UNDERSTANDING NEUTRON STARS THROUGH GRAVITATIONAL-WAVE OBSERVATIONS

Team

VIRGO

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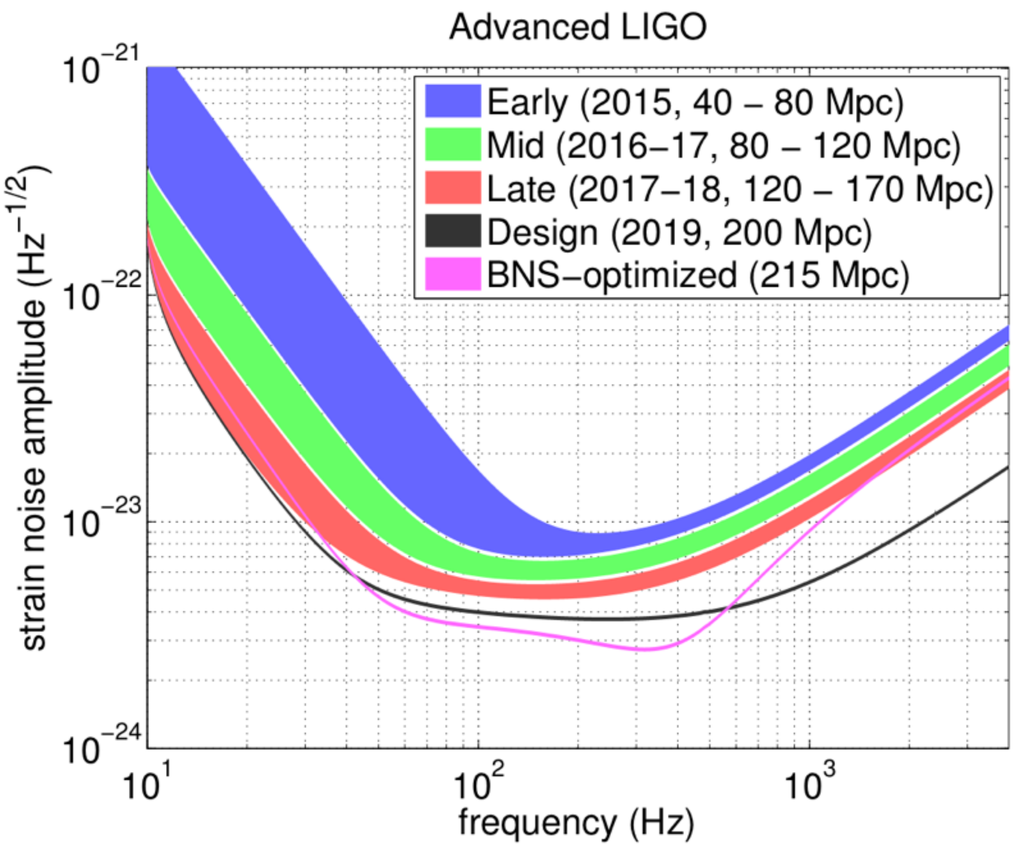
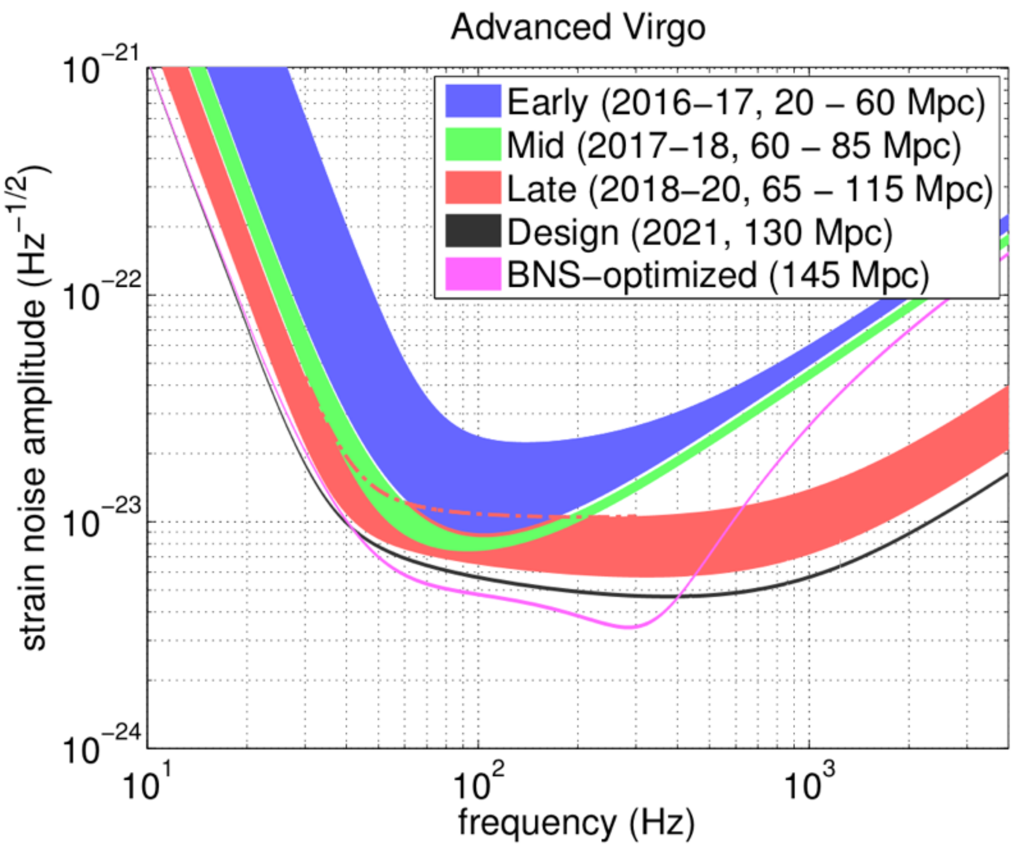
Gravitational Wave Detectors

Advanced LIGO & Advanced VIRGO





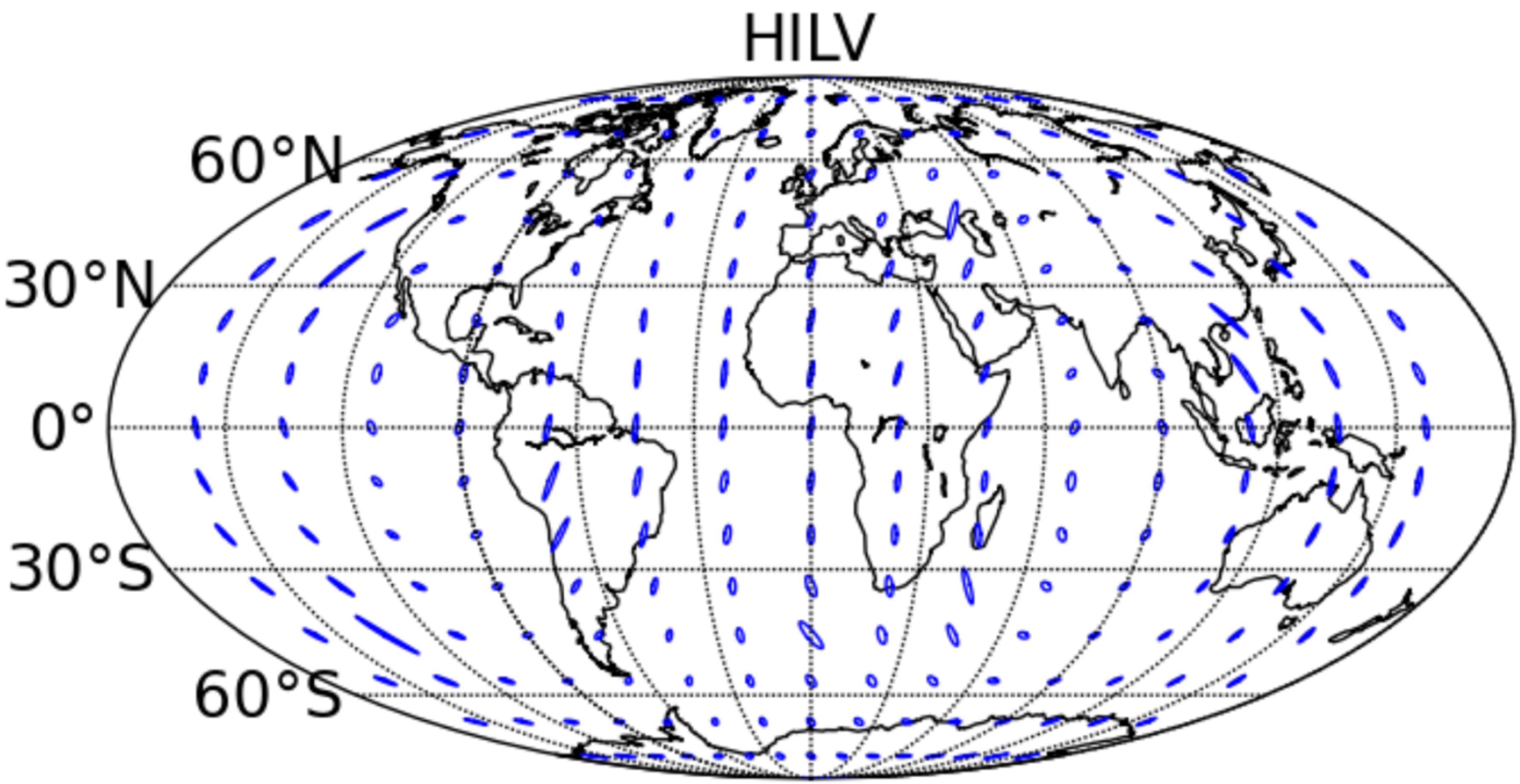
A Network of detectors

2.2 Estimated observing schedule

Keeping in mind the mentioned important caveats about commissioning affecting the scheduling and length of science runs, the following is a plausible scenario for the operation of the LIGO-Virgo network over the next decade:

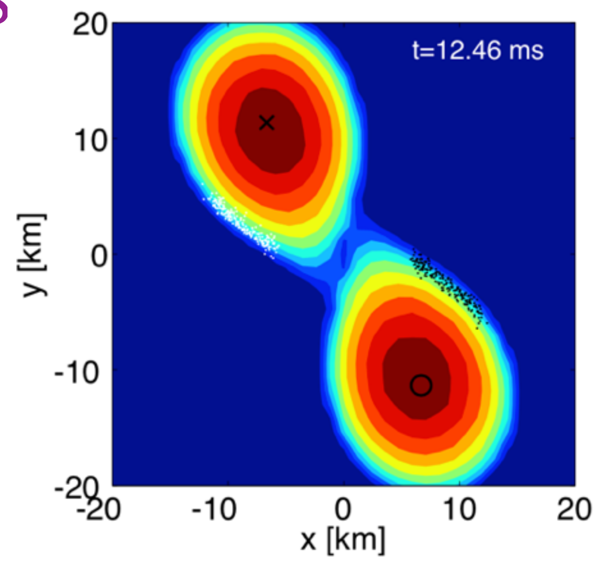
- 2015: A 3 month run with the two-detector H1L1 network at early aLIGO sensitivity (40 – 80 Mpc BNS range). Virgo in commissioning at $\sim$20 Mpc with a chance to join the run.
- 2016–17: A 6 month run with H1L1 at 80 – 120 Mpc and Virgo at 20 – 60 Mpc.
- 2017–18: A 9 month run with H1L1 at 120 – 170 Mpc and Virgo at 60 – 85 Mpc.
- 2019+: Three-detector network with H1L1 at full sensitivity of 200 Mpc and V1 at 65 – 130 Mpc.
- 2022+: Four-detector H1L1V1+LIGO-India network at full sensitivity (aLIGO at 200 Mpc, AdV at 130 Mpc).

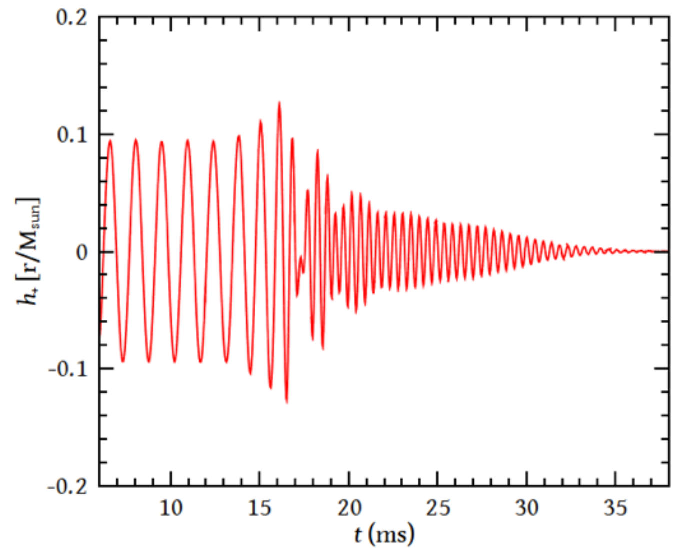
Sky localization of sources



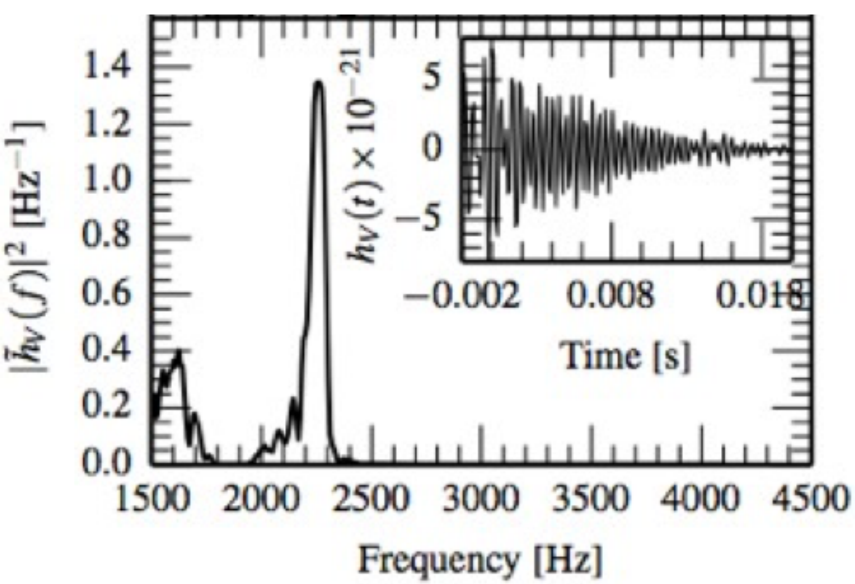
2 POSSIBLE PhD PROJECTS

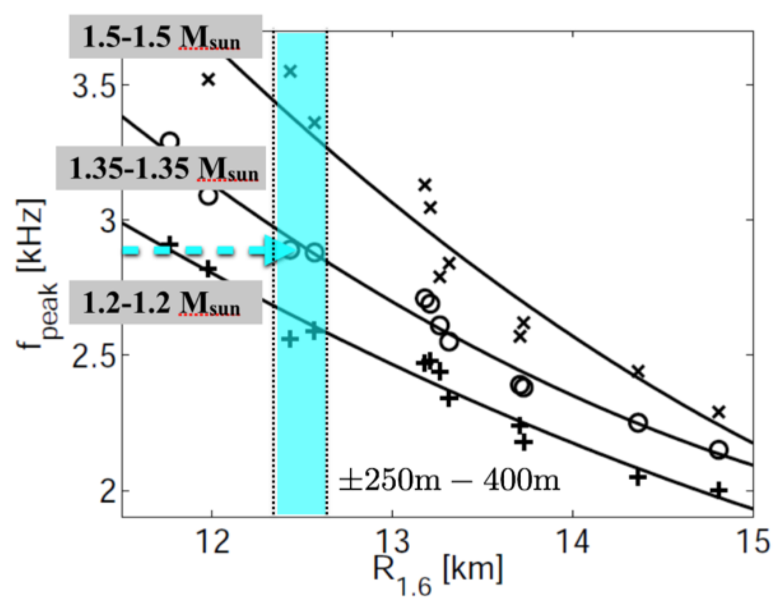
A. SUPERCOMPUTING SIMULATIONS OF BINARY NEUTRON STAR MERGERS





B. DATA ANALYSIS OF ADVANCED VIRGO/LIGO OBSERVATIONS





3D Simulation Code

einstein toolkit

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  - Citing
  - User's Guide
  - Thorn Guide
  - Reference Manual

Consortium Members

We are building a consortium of users and developers for the Einstein Toolkit. Users of the Einstein Toolkit are encouraged to register on this page.

Current users include:

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  - Ian Hinder
- **Aristotle University of Thessaloniki**
  - Nick Stergioulas
- **Aveiro University**
  - Juan Carlos Degollado
  - Carlos Herdeiro
- **Belmont University**
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- **Universität Bremen**
  - Oleg Korobkin
- **University of California**

3D Simulation Code current requirements

Current capacity:

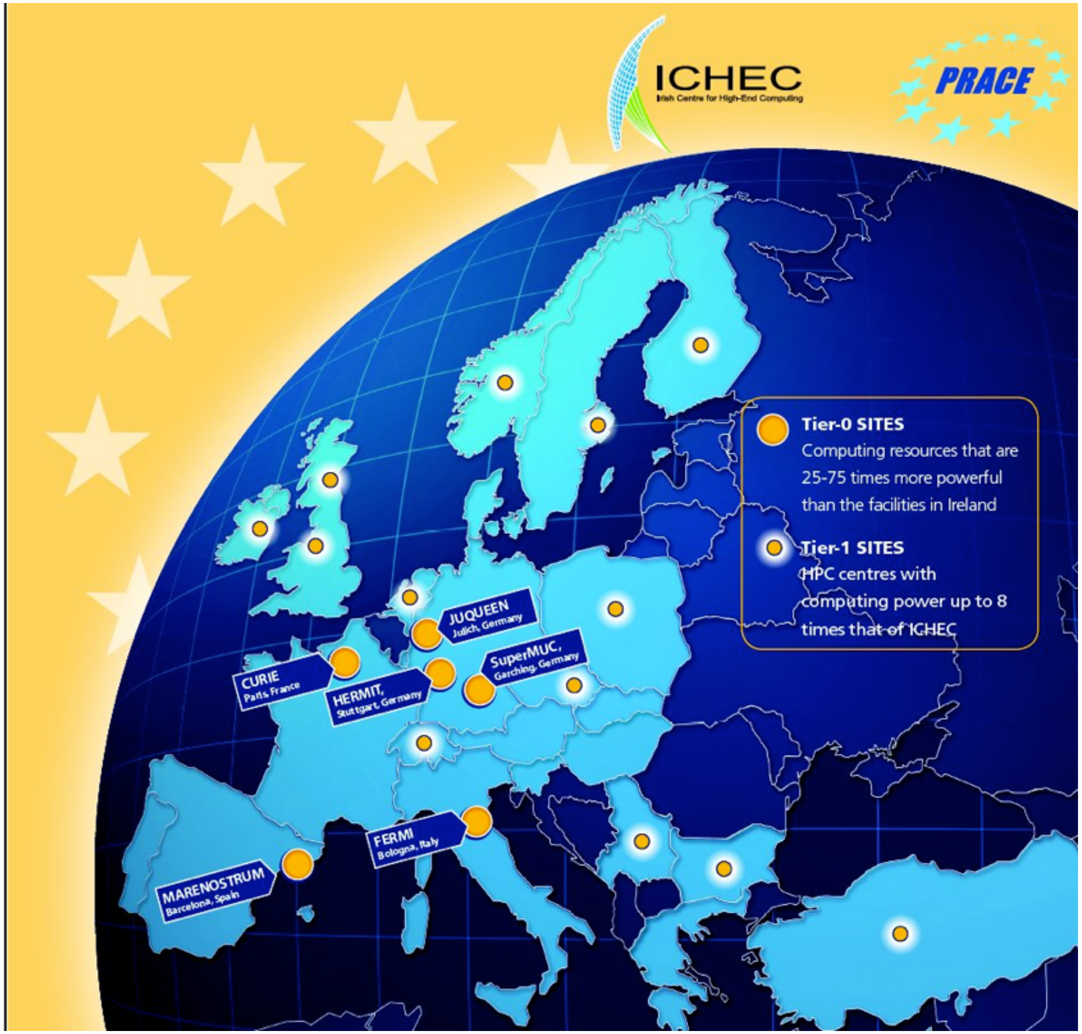
$\triangle x$ (CU)	0.75	0.50	0.375	0.25	0.185	0.125
# threads	16	64	128	256	512	2048
# MPI	2	8	16	32	64	256
Memory (GBytes)	3.8	19	40	108	237	768
speed (CU/h)	252	160	124	53	36	16
speed (ms/h)	1.24	0.78	0.61	0.26	0.18	0.08
cost (SU/ms)	13	81	209	974	2915	26053
total cost (kSU, 50 ms)	0.65	4	10.5	49	146	1300

TABLE VI. Computational cost of the simulations, for the example of using BSSN-NOK, with WENO reconstruction for the hydrodynamics. SU stands for service unit: one hour on one CPU core. The reported values refers to the "GALILEO" PRACE-Tier1 machine locate at CINECA (Bologna, Italy) equipped with 521 nodes, two-8 cores Haswell 2.40 GHz, with 128 GBytes/node memory and 4xQDR Infiniband interconnect. Also, these are only correct for evolutions that do not end with the formation of a BH, as an additional refinement level was used to resolve the BH surroundings, and more analysis quantities had to be computed (e.g., the apparent horizon had to be found). In addition, the simulations resulting in a BH were performed on facilities at Louisiana State University: SuperMike II (LSU HPC) and QB2 (Loni).

3D Simulation Code requirements

At current resolution: ~30M cu total for 20 runs

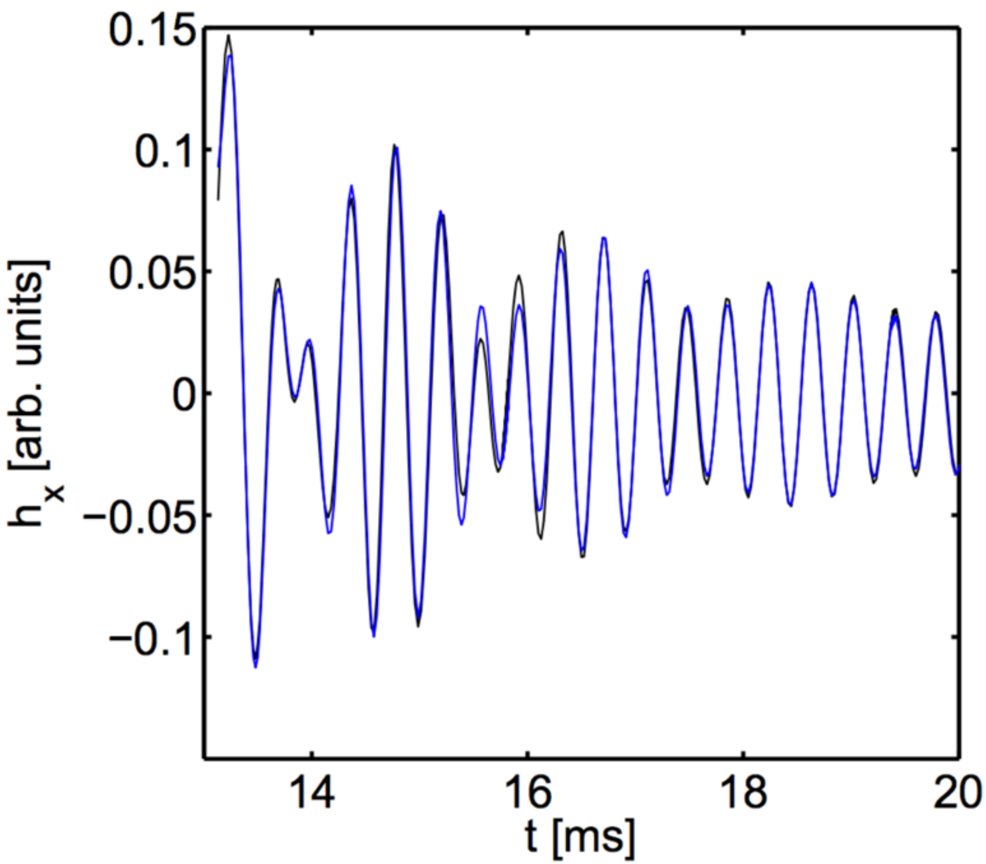
To achieve twice the resolution: 16 x higher, i.e. ~ 20M cu/run



Analytic Templates with Physical Parameters

Bauswein, NS, Janka (2015)

We initially define 12 physical parameters, whith which we can recover the waveform to high accuracy:



$$
\begin{aligned}
h_\times \propto Q_{xy} =& A_{\text{peak}} \exp\left(-(t-t_0)/\tau_{\text{peak}}\right) \\
& \sin\left(2\pi f_{\text{peak}}(t-t_0)+\phi_{\text{peak}}\right) \\
& + A_{\text{spiral}} \exp\left(-(t-t_0)/\tau_{\text{spiral}}\right) \\
& \sin\left(2\pi f_{\text{spiral}}(t-t_0)+\phi_{\text{spiral}}\right) \\
& + A_{2-0} \exp\left(-(t-t_0)/\tau_{2-0}\right) \\
& \sin\left(2\pi f_{2-0}(t-t_0)+\phi_{2-0}\right),
\end{aligned}
$$

Discover and use correlations between physical parameters to reduce parameter space!

Data analysis requirements for BNS mergers

Pipeline	**Development & review status**	**Xeon Sandybridge® Cores needed to run search pipeline on detector network data in time taken to acquire data**		
low-latency GSTLAL-CBC	Analysis run on LIGO-Caltech Pipeline mature and exercised Review already started	2015–16 Spinning: **500**	2016–17 Spinning: **1,800**	2017–18 Spinning: **4,700**
low-latency MBTA	Pipeline tuning for adv Detectors update review start end 2014	Cascina cluster (Virgo resources)		
Daily DetChar Pipeline	Analysis run at LHO and LLO Daily analysis of sub-set of parameter space for detector characterization	2015–16 **1100**	2016–17 **1200**	2017–18 **2800**
Offline Search	Analysis run on Offline XSEDE (Benchmarked on TACC/Stampede) pycbc/ahope upgrade near completion Review readiness April 2014 single-stage ihope as fall-back	2015–16 Non-spinning: **500** Spinning: **4,800**	2016–17 Non-spinning: **1,400** Spinning: **14,300**	2017–18 Non-spinning **2,600** Spinning: **30,000**
Parameter Estimation	LALInference: medium-high latency mature Review underway (Dec 2013) BAYESTAR: rapid localisation	20 cores for medium latency 400 cores for high latency 32+ core parallel node for low latency		
Testing GR	TIGER pipeline in place Testing in real data	1000 cores (Virgo resources)		

Table 1: Summary of resource requirements to deliver BNS science goals, broken down by search pipeline. The baseline plan is to conduct a spinning BNS search, however the cost for an alternative non-spinning BNS search is also given.

Supplementary Material

Neutron Stars

First neutron star detected almost 50 years ago. Still, the fundamental properties of matter in the core of neutron stars remain largely uncertain.

No accurate radius determination!

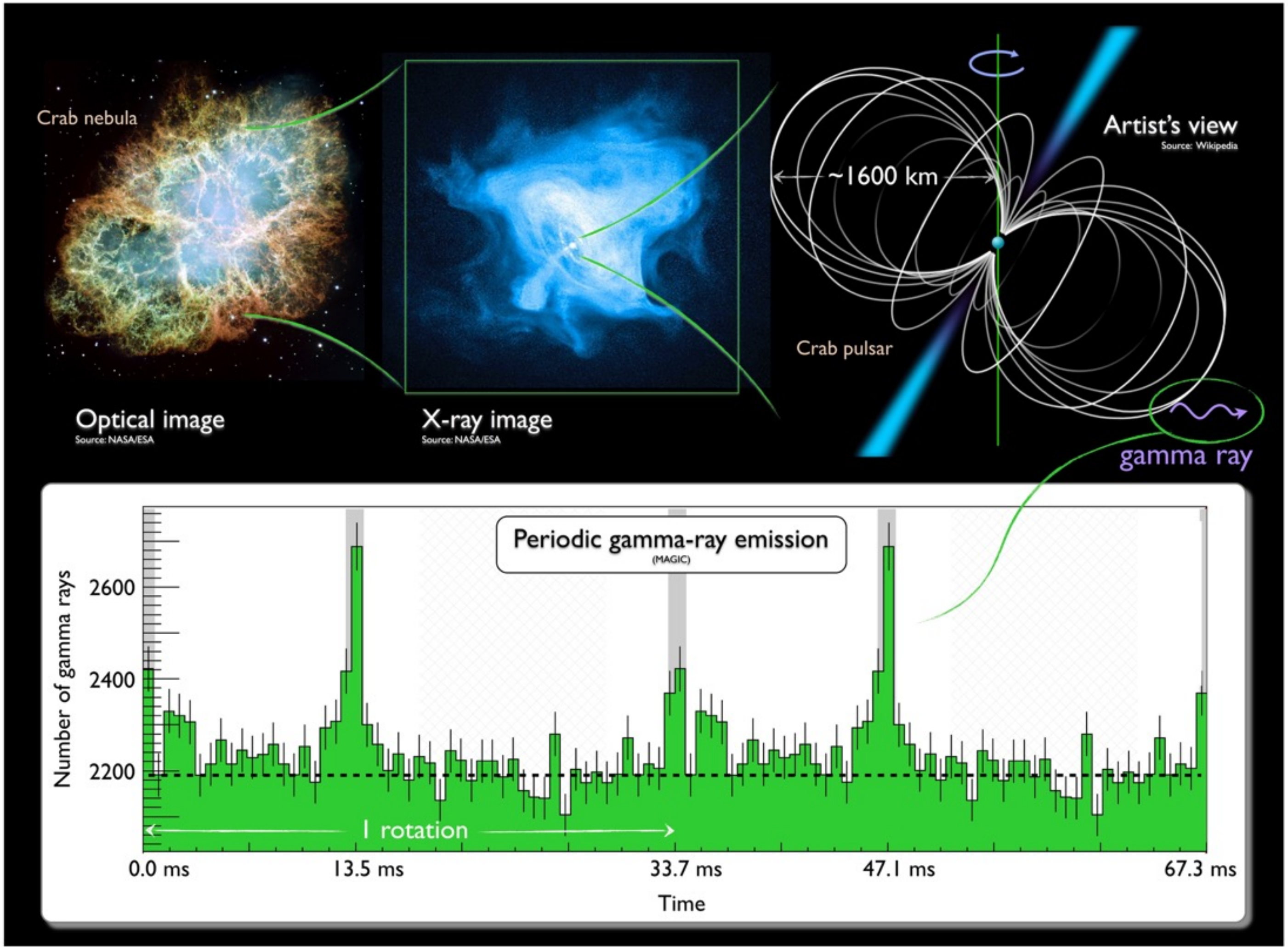
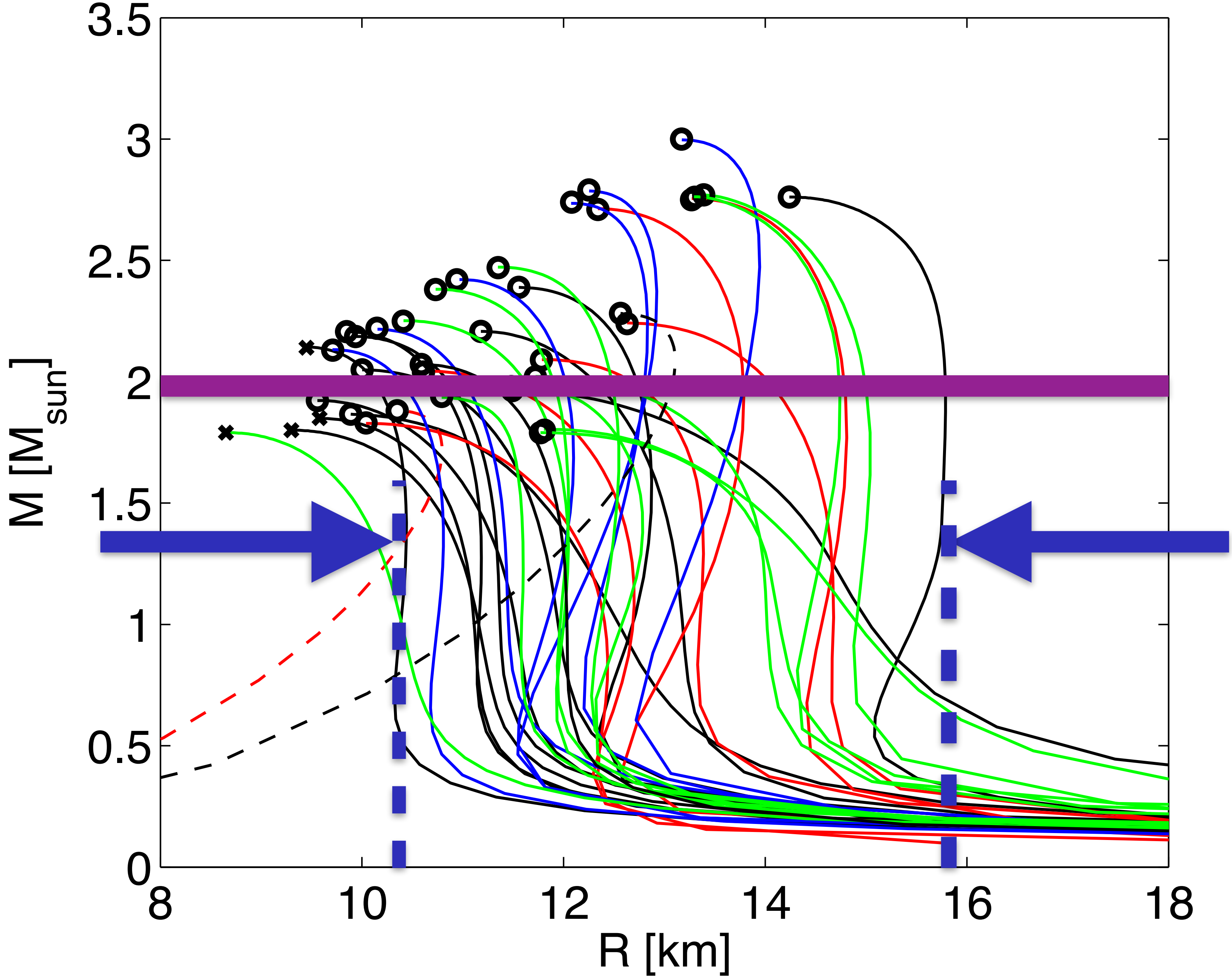


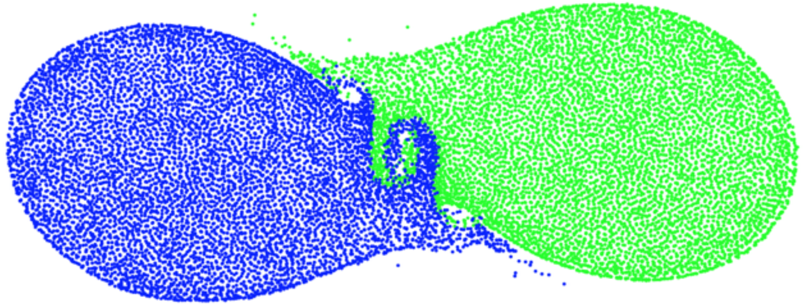
Image credit: MAGIC collaboration

Sample of Neutron Star Equations of State

Bauswein, Janka, Hebeler & Schwenk (2012)



Outcome of Binary NS Mergers



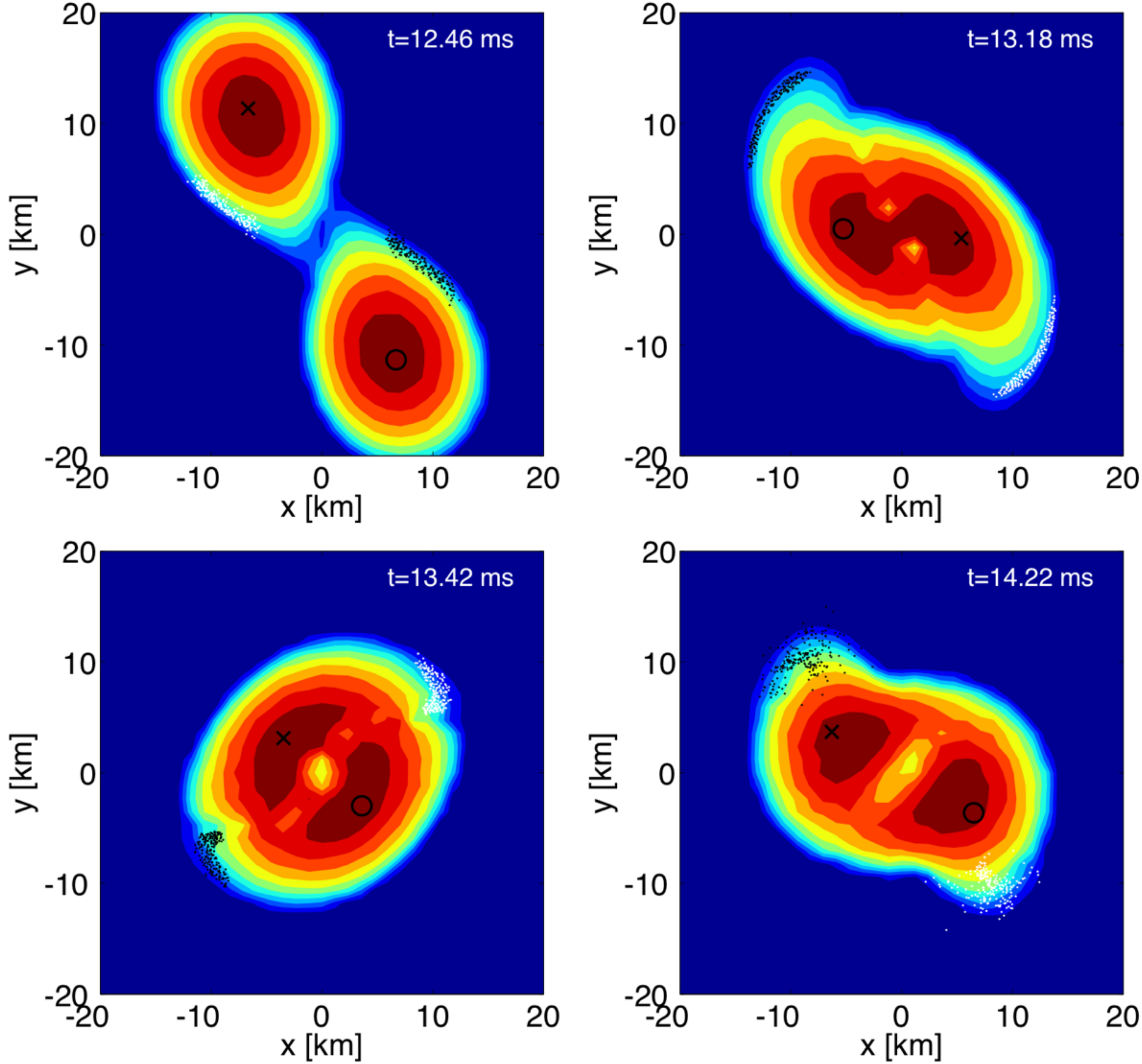
Most likely range of total mass for binary system:

$$2.4M_{\odot} < M_{\rm tot} < 3M_{\odot}$$

Because nonrotating $M_{\rm max} > 2M_{\odot}$ (as required by observations), a long-lived (τ >10ms) remnant is likely to be formed.

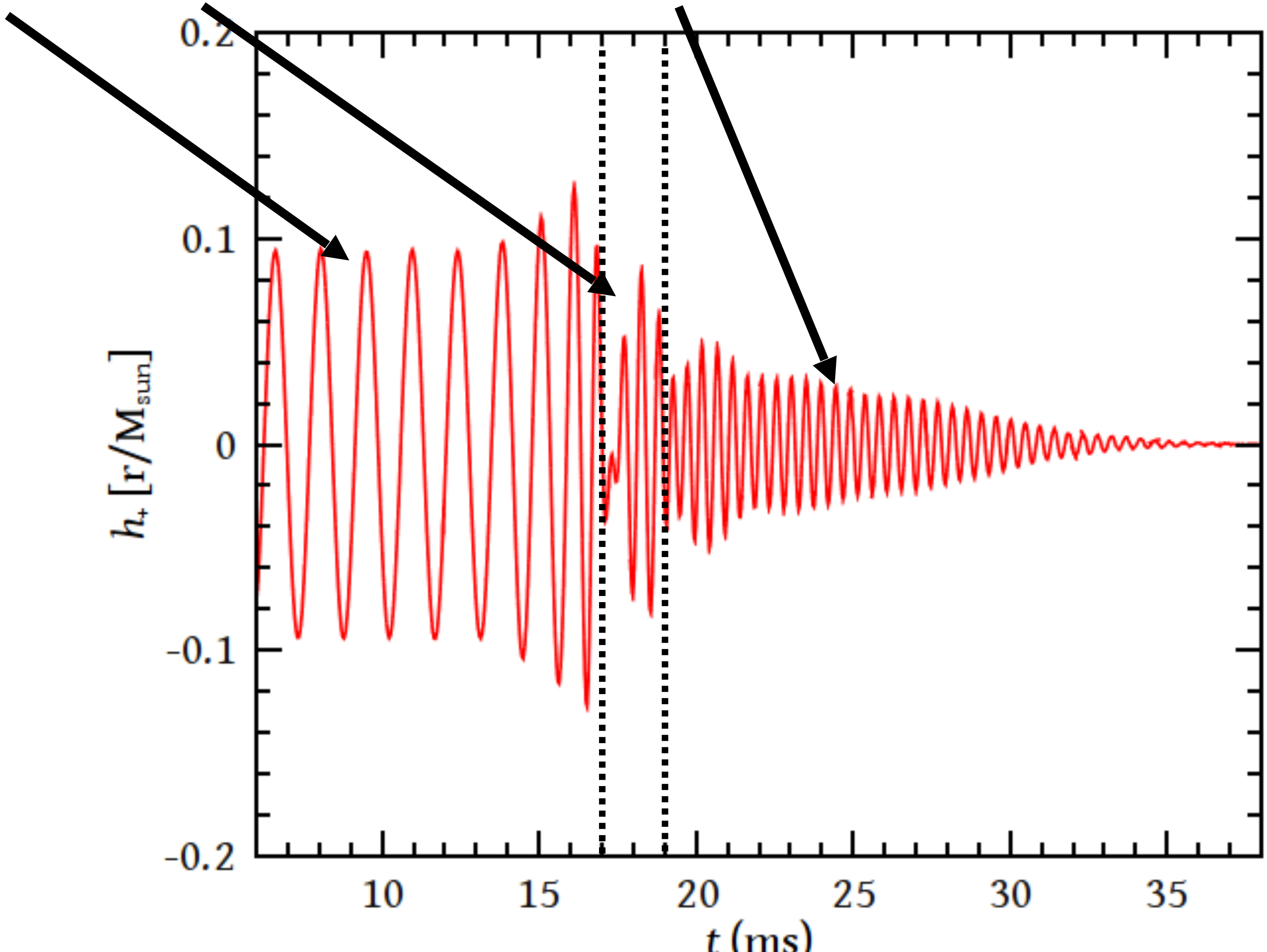
The remnant is a *hypermassive neutron star (HMNS)*, supported by *differential rotation*, with a mass larger than the maximum mass allowed for uniform rotation.

Simulations of BNS mergers



Post-Merger Gravitational Waves

The GW signal can be divided into three distinct phases:
inspiral, *merger* and *post-merger ringdown*. *(@40Mpc)*



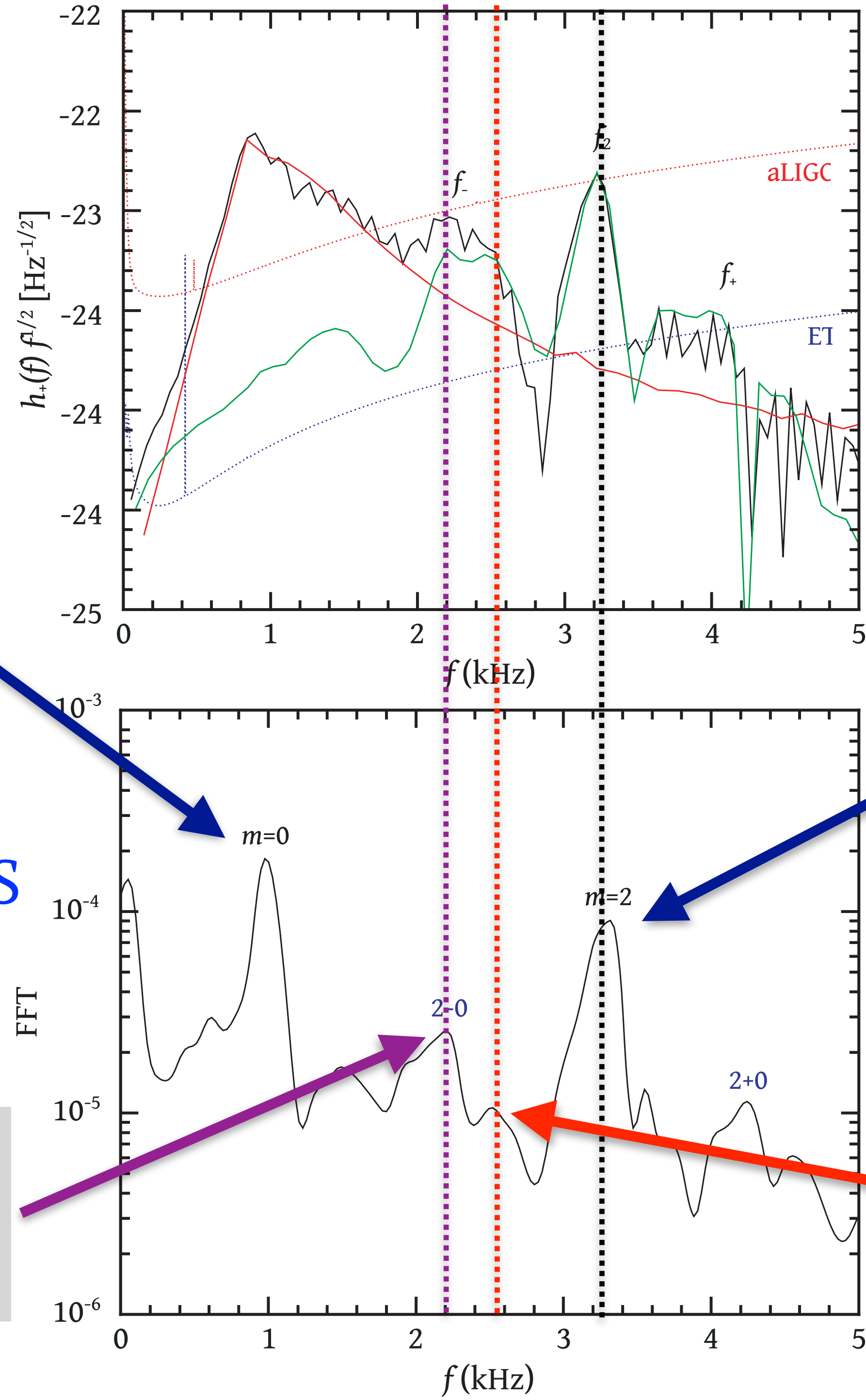
Lattimer-Swesty 220 EOS 1.35+1.35

GRAVITATIONAL WAVE SPECTRUM

l=m=0
linear quasi-radial mode

FFT OF HYDRODYNAMICS IN EQUATORIAL PLANE

“2-0” quasi-linear
combination frequency



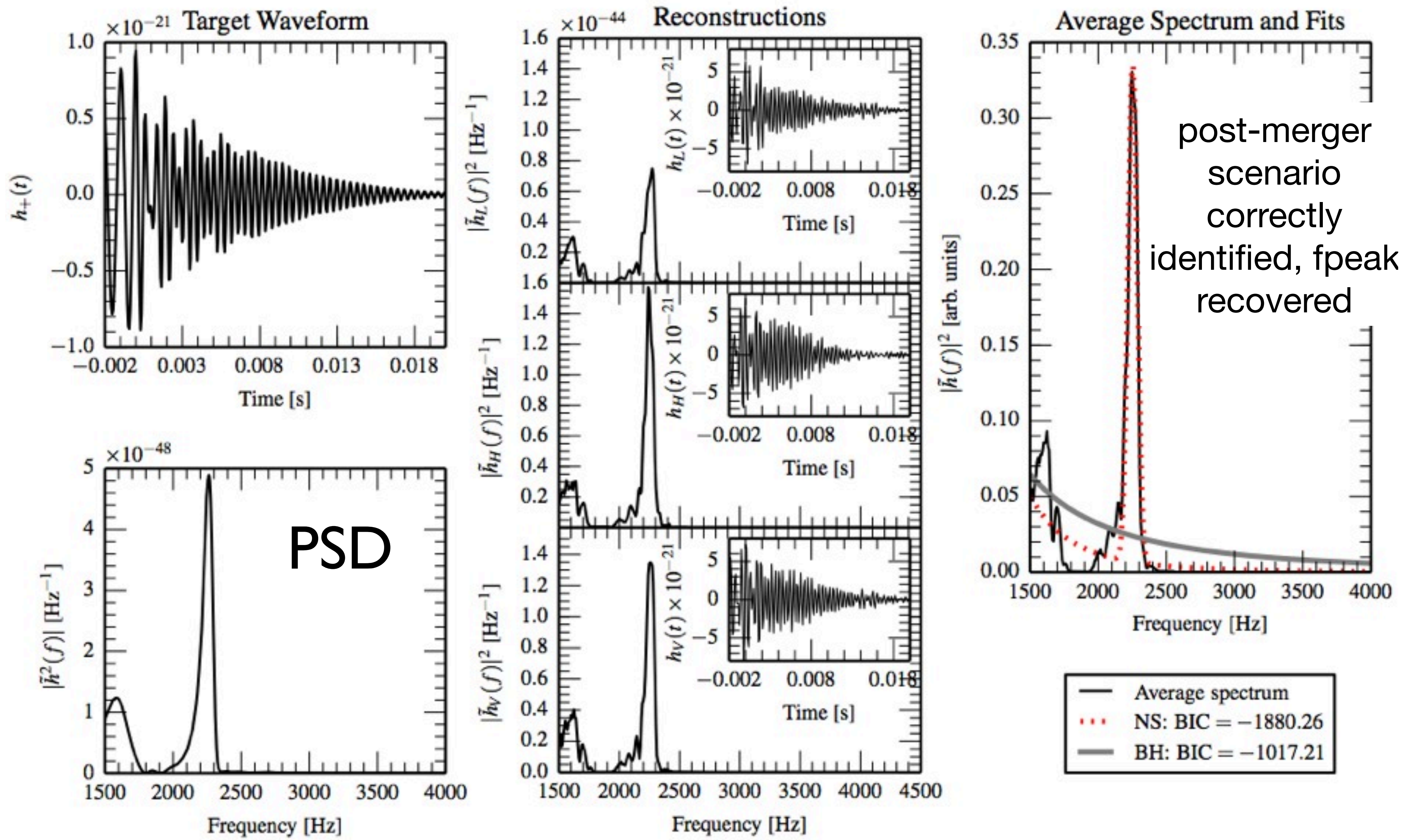
l=m=2
linear f-mode

nonlinear
spiral frequency

Coherent Wave Burst Analysis

Clark, Bauswein, Cadonati, Janka, Pankow, NS (2014)

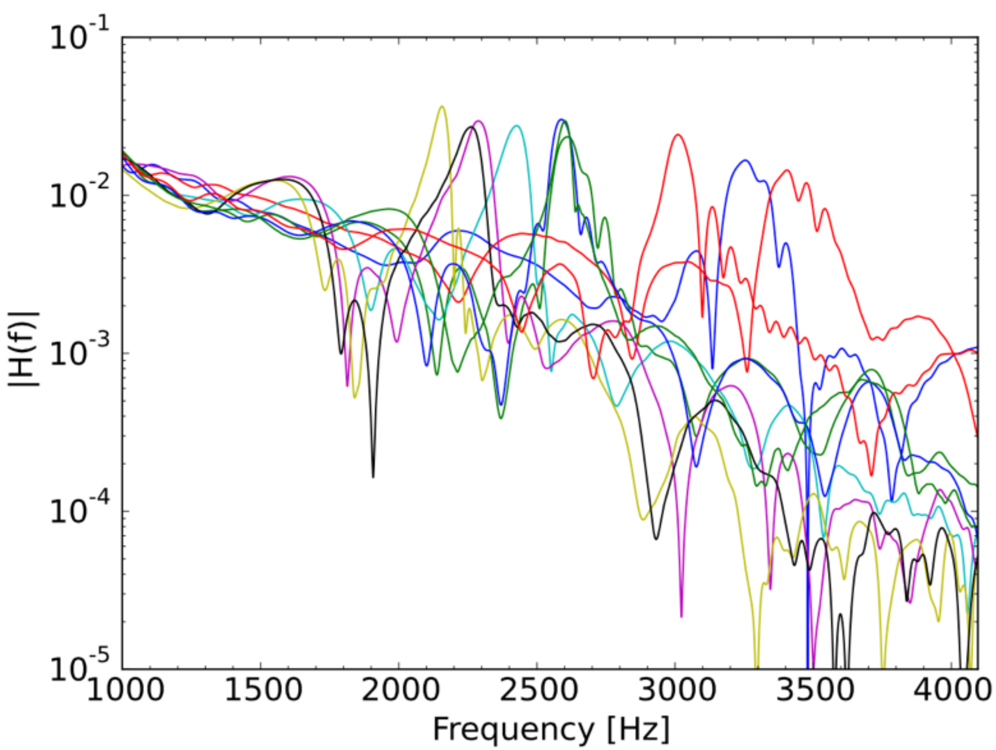
Target (noise free) | **Reconstructions** | **Fit to reconstructed spectrum**

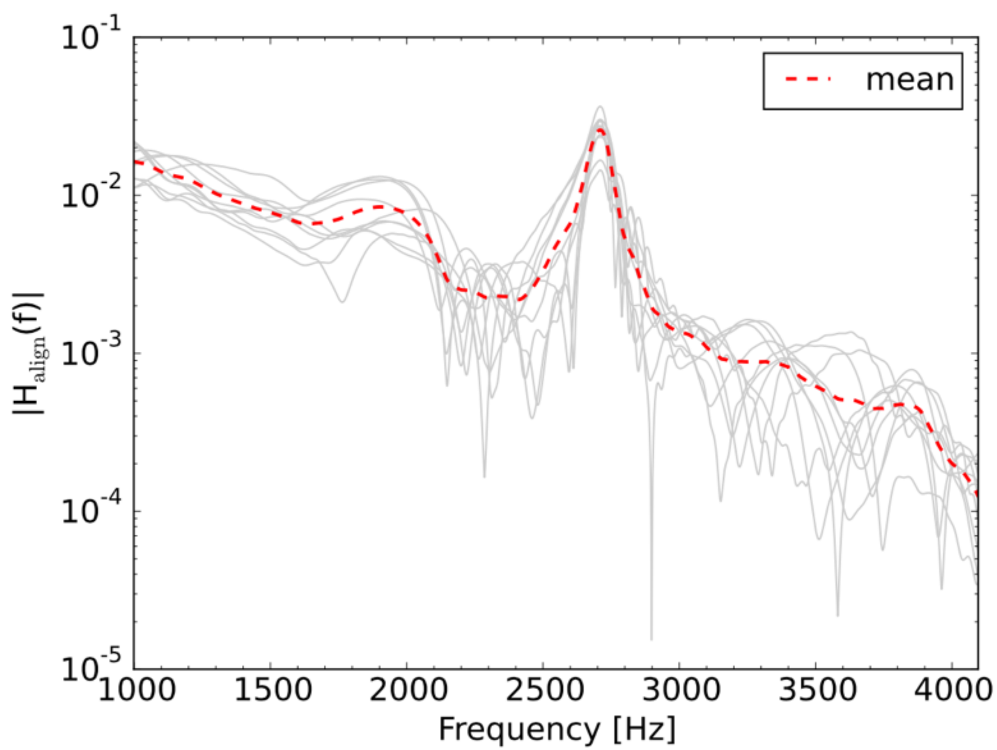


Principal Component Analysis

Clark, Bauswein, NS, Shoemaker (2015)

Post-merger spectra cover different frequency regimes for various EOS, but when scaled to peak frequency, a common pattern emerges. One can then define a set of ***principal components*** and an average spectrum.





Principal Component Analysis

Clark, Bauswein, NS, Shoemaker (2015)

The signal and the spectrum can be reconstructed with high accuracy, using the basis of principal components.