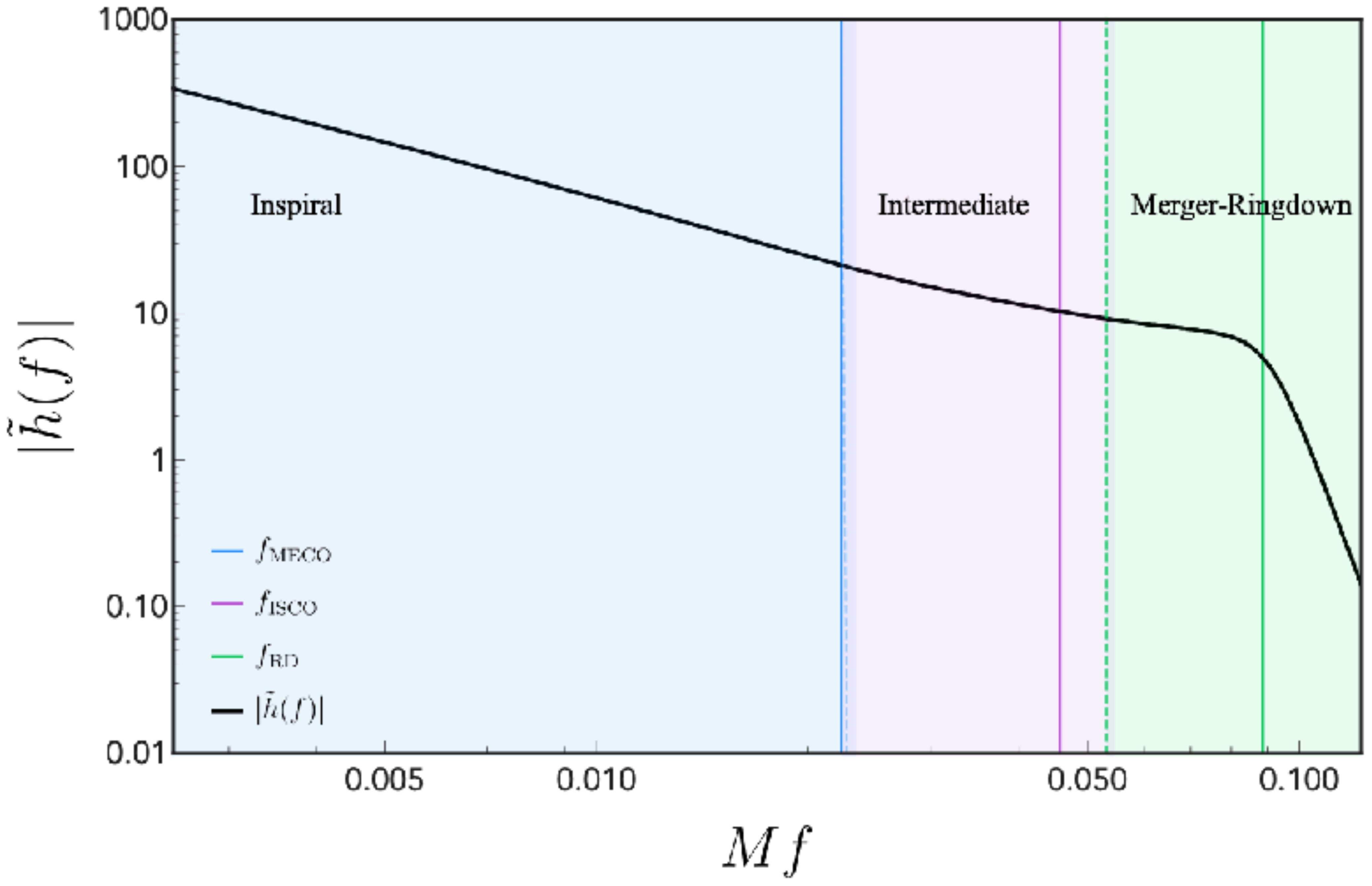
EFFECTIVE-ONE-BODY MODELS

- Semianalytic waveform model that is trained to cover the whole parameter space
- Maps the two-body problem to an effective test mass moving in a deformed Schwarzschild or Kerr background
- Has been making progress towards eccentric, precessing model
- See section 4.5 of "Waveform Modelling for the Laser Interferometer Space Antenna" for more information and references



PHENOMENOLOGICAL MODELS

- Analytic models trained on numerical relativity and post-Newtonian waveforms
- Very fast to generate making them ideal for rapid searches and parameter estimation
- IMRPhenomX - one of the recent cutting edge models
- Both time domain and frequency domain models have been developed
- Piecewise construction using an ansatz for each region of the waveform (shown on right)



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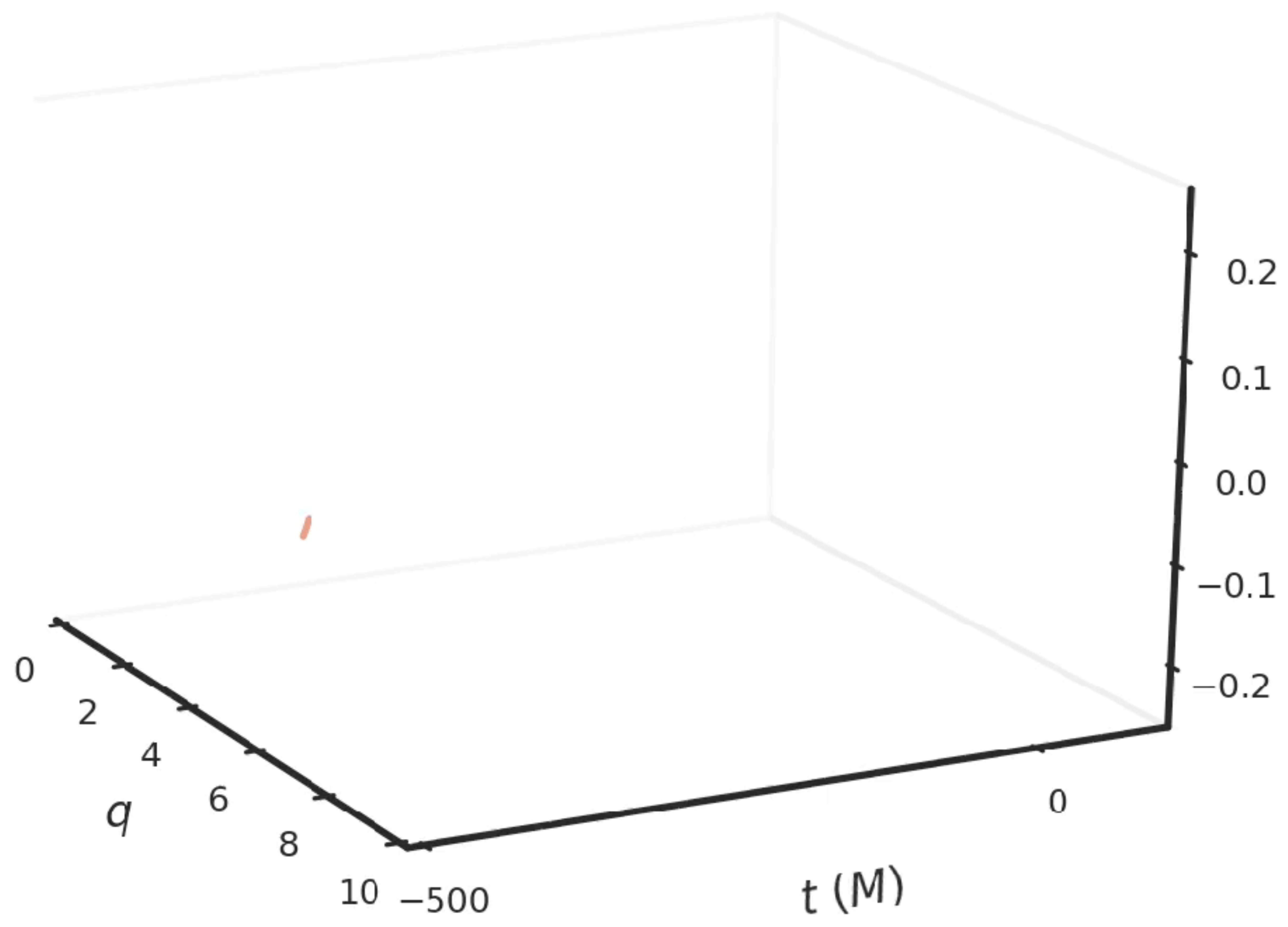
NR SURROGATE MODELS

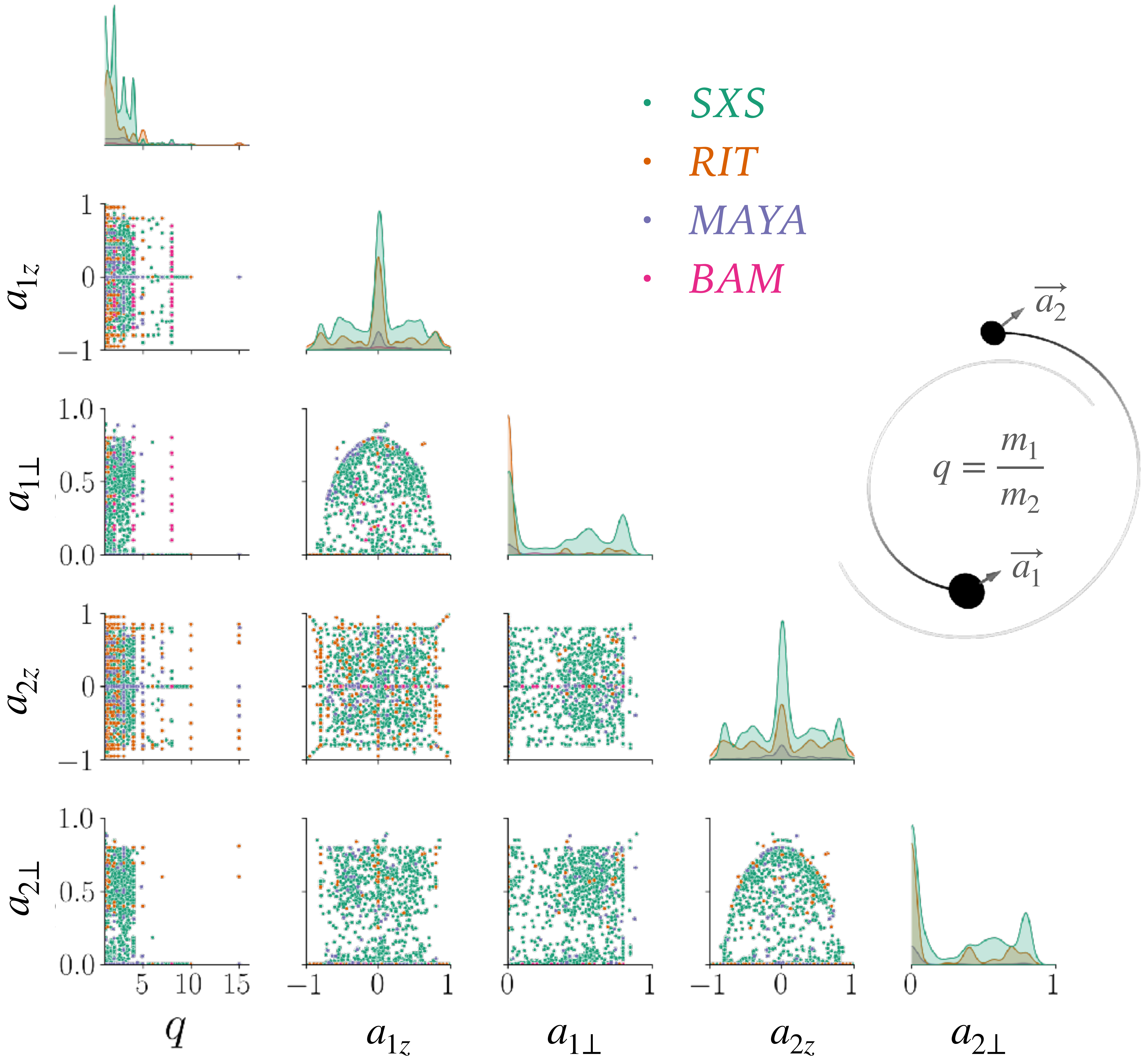
- Interpolate between numerical relativity waveforms to create a surrogate model
- Very accurate
- Limited to the same coverage as numerical relativity waveforms
- Hybrid surrogate models exist to include longer inspiral



Vijay Varma, https://vijayvarma392.github.io/SurrogateMovie/

NUMERICAL RELATIVITY

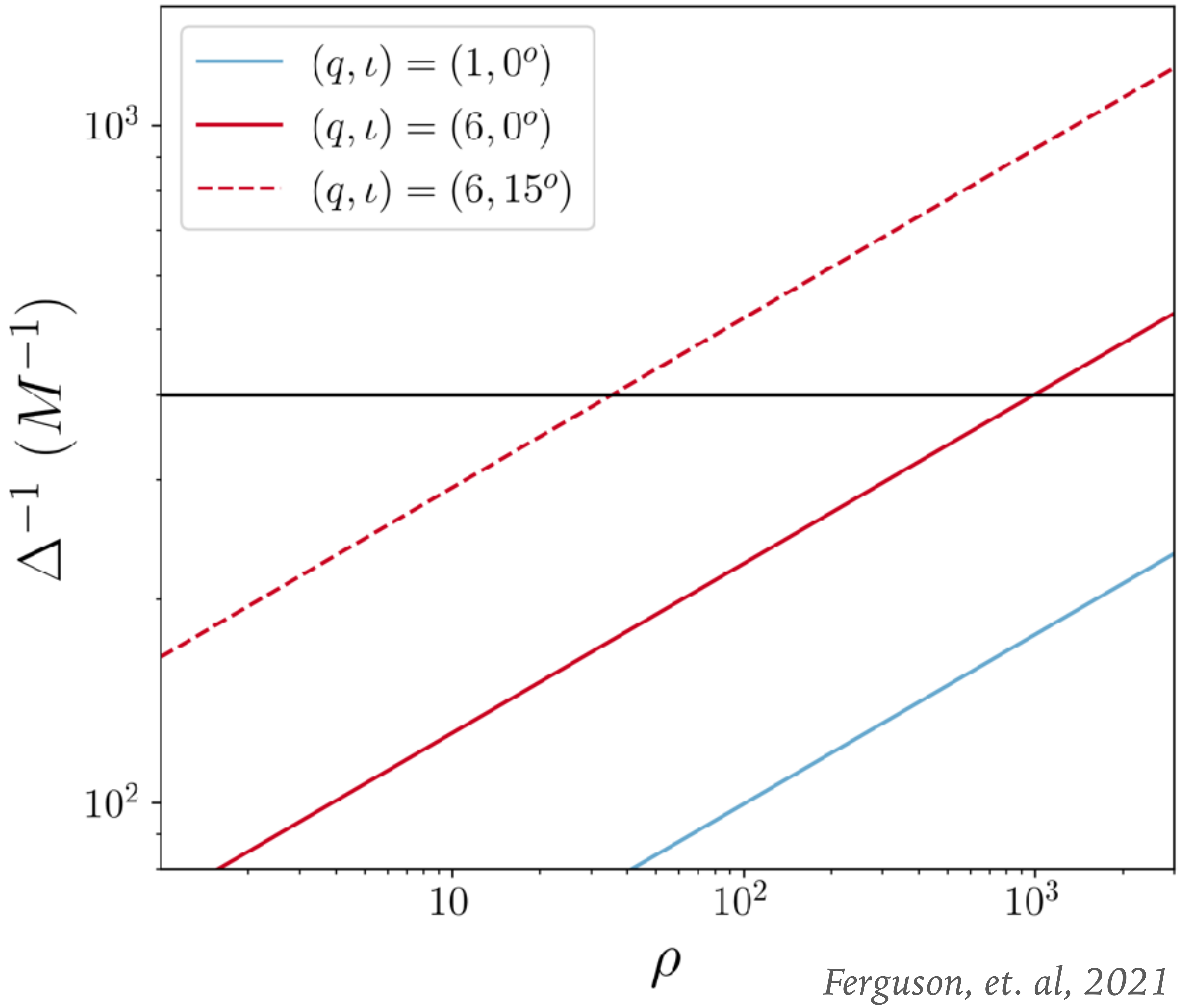
- Comparable-mass systems
- Near merger
- Eccentric, precessing systems
- Matter
- Beyond-GR theories
- Used to construct models
- Also used directly with data analysis



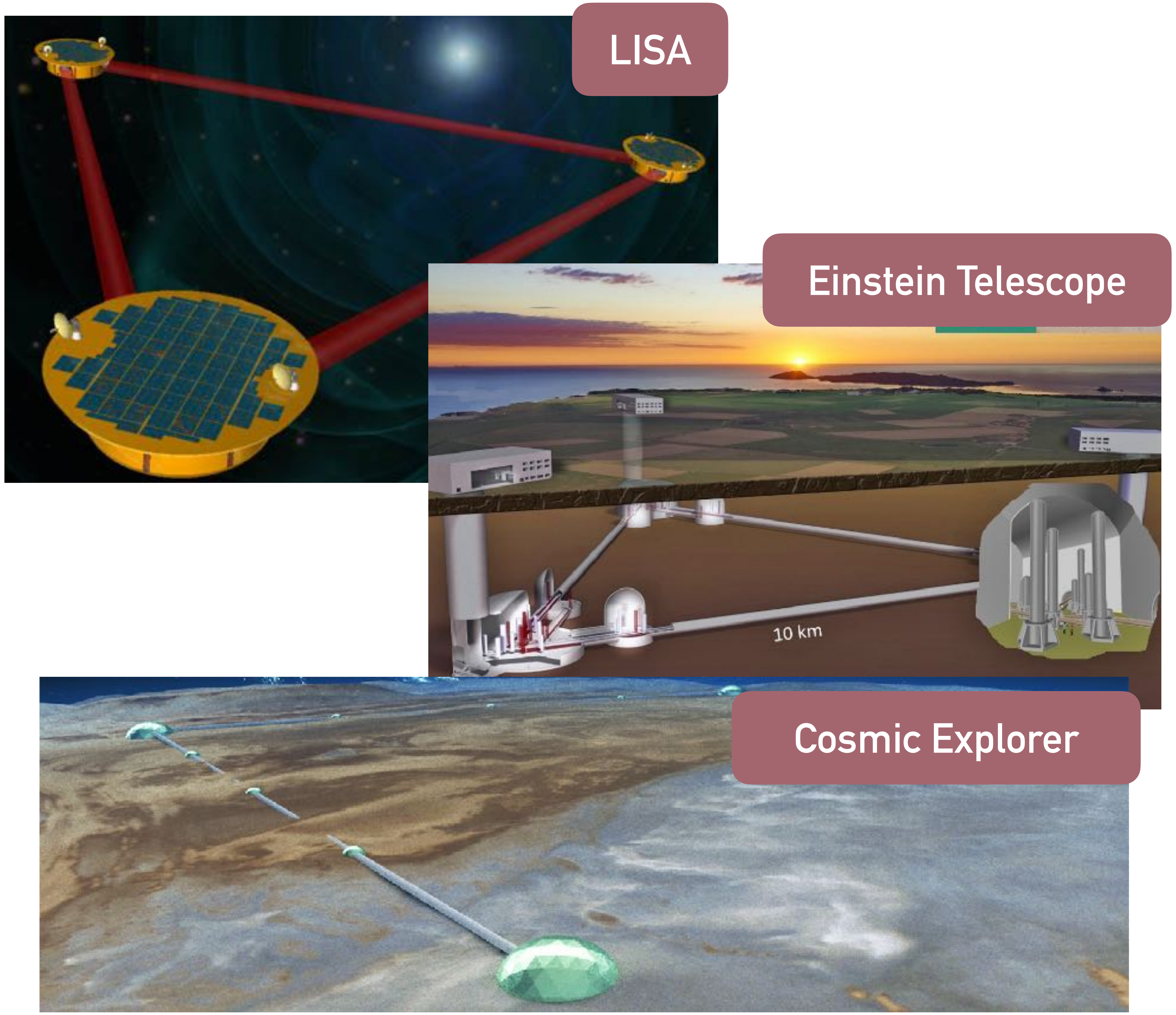
Ferguson, LISA Waveform Working Group Whitepaper

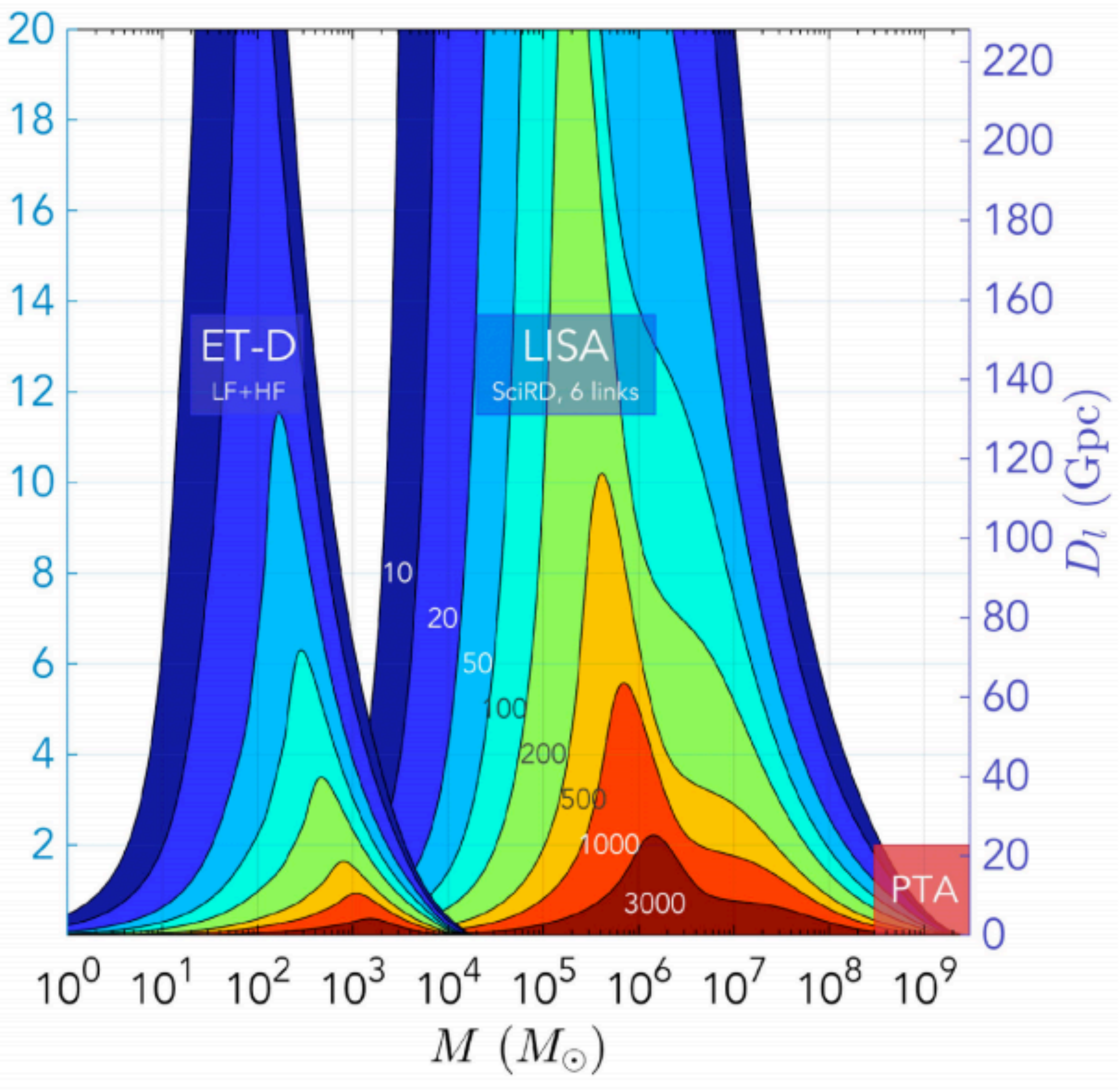
CHALLENGES FACING NUMERICAL RELATIVITY

- High resolutions will be necessary
- Longer waveforms will be required to minimize hybridization errors
- Need to expand parameter space
  - High mass ratio
  - Eccentricity
  - High spins (especially precessing)



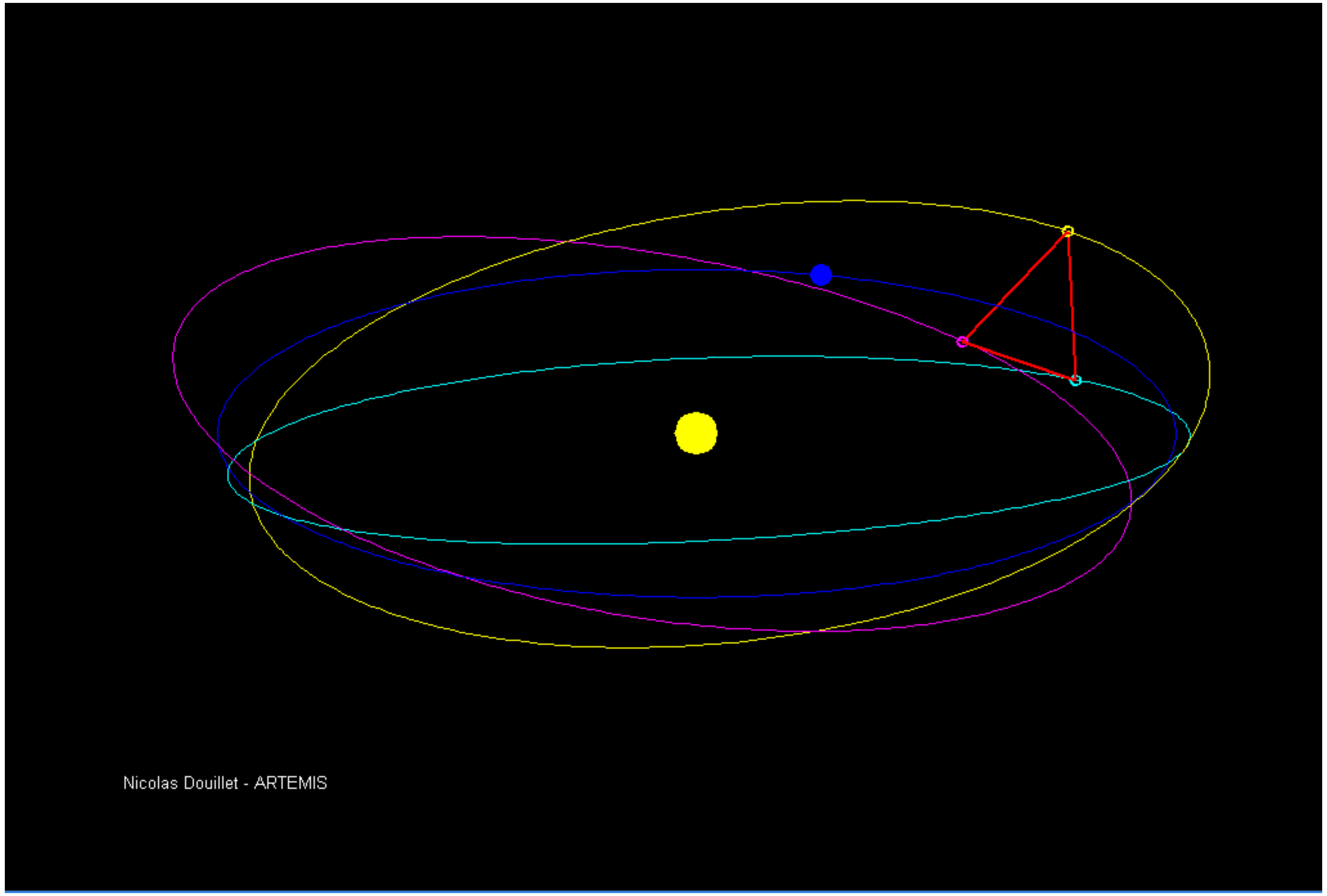
Ferguson, et. al, 2021





N. Cornish, M. Hewitson

LASER INTERFEROMETER SPACE ANTENNA (LISA)

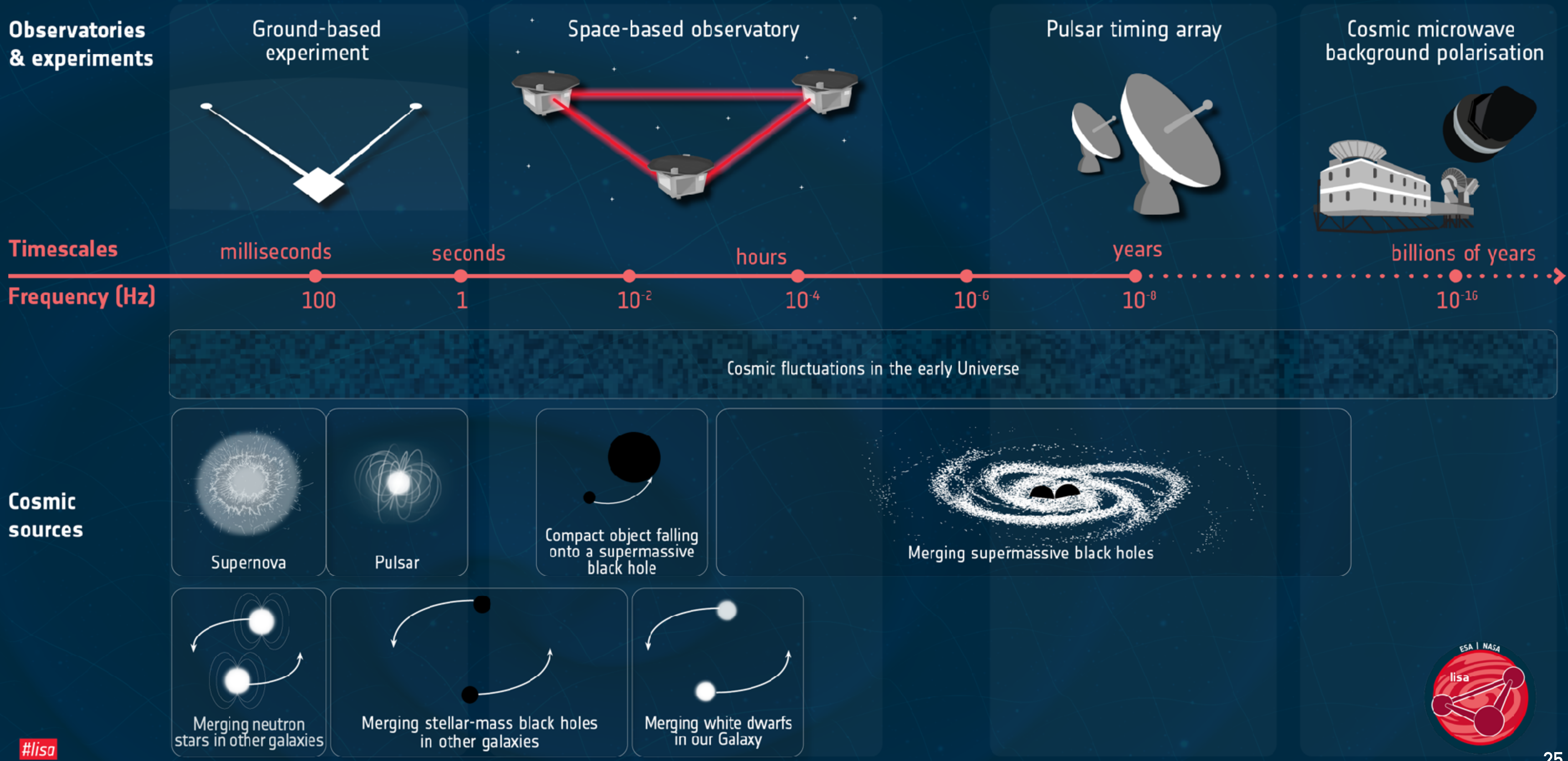


Nicolas Douillet - ARTEMIS

- Now officially adopted!
- Will fly in ~2034
- Chair of the LISA Early Career Scientists
- Co-coordinator for the LISA Waveform Working Group Whitepaper (arXiv:2311.01300)
- Unprecedented sensitivity for supermassive black holes
- Localization on order of arc minutes

THE SPECTRUM OF GRAVITATIONAL WAVES

esa



#lisa

SUMMARY

- Gravitational-wave detectors have observed ~90 compact binary mergers including BBH, NSBH, and BNS
- Searching for and characterizing these signals as well as using them to test general relativity relies upon template waveforms
- Several techniques exist to create such templates
  - For comparable-mass systems near merger, we need numerical relativity
- As we prepare for future detectors, there are still many challenges facing numerical relativity