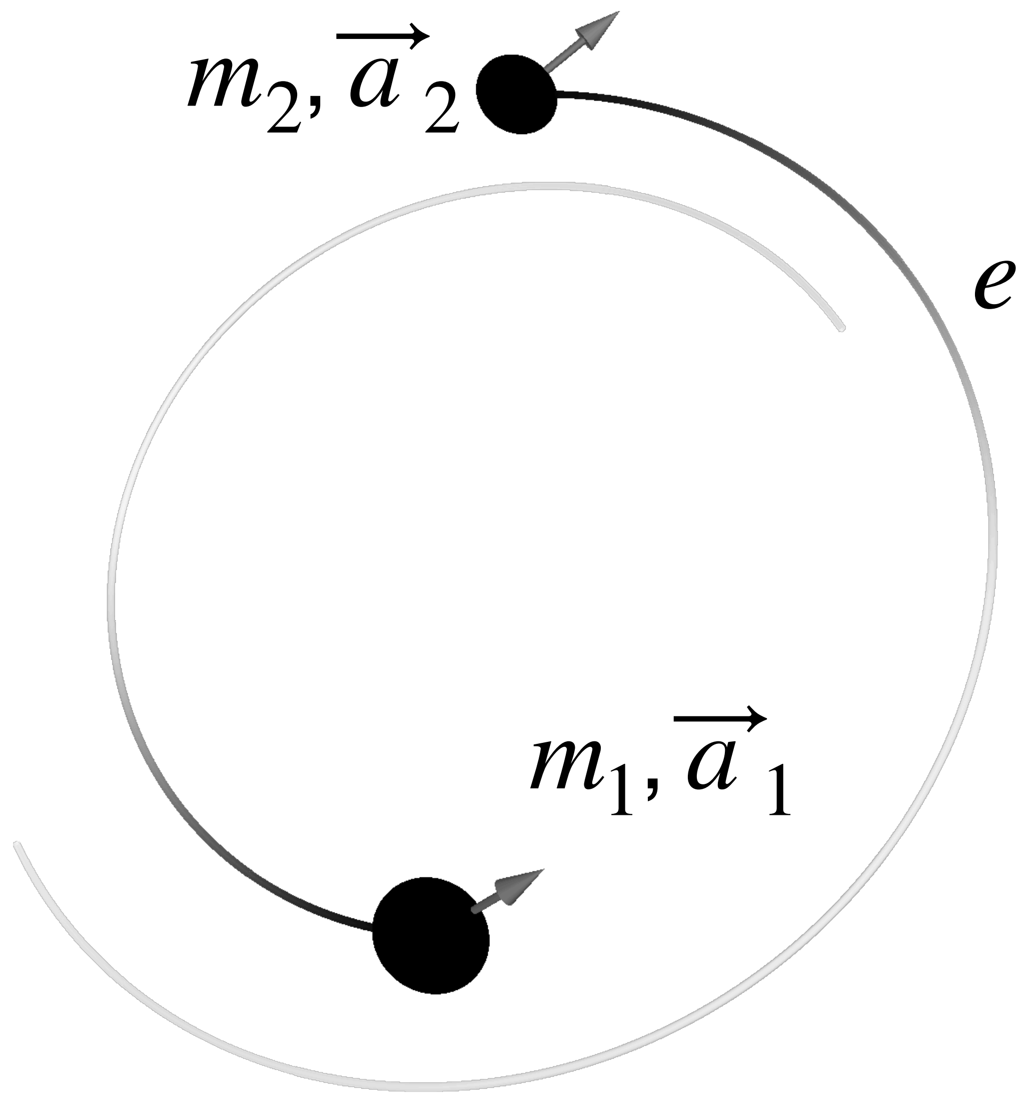
WAVEFORMS FOR GRAVITATIONAL WAVE ASTRONOMY

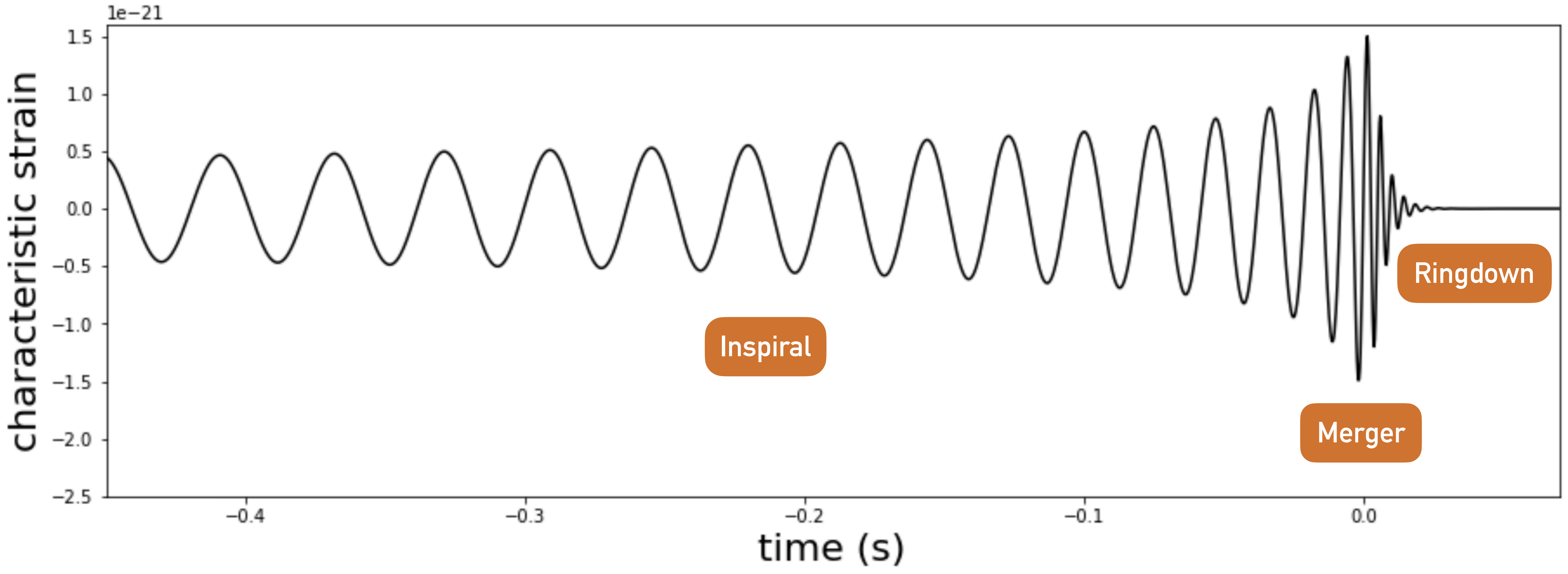
Deborah Ferguson

Petnica Summer Institute | August 2022

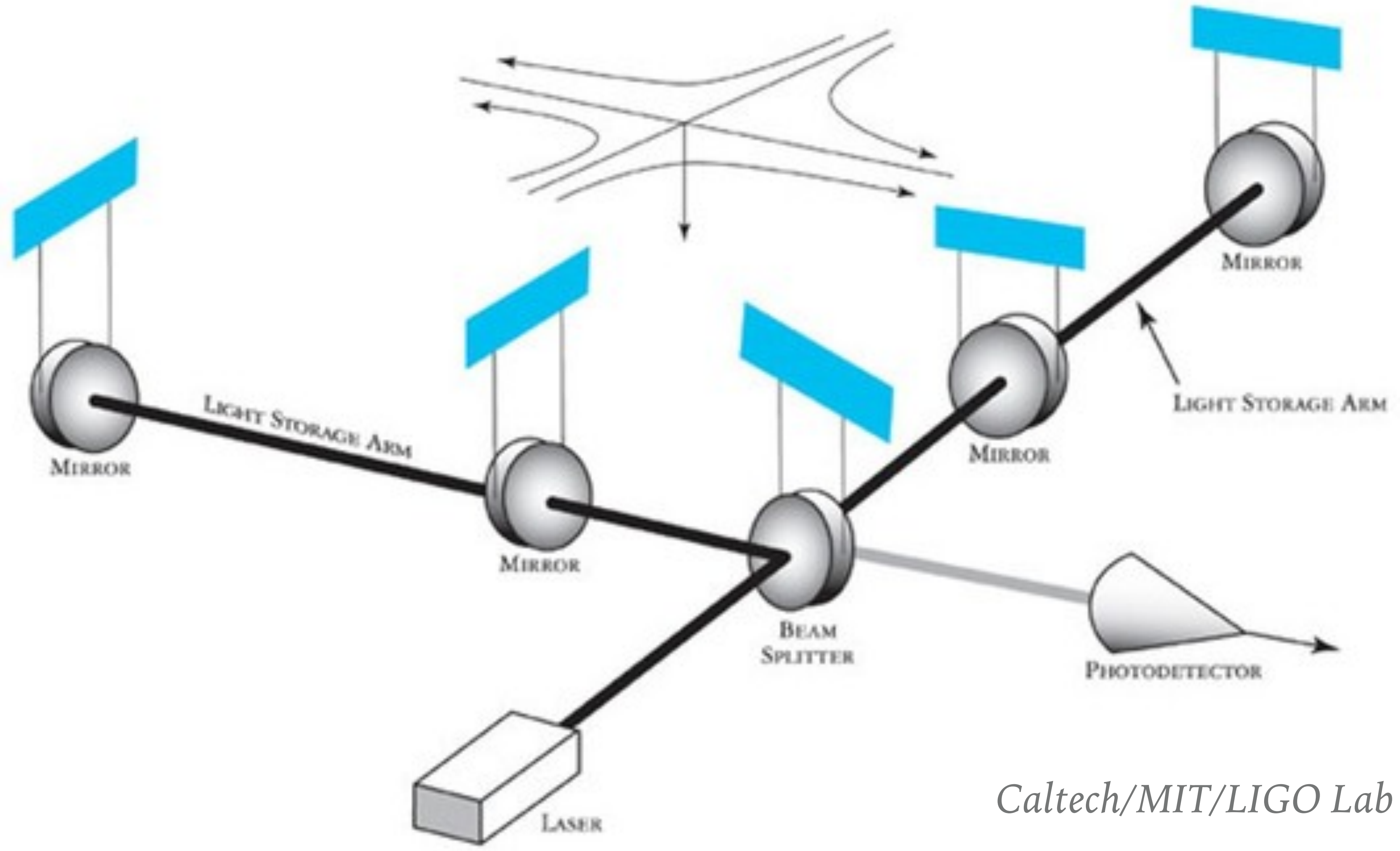
MERGING BINARY BLACK HOLES PRODUCE GRAVITATIONAL WAVES



9 dimensional parameter space



➤ These waves can be observed by interferometer gravitational wave detectors

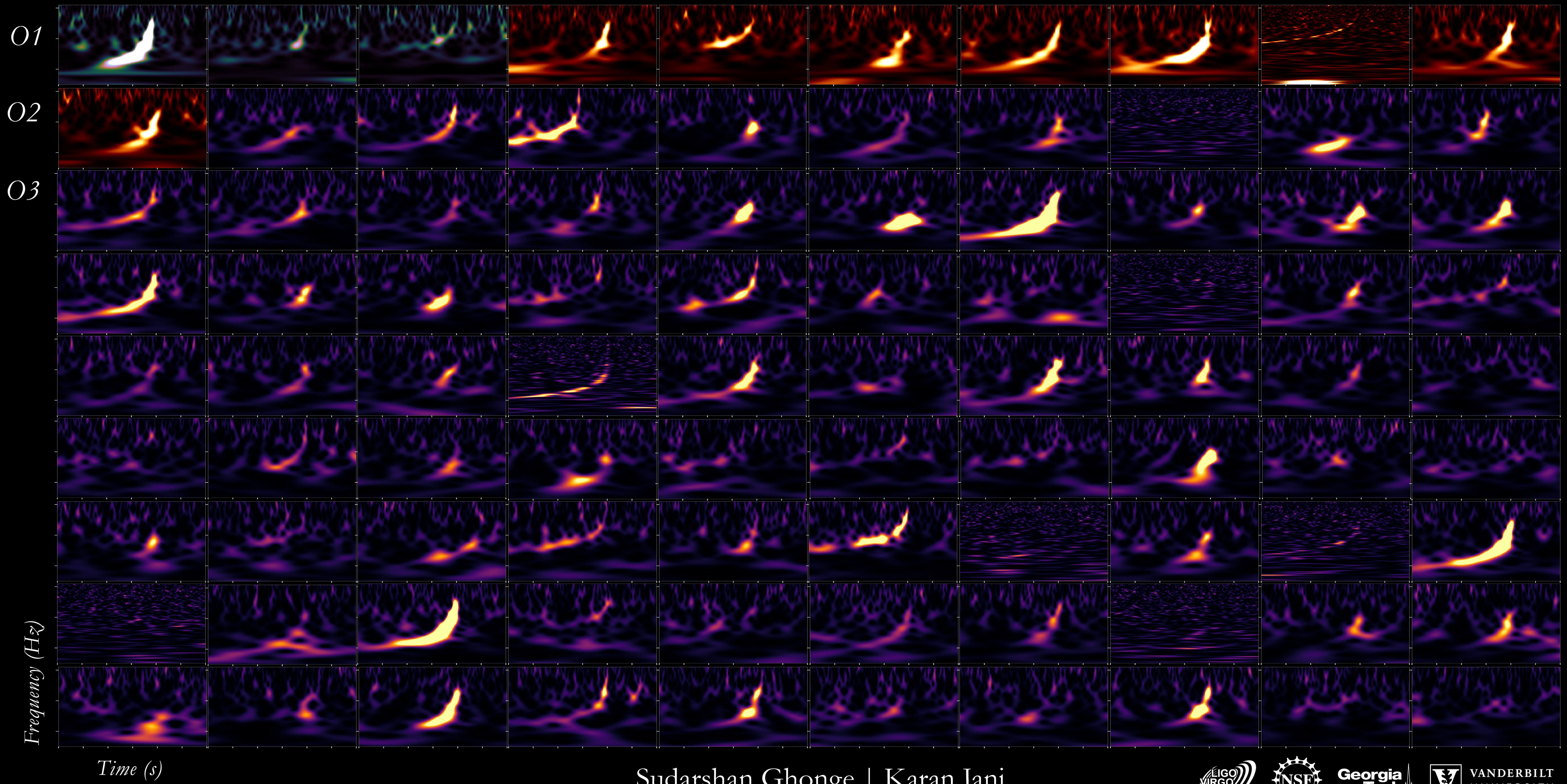


Caltech/MIT/LIGO Lab

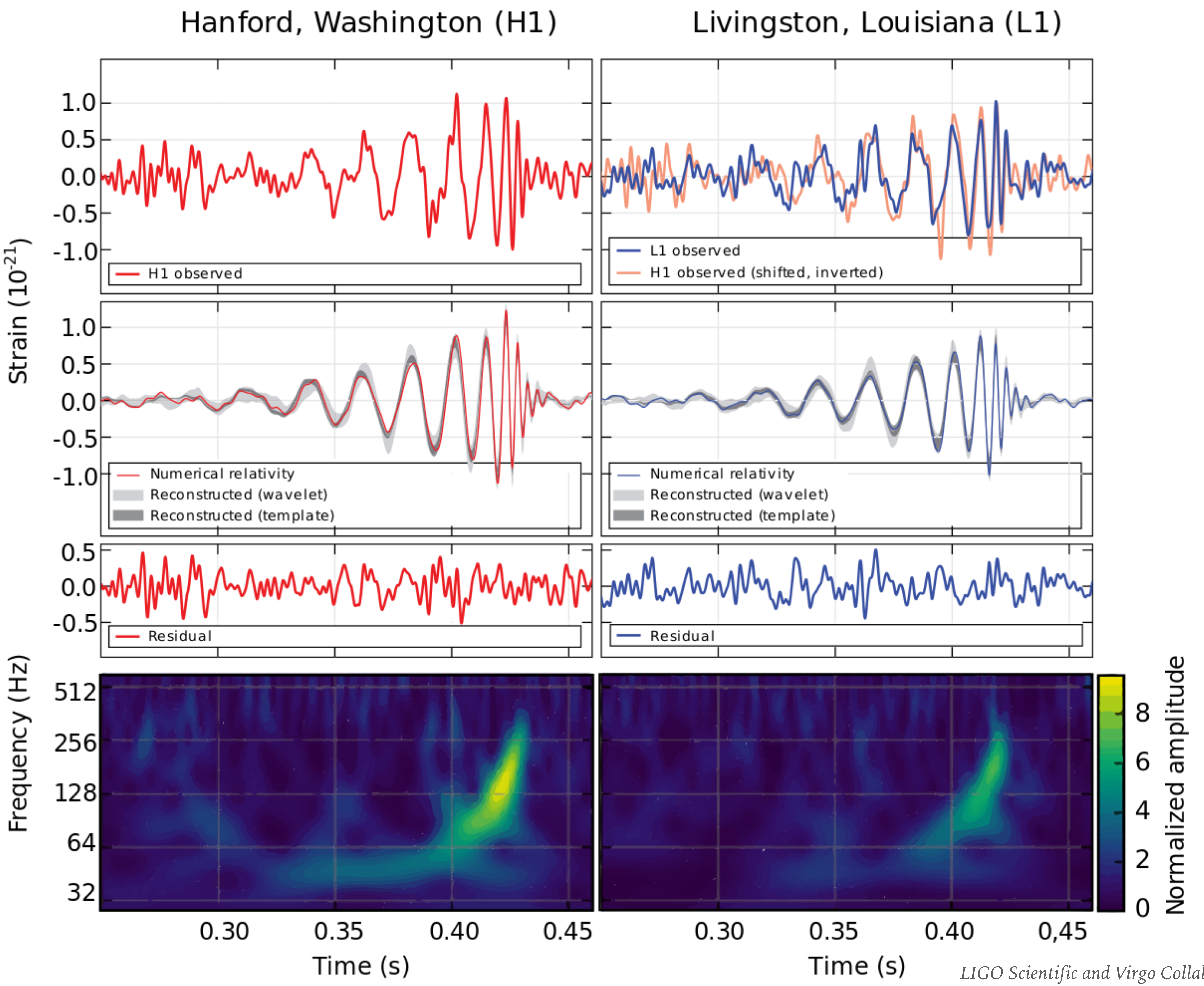

3 km
3 km
© ICRR 東京大学宇宙線研究所附属重力波観測研究施設
GEO600
LIGO Hanford
LIGO Livingston
Virgo
KAGRA
LIGO India
Operational
Planned
Gravitational Wave Observatories

Gravitational-Wave Transient Catalog

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



Sudarshan Ghonge | Karan Jani



LIGO Scientific and Virgo Collaborations (2016)

GRAVITATIONAL WAVE SEARCHES

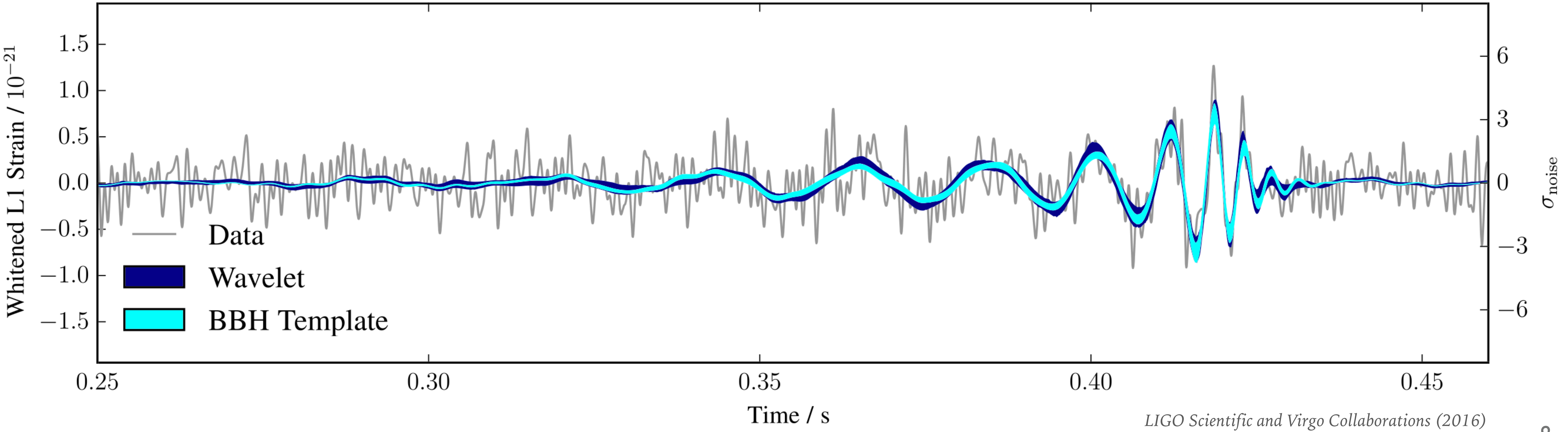
DATA ANALYSIS

Modeled Searches (Light Blue)

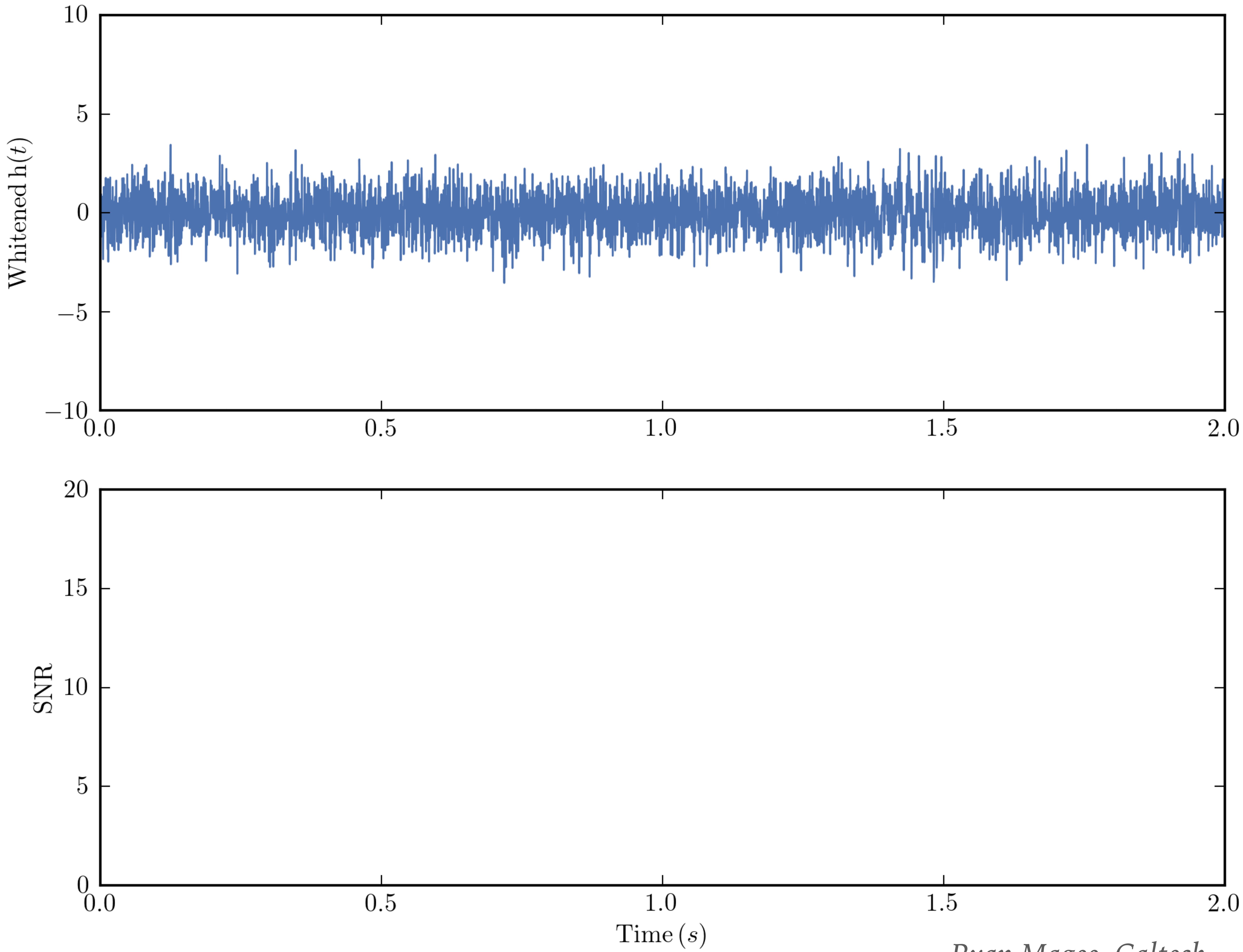
- Use waveform template banks to detect and characterize GW signals

Unmodeled Searches (Dark Blue)

- Identify excess power and reconstruct the signal without models, e.g. using sine-Gaussians



LIGO Scientific and Virgo Collaborations (2016)



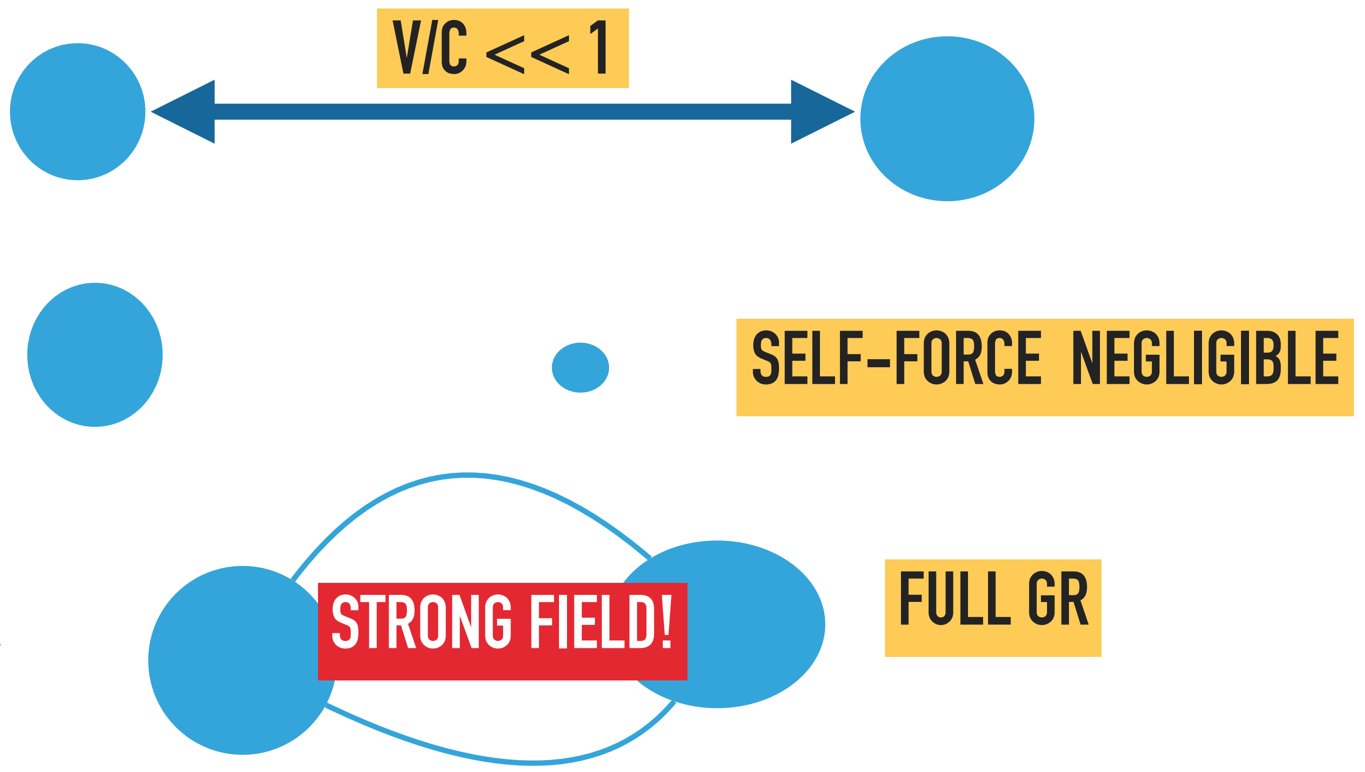
Ryan Magee, Caltech

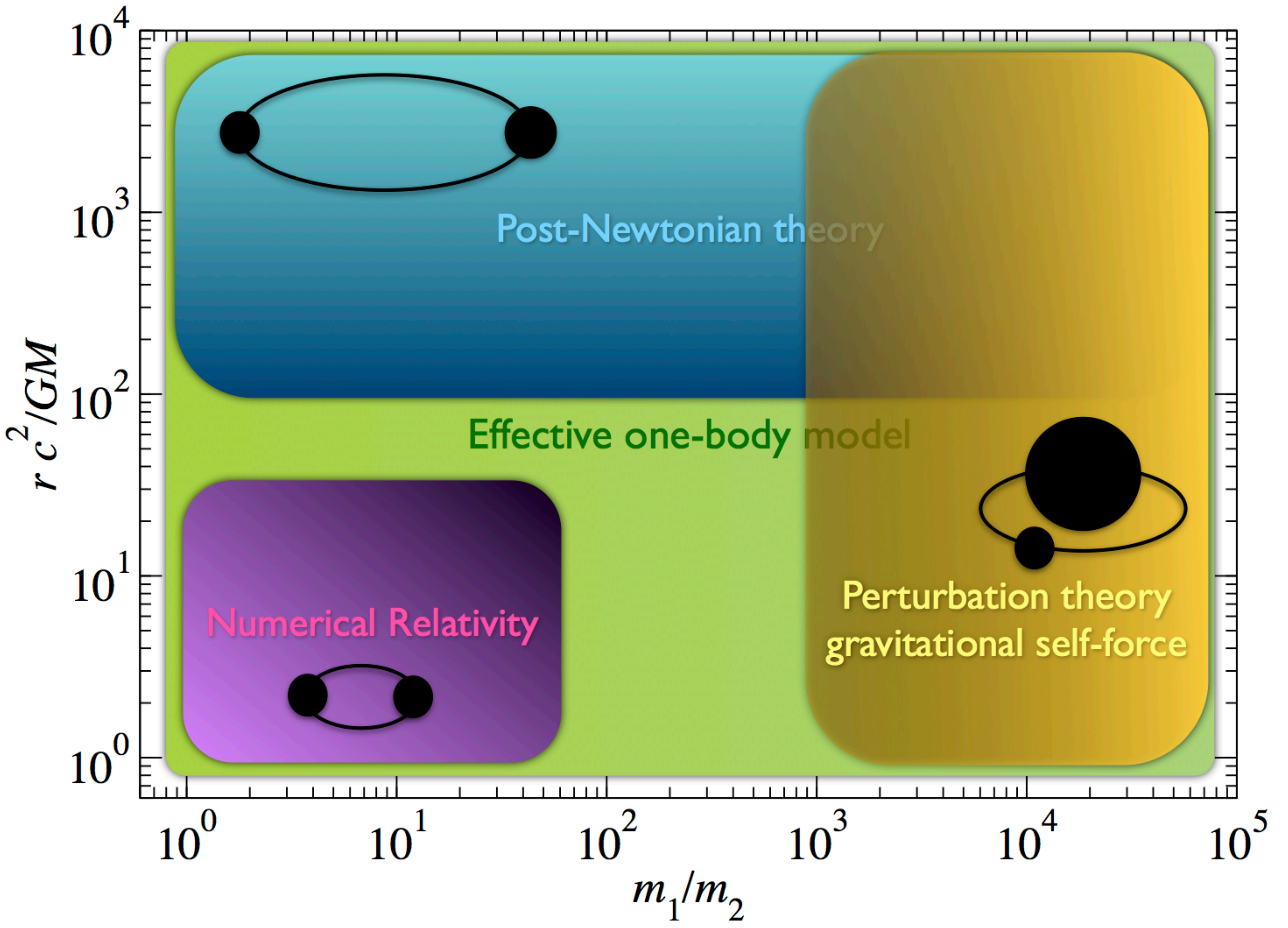
WAVEFORM GENERATION

Post-Newtonian

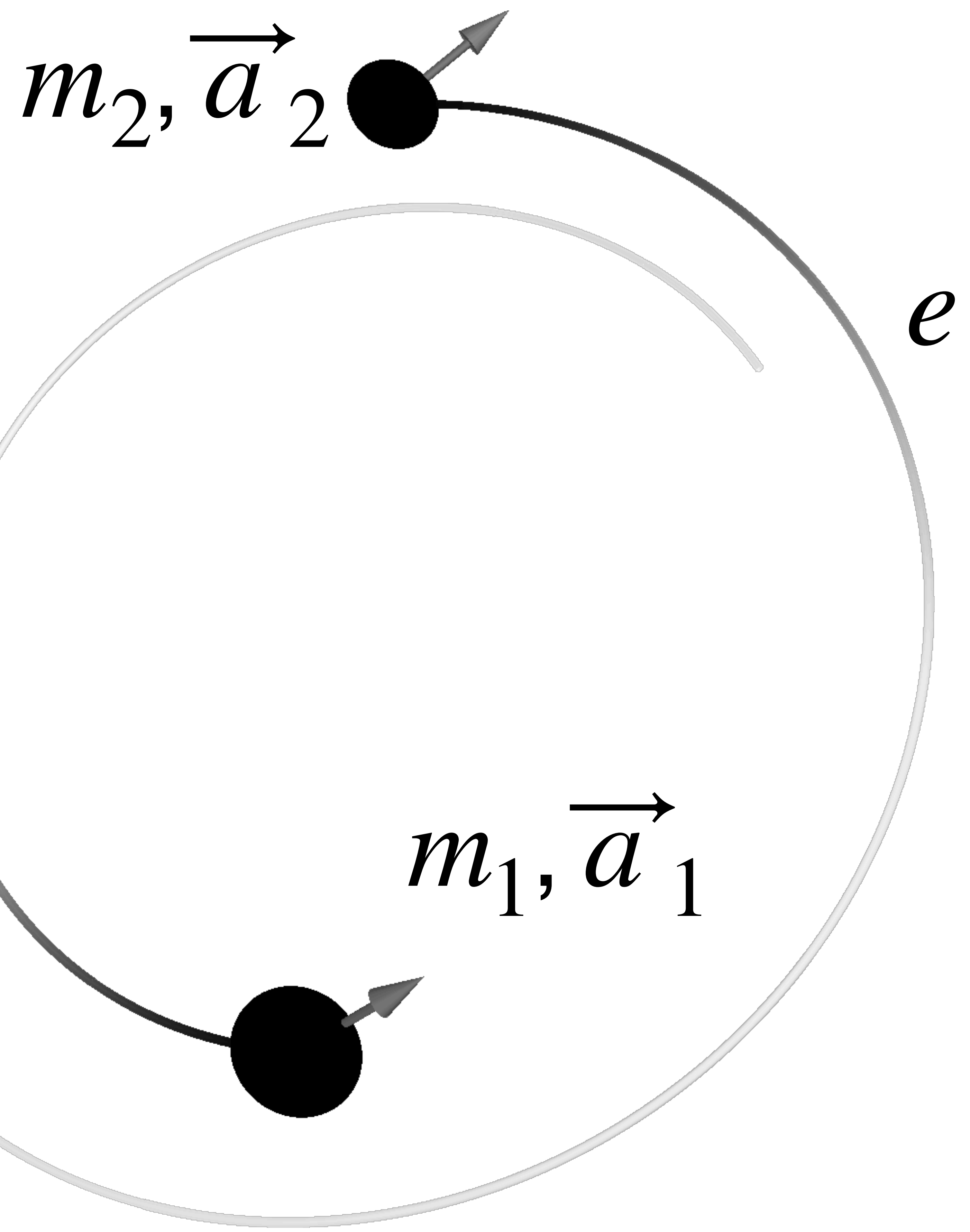
Perturbation

Numerical relativity





Buonanno and Sathyaprakash 2014



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

NUMERICAL RELATIVITY WAVEFORMS

- Numerically solve Einstein's Equations
- Decompose into 3+1 to create an initial value / boundary problem
  - Solve constraint equations
  - Solve evolution equations
- Most accurate method of studying merger of comparable mass compact objects
- Limitations
  - Computationally expensive
  - Discrete parameter space coverage
  - Challenging at near maximal spins and high mass ratio

ANALYTIC MODELS

- Quicker to compute
- Continuous coverage within valid parameter space
- Limitations
  - Additional sources of error due to fitting
  - Still limited by parameter space

SOME TYPES OF MODELS

Phenomenological Models

- e.g. IMRPhenomXHM
- Use an analytical ansatz
- Fit to NR, PE, EOB waveforms

NR Surrogate Models

- e.g. NRSur7dq4
- Create a basis to represent the NR training set
- Interpolate between NR waveforms

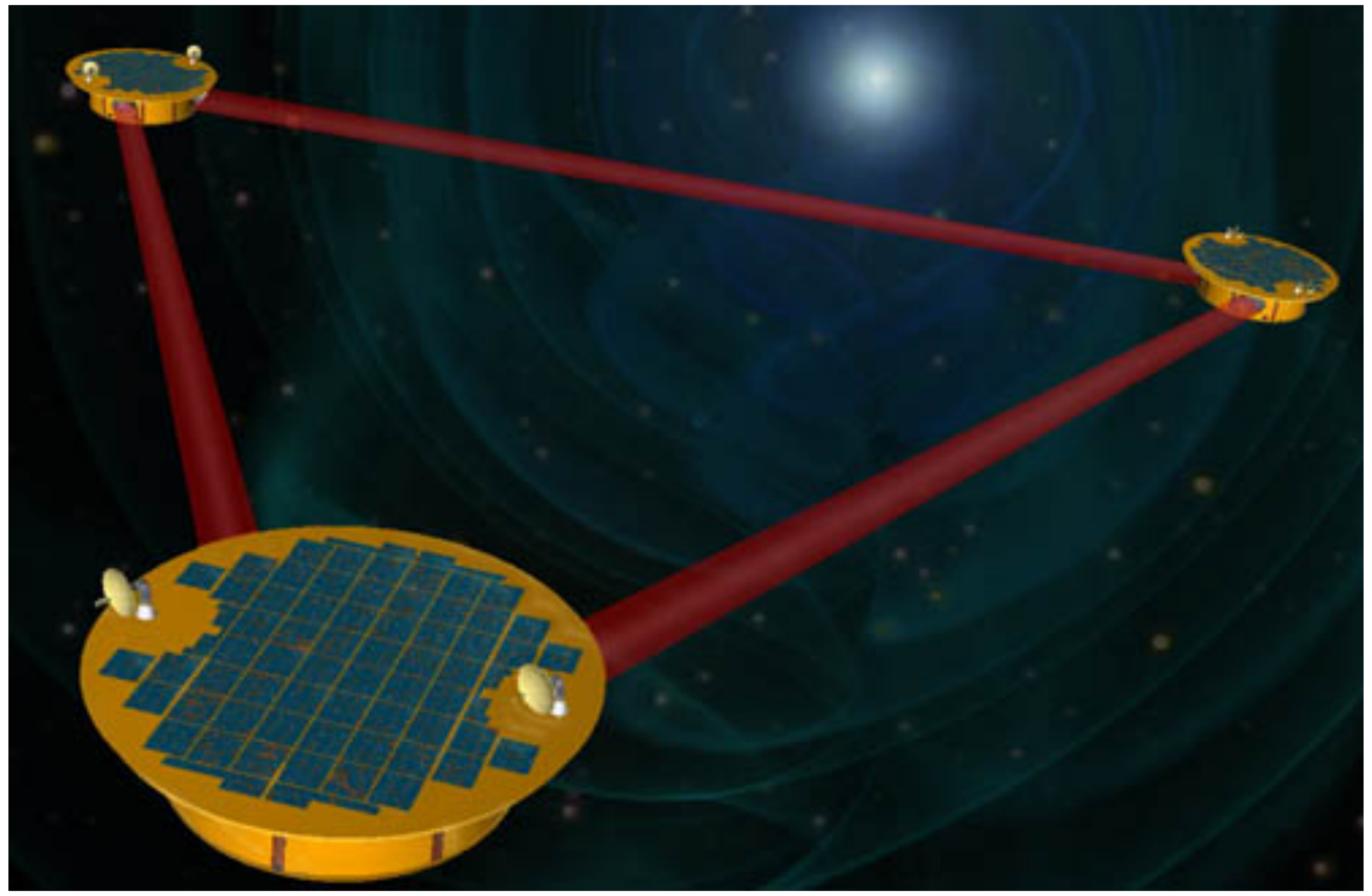
Effective-One-Body Models

- e.g. SEOBNRv4PHM
- Maps the two body problem to that of a test mass orbiting around a single BH in a deformed Kerr metric
- Aligned spin version calibrated to NR
- Precessing version tested on, but not calibrated to NR waveforms

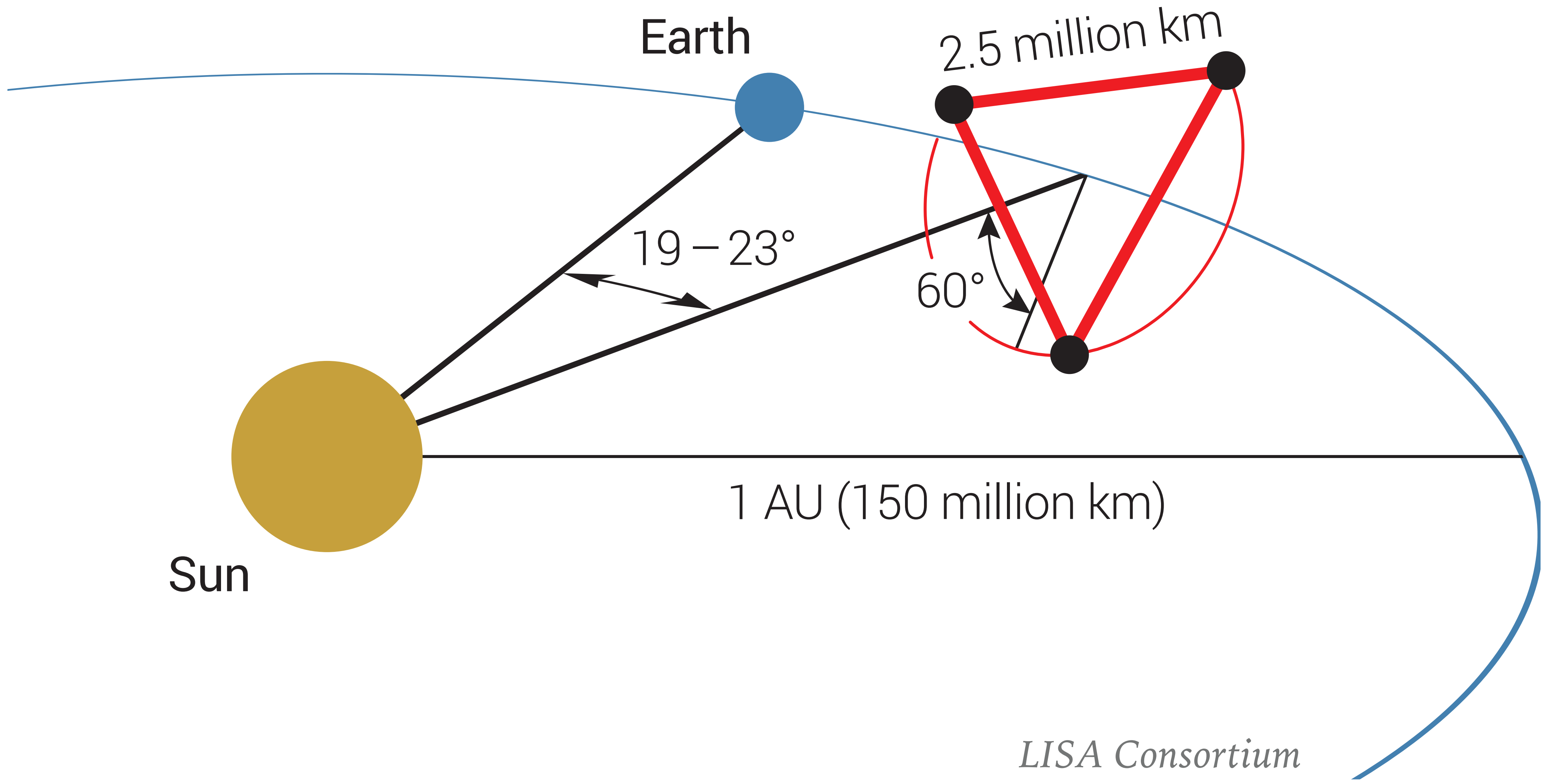
NEXT GENERATION GRAVITATIONAL WAVE DETECTORS

SPACE BASED - LASER INTERFEROMETER SPACE ANTENNA (LISA)

- Millihertz band
- ESA mission with NASA as a junior partner
- 4 year mission with possible 6 year extension
- 3 arm structure
- 2.5 Mkm arm length



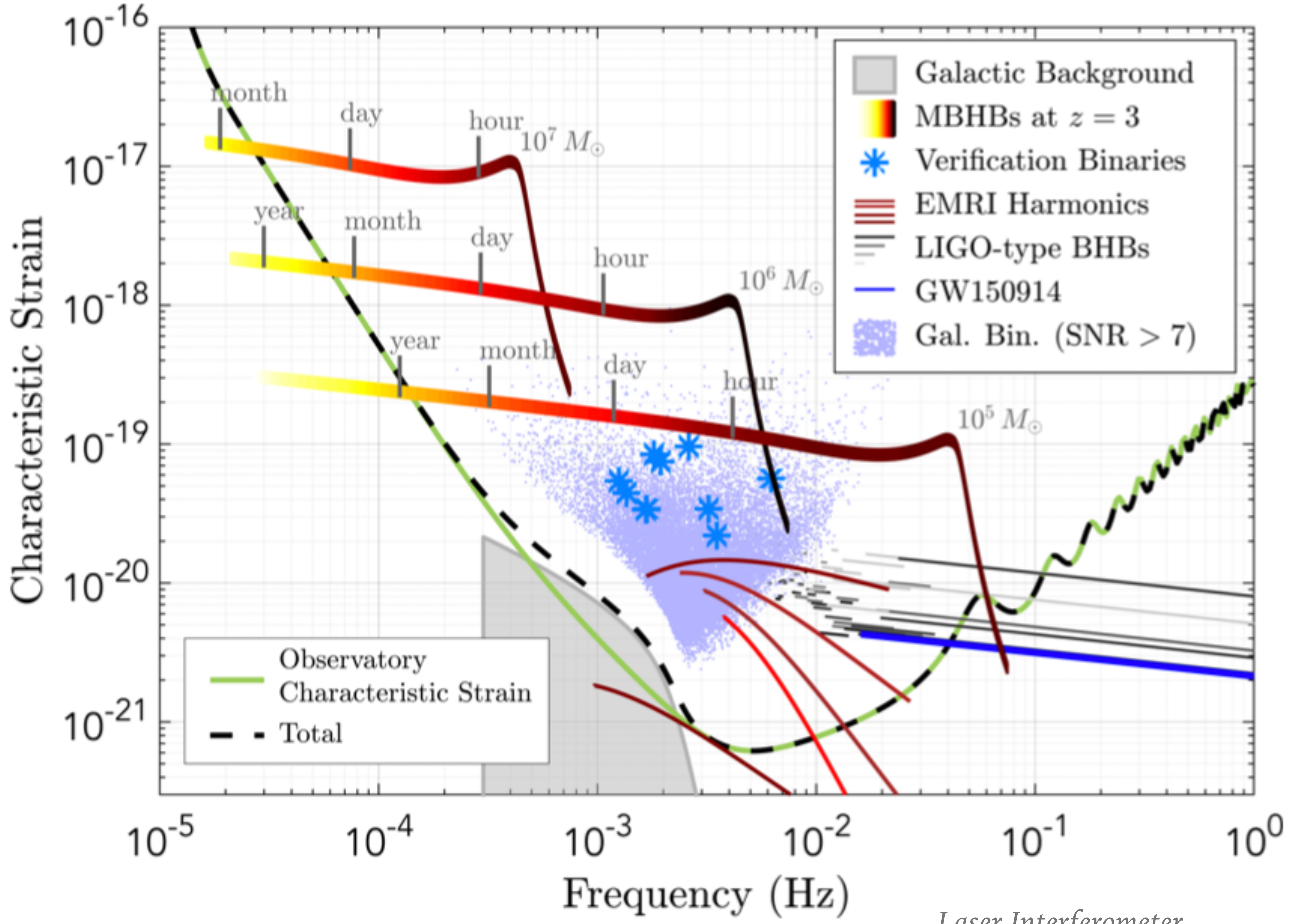
NASA



LISA Consortium

LISA SOURCES

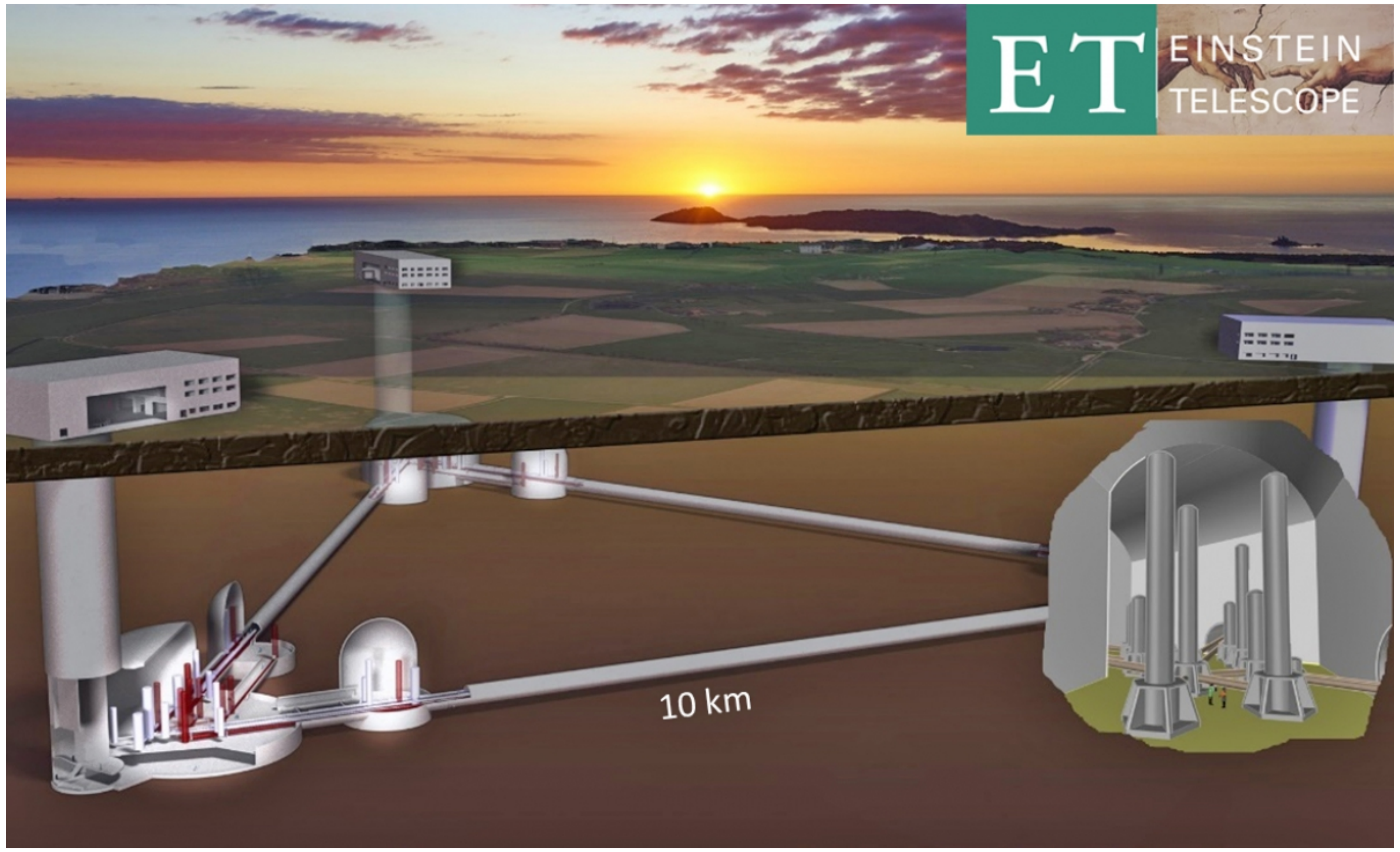
- Massive black hole binaries (MBHBs)
- Extreme mass-ratio inspirals (EMRIs)
- Intermediate mass-ratio inspirals (IMRIs)
- Galactic binaries (GBs)
- Stellar-origin black hole binaries (SOBHBs)
- Transients
- Beyond GR



Laser Interferometer Space Antenna Proposal, lead proposer Danzmann, 2017

GROUND BASED - EINSTEIN TELESCOPE (ET)

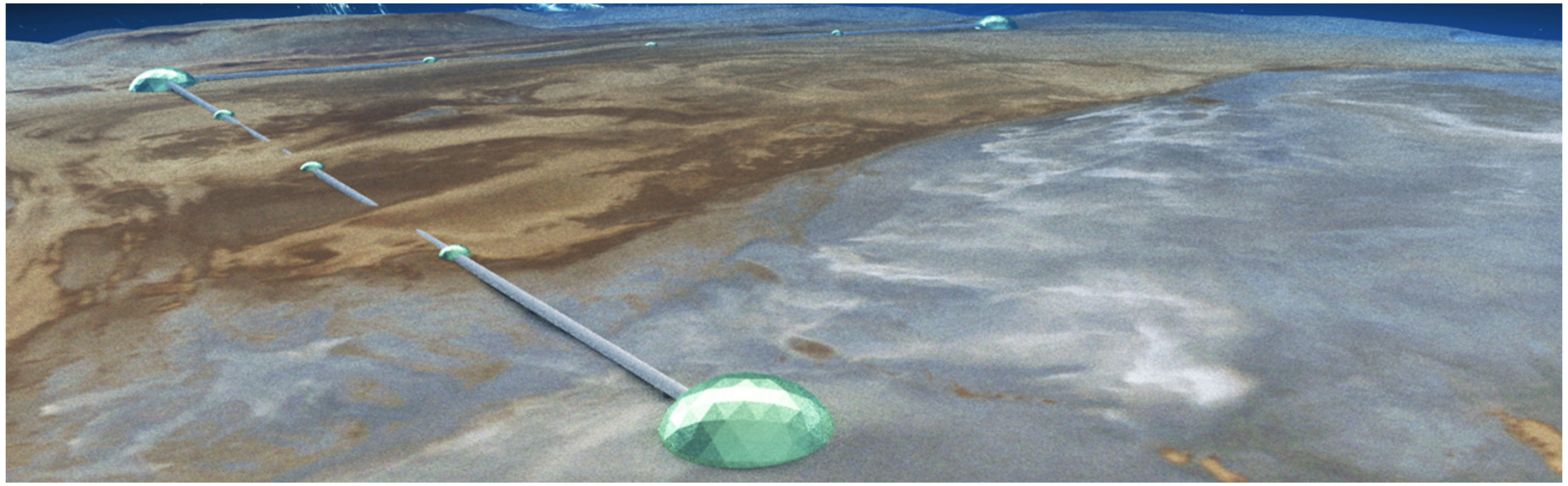
- Similar frequency band to LIGO, but with reach to lower frequencies
- Much more sensitive
- Triangular structure with three nested detectors
- Underground
- Two interferometers for each detector, one sensitive at lower frequencies, and one at higher



ET Design Study Team

GROUND BASED – COSMIC EXPLORER (CE)

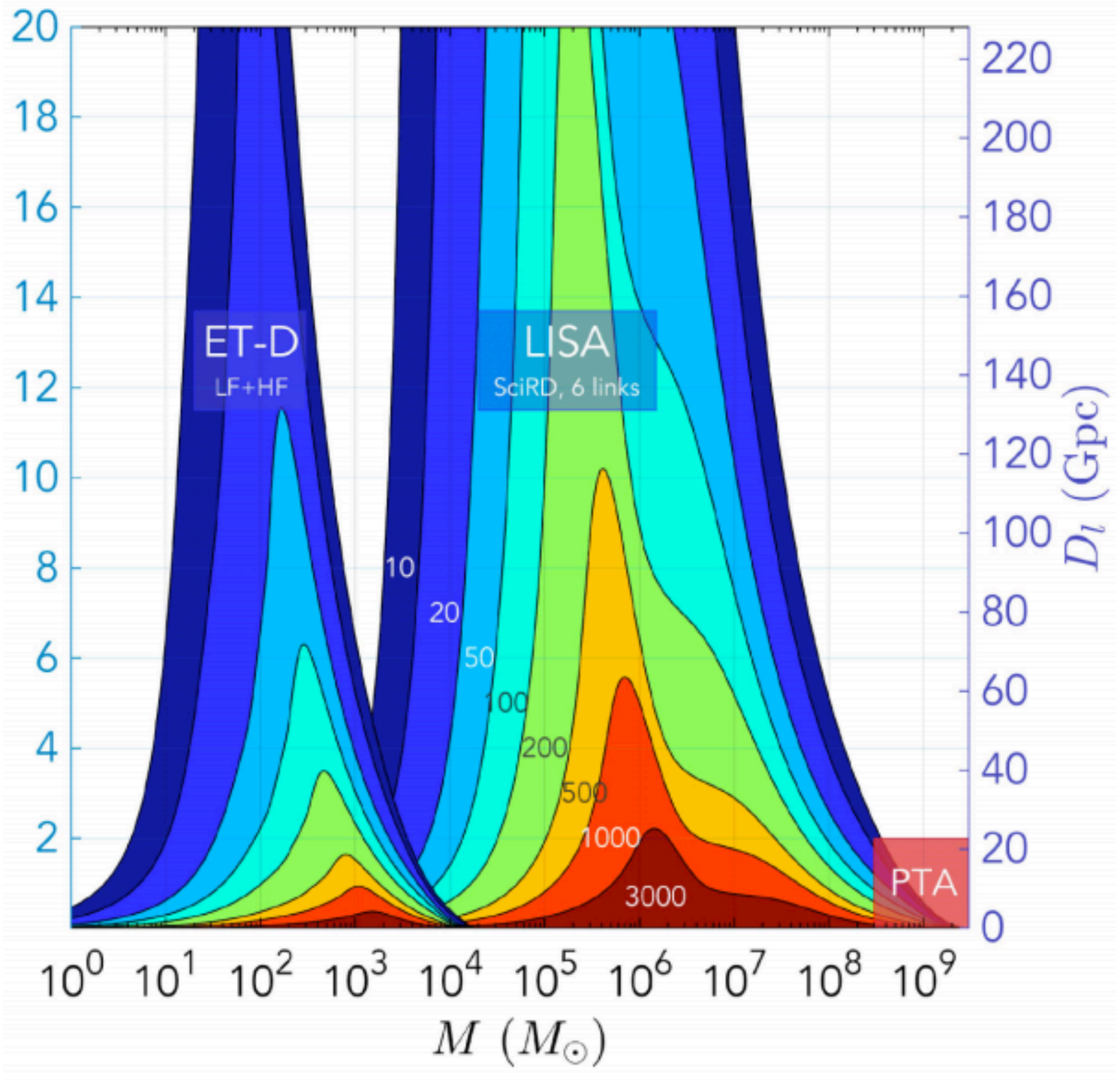
- Similar frequency band to LIGO, but with reach to lower frequencies
- Much more sensitive
- L shaped
- 40 km arms



Evan Hall/Massachusetts Institute of Technology; B. S. Sathyaprakash/Pennsylvania State University

CHALLENGES

- Loud signals
- Long signals
- Overlapping signals
- Anticipated significant eccentricity
- Anticipated high spins



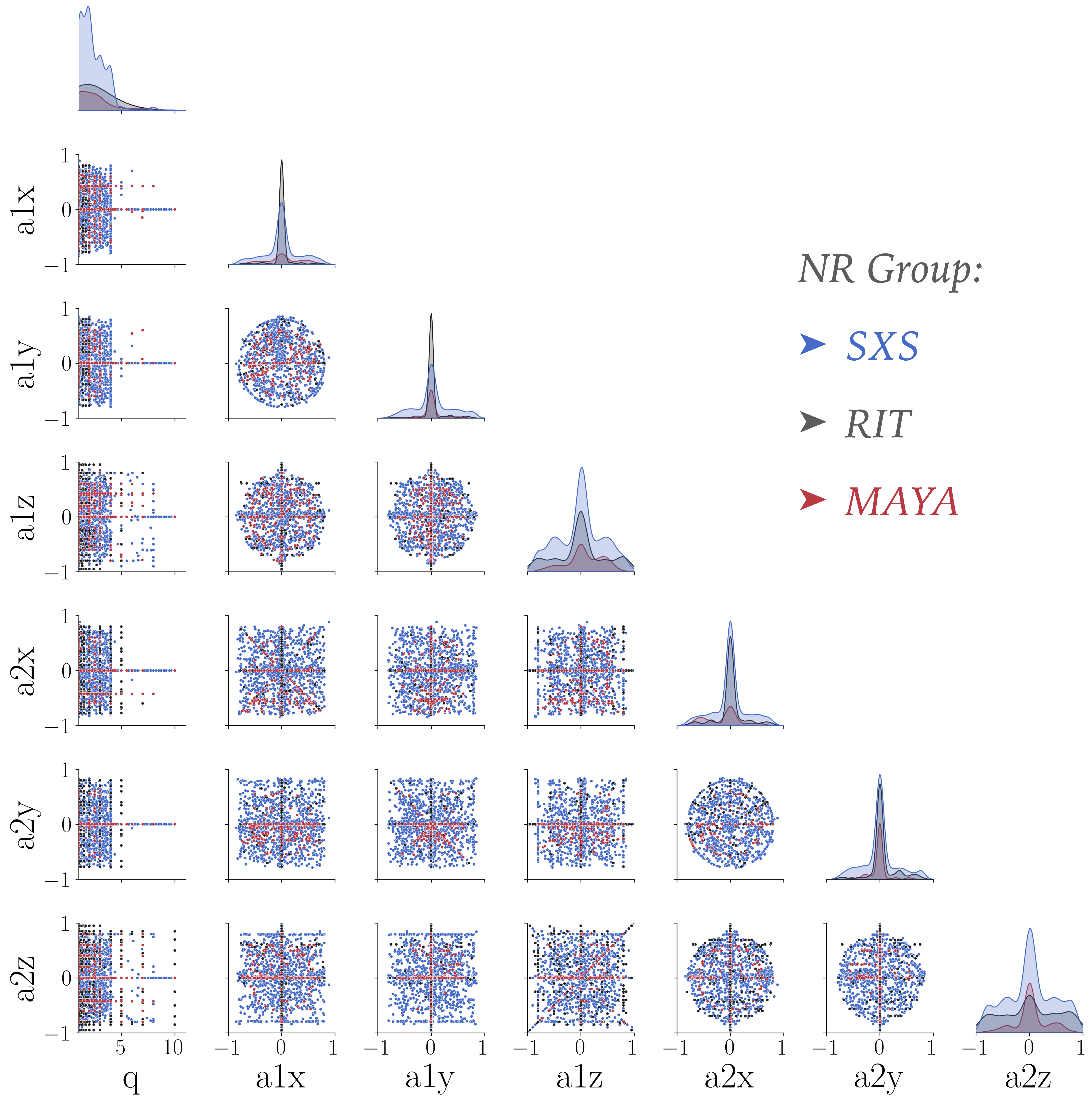
CHALLENGES

WAVEFORM CHALLENGES

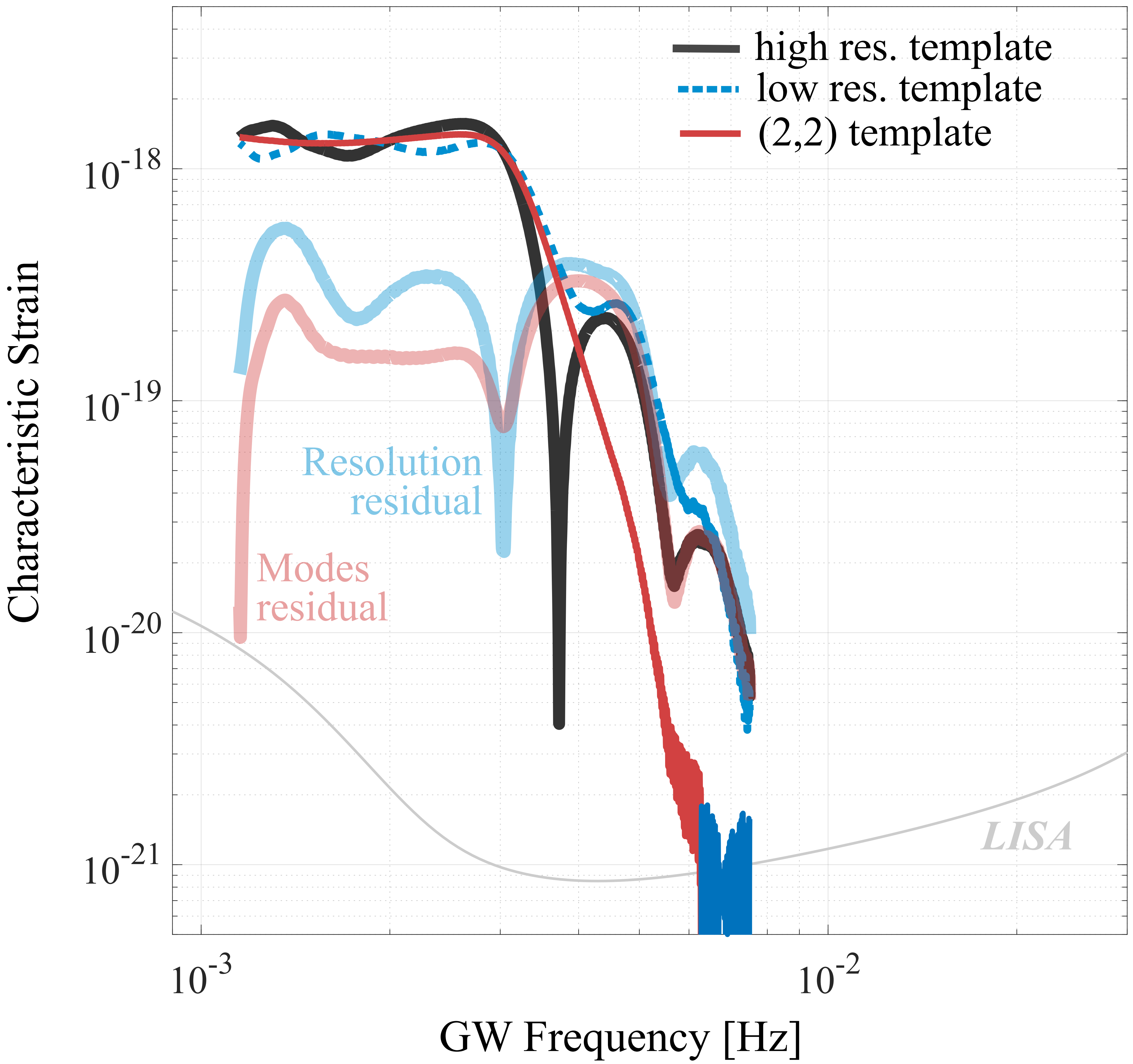
- Improved waveform accuracy
  - Detection
  - Parameter estimation
  - Contamination
- Longer waveforms (hybridized?)
- Expansion of parameter space and denser catalogs
  - Eccentricity
  - Intermediate mass ratio
  - Increased efficiency
- Beyond GR catalogs
- Matter effects

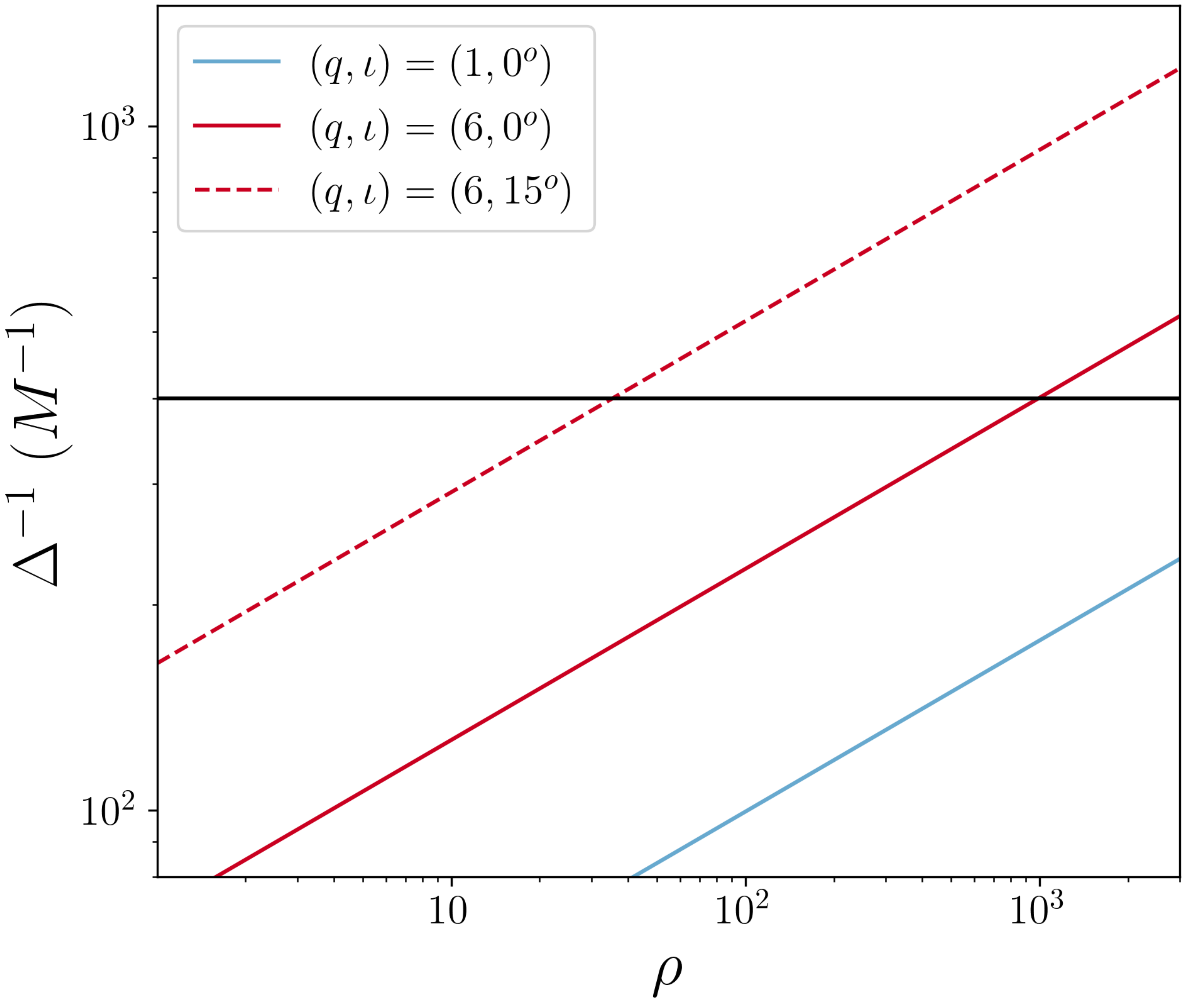
PARAMETER SPACE COVERAGE

- ➤ Needs
  - ➤ High mass ratio
  - ➤ Eccentricity
  - ➤ Precession



NUMERICAL RELATIVITY RESOLUTION REQUIREMENTS

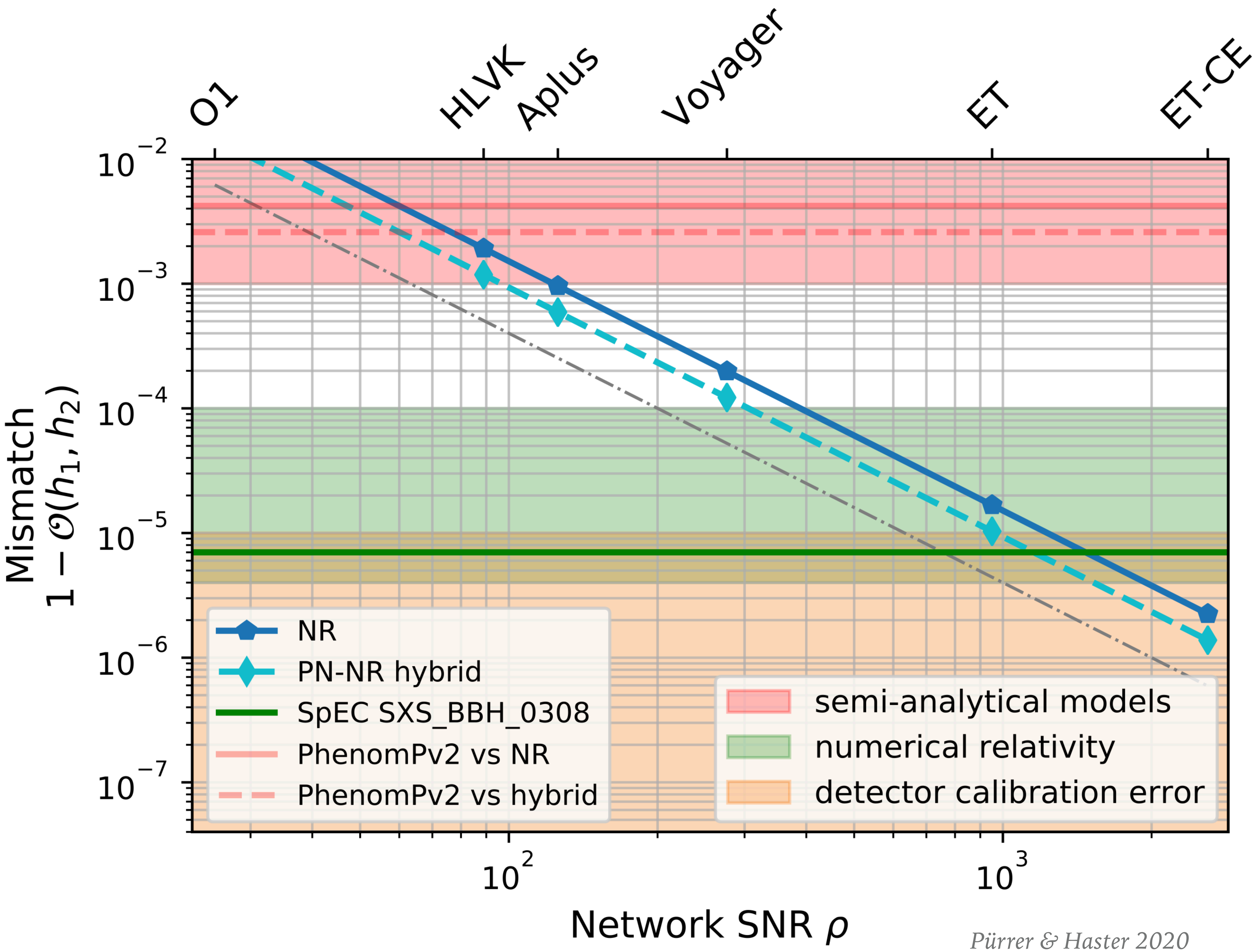




Ferguson, et al. 2021

CHALLENGES FACING MODELS

- Shaded regions show the mismatches for models and numerical relativity
- Diagonal lines show the required mismatches for a given SNR depending
- High SNRs of future detectors will require significant improvement



Pürrer & Haster 2020

SUMMARY

- Gravitational-wave detectors have observed 90 compact binary mergers including BBH, NSBH, and BNS
- Searching for and characterizing these signals relies upon template waveforms
- These waveform templates can come from:
  - Self-force
  - Post-newtonian
  - Numerical relativity
  - Analytic models
- As we prepare for future detectors, there are still many challenges facing the waveform community

SUPPLEMENTAL

BURST SEARCHES

- Searches for excess power
- Coherent Wave-Burst (cWB)
- omicron-LIB (oLIB)
- BayesWave (BW)

CBC SEARCHES

- Search for signals based on templates
- Matched filtering
- PyCBC
- GstLAL
- RIFT