What can be learned from gravitational-waves on the physics of bursts and compact binaries

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LSC LIGO Scientific Collaboration VIRGO

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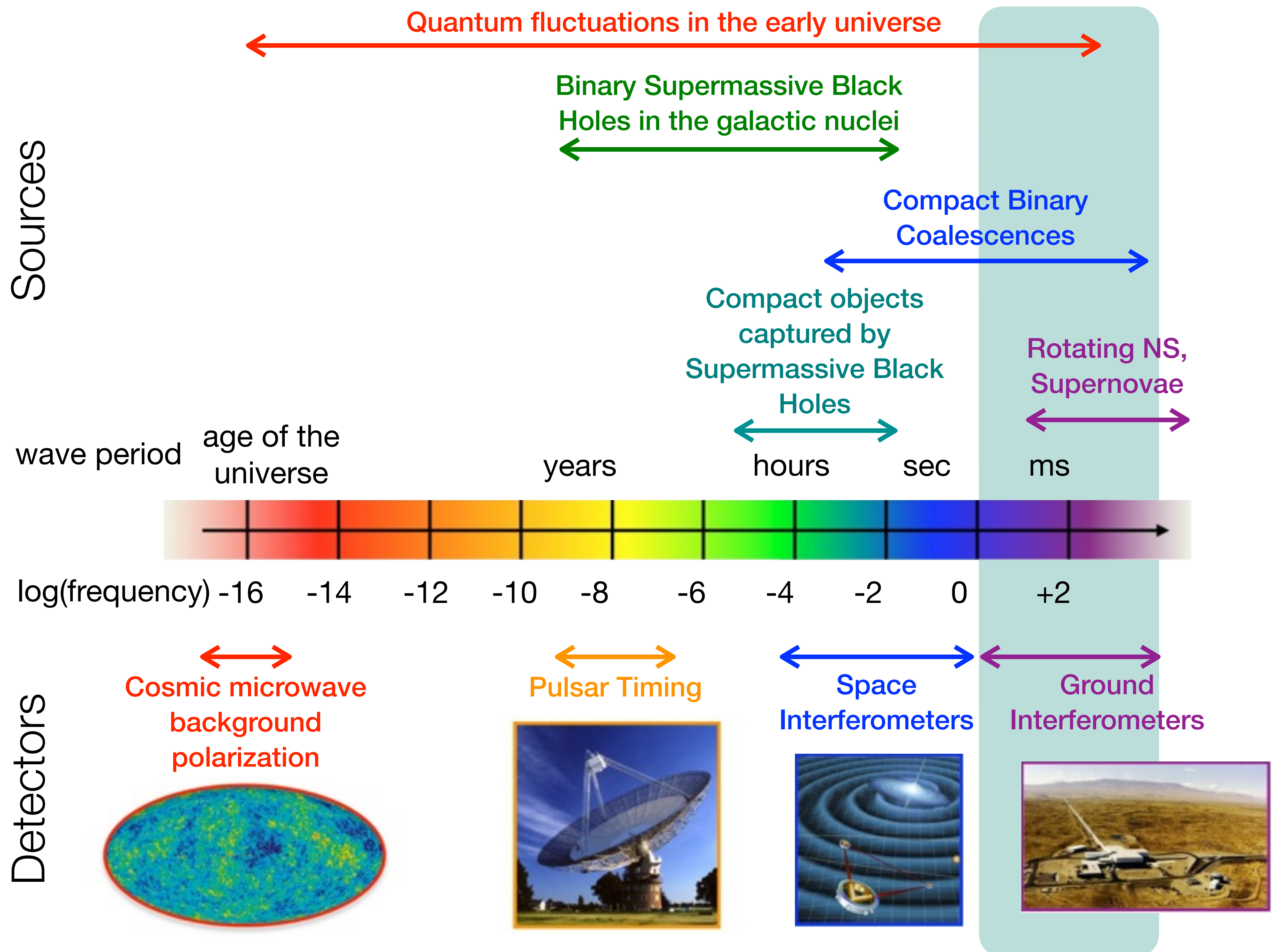
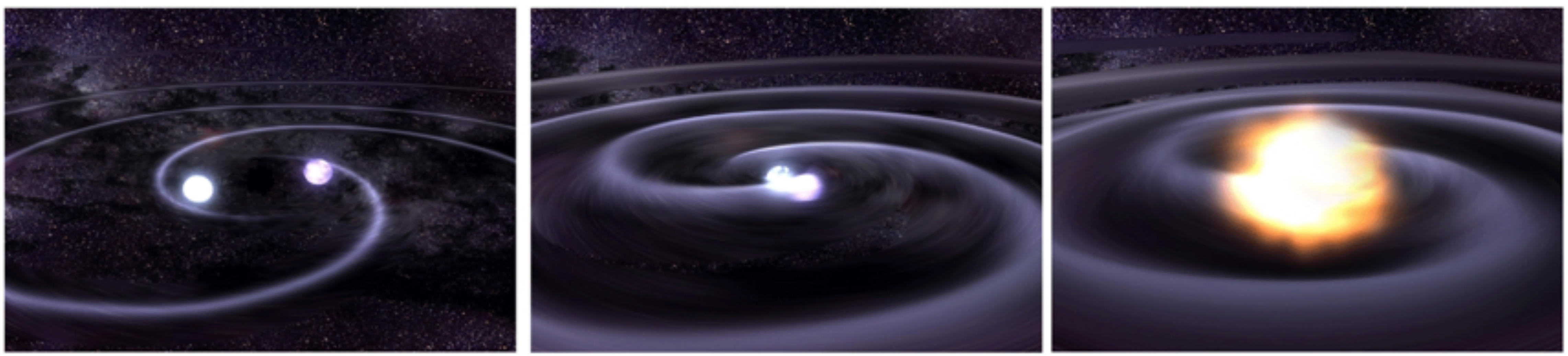
The Gravitational Wave Spectrum



[Inspired from http://science.gsfc.nasa.gov/663/research/]

Gravitational Wave Astronomy

- Gravitational wave detectors will study sources characterised by extreme physical conditions: strong non-linear gravity and relativistic motions, very high densities, …



[Image: NASA/CXC/GSFC/T.Strohmayer]

- Here are some examples of questions which will hopefully be answered:

Fundamental physics:

- What are the properties of gravitational waves?
- Is General Relativity still valid under strong-gravity conditions?
- Are nature's black holes the black holes of General Relativity?
- How does matter behave under extremes of density and pressure?

Astrophysics

- How abundant are stellar-mass binary black holes?
- Is the mechanism that generates gamma-ray bursts a compact binary coalescence?
- How do compact binary stars form and evolve, and what has been their effect on star formation rates?
- Where and when do massive black holes form, and what role do they play in the formation and evolution of galaxies?
- What happens when a massive star collapses?

Prediction for Detection Rates

TABLE V: Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{\mathrm{low}}$ yr^{-1}	$\dot{N}_{\mathrm{re}}$ yr^{-1}	$\dot{N}_{\mathrm{high}}$ yr^{-1}	$\dot{N}_{\mathrm{max}}$ yr^{-1}
Initial	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			< 0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
Advanced	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
	BH-BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

[Abadie et al., Class. Quant. Grav.27:173001 (2010)]

Upper Limits

- No inspiral signals detected
- 90% confidence limits on coalescence rates:
  - For binary neutron stars: $< 1.3\times10^{-4}$ Mpc^{-3} yr^{-1}
  - For binary black holes with $5+5M_{\odot}$: $< 6.4\times10^{-6}$ Mpc^{-3} yr^{-1}
- Soon to confront expected range of merger rates

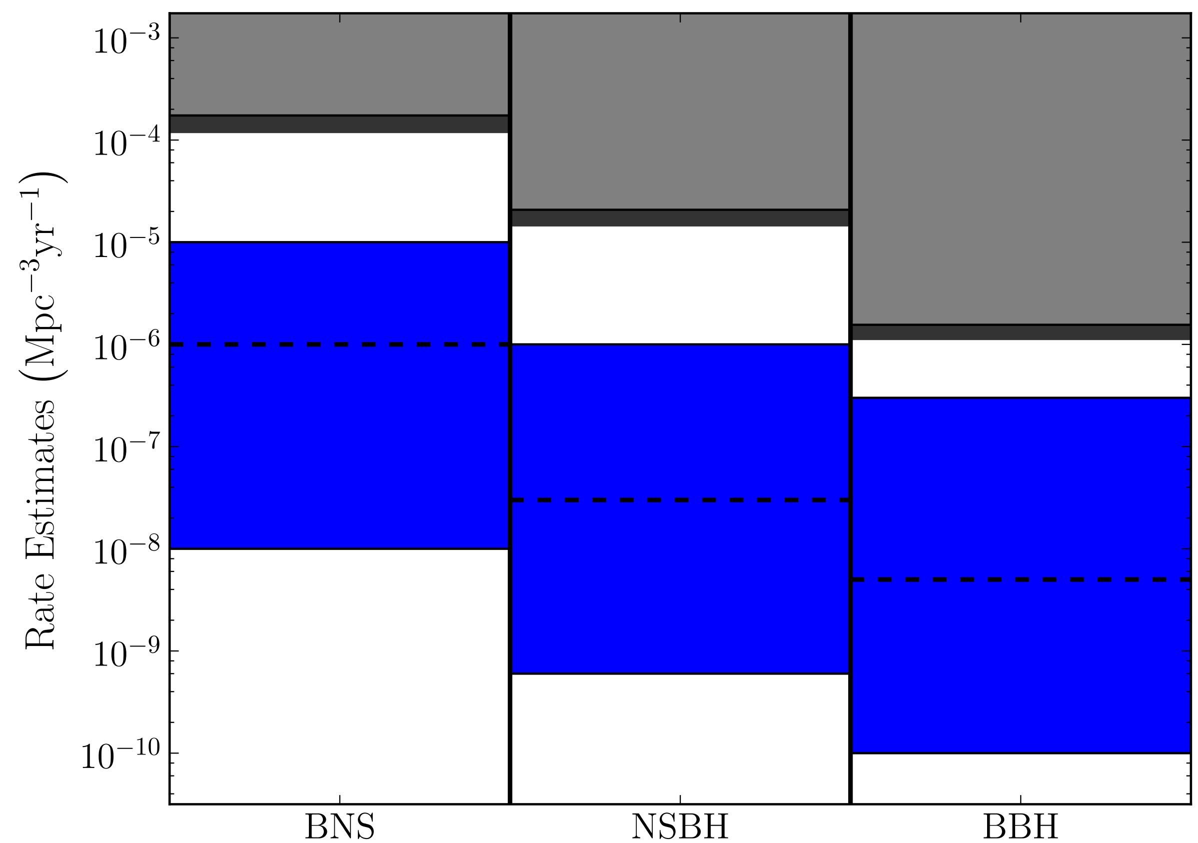


FIG. 5: Comparison of CBC upper limit rates for BNS, NSBH and BBH systems.

[Abadie et al., PRD 85, 082002 (2012)]

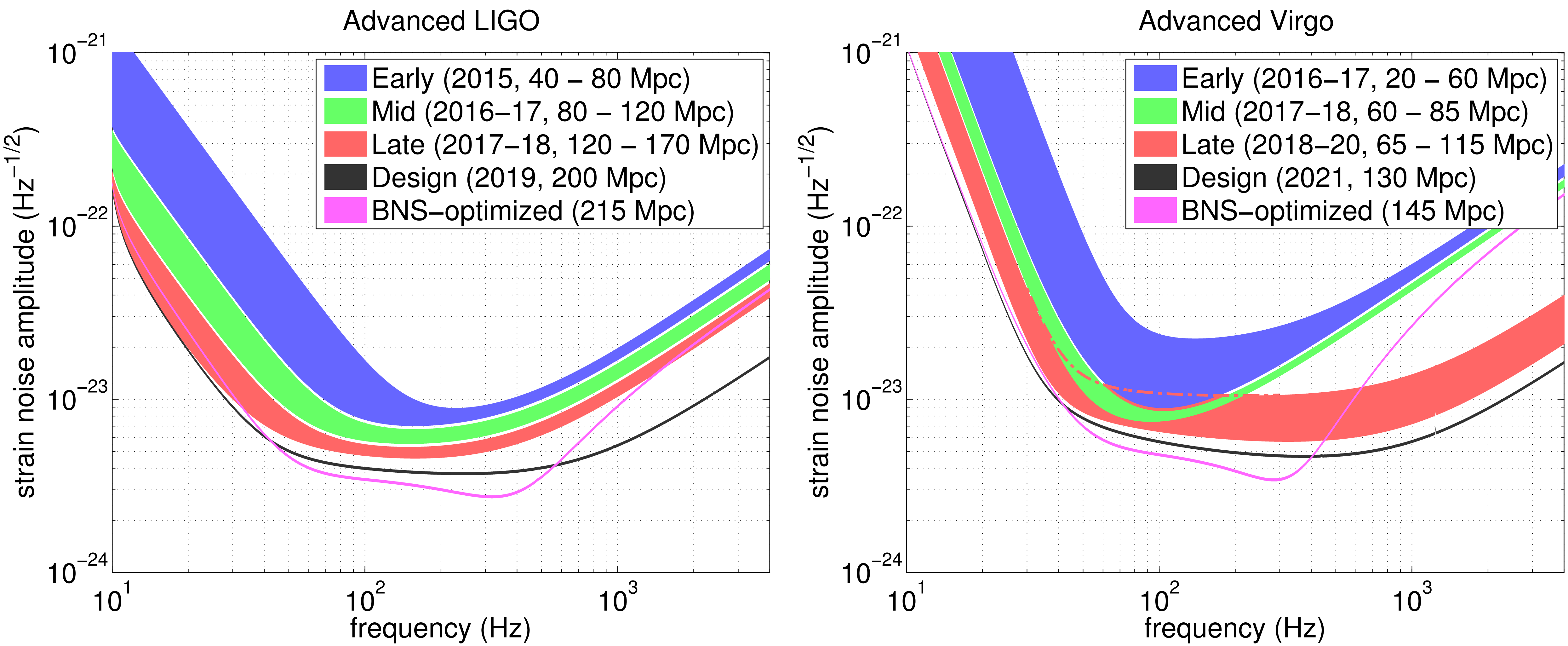
2018 Preview

source	current upper limit	2nd gen rate	predicted rate
neutron star binaries ($1.35 + 1.35\ M_\odot$)	$1.3\text{x}10^{-4}$ Mpc^{-3} yr^{-1}	1.3×10^{-7} Mpc^{-3} yr^{-1} $<$	10^{-6} Mpc^{-3} yr^{-1}
stellar mass BH binaries ($5 + 5\ M_\odot$)	6.4×10^{-6} Mpc^{-3} yr^{-1}	6.4×10^{-9} Mpc^{-3} yr^{-1} $=$	5×10^{-9} Mpc^{-3} yr^{-1}
mixed binaries ($1.35 + 5\ M_\odot$)	3.1×10^{-5} Mpc^{-3} yr^{-1}	3.1×10^{-8} Mpc^{-3} yr^{-1} $=$	3×10^{-8} Mpc^{-3} yr^{-1}
"high stellar mass" BH binaries ($50 + 50\ M_\odot$)	7×10^{-8} Mpc^{-3} yr^{-1}	7×10^{-11} Mpc^{-3} yr^{-1}	—
intermediate mass BH binaries (center of $88 + 88\ M_\odot$)	1.2×10^{-7} Mpc^{-3} yr^{-1}	1.2×10^{-10} Mpc^{-3} yr^{-1} $<$	3×10^{-10} Mpc^{-3} yr^{-1}
ringdowns (BH merger, q=1:4, $M_T=125\ M_\odot$)	1.1×10^{-7} Mpc^{-3} yr^{-1}	1.1×10^{-10} Mpc^{-3} yr^{-1} $<$	3×10^{-10} Mpc^{-3} yr^{-1}
generic short-duration transient (BH merger, supernova, etc...)	1.3 yr^{-1}	1.3 yr^{-1}	—

[Phys. Rev. D 85 082002; Phys. Rev. D 85 122007; Phys. Rev. D 87 022002; Phys. Rev. D 89 102006; Phys. Rev. D 89 122003]

Does Not Include Improvements to Detector Bandwidth

Advanced network expected ranges



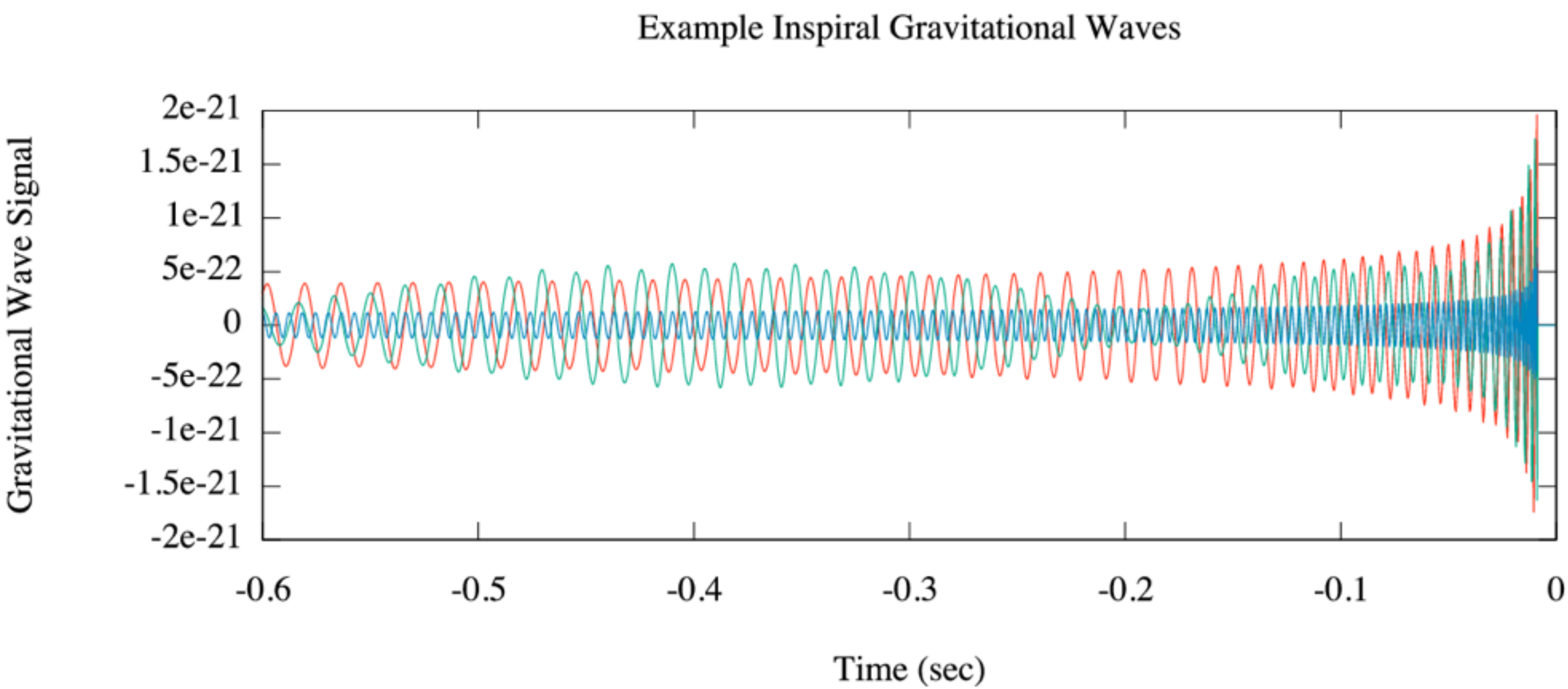
[Aasi et al. arXiv:1304.0670 (2013)]

Parameter Estimation

- Fit a model to the data (**noise** and **signal** models)
- Build a Likelihood function
- Specify prior knowledge
- Numerically estimates the resulting Posterior Distribution Function (sampling algorithms)

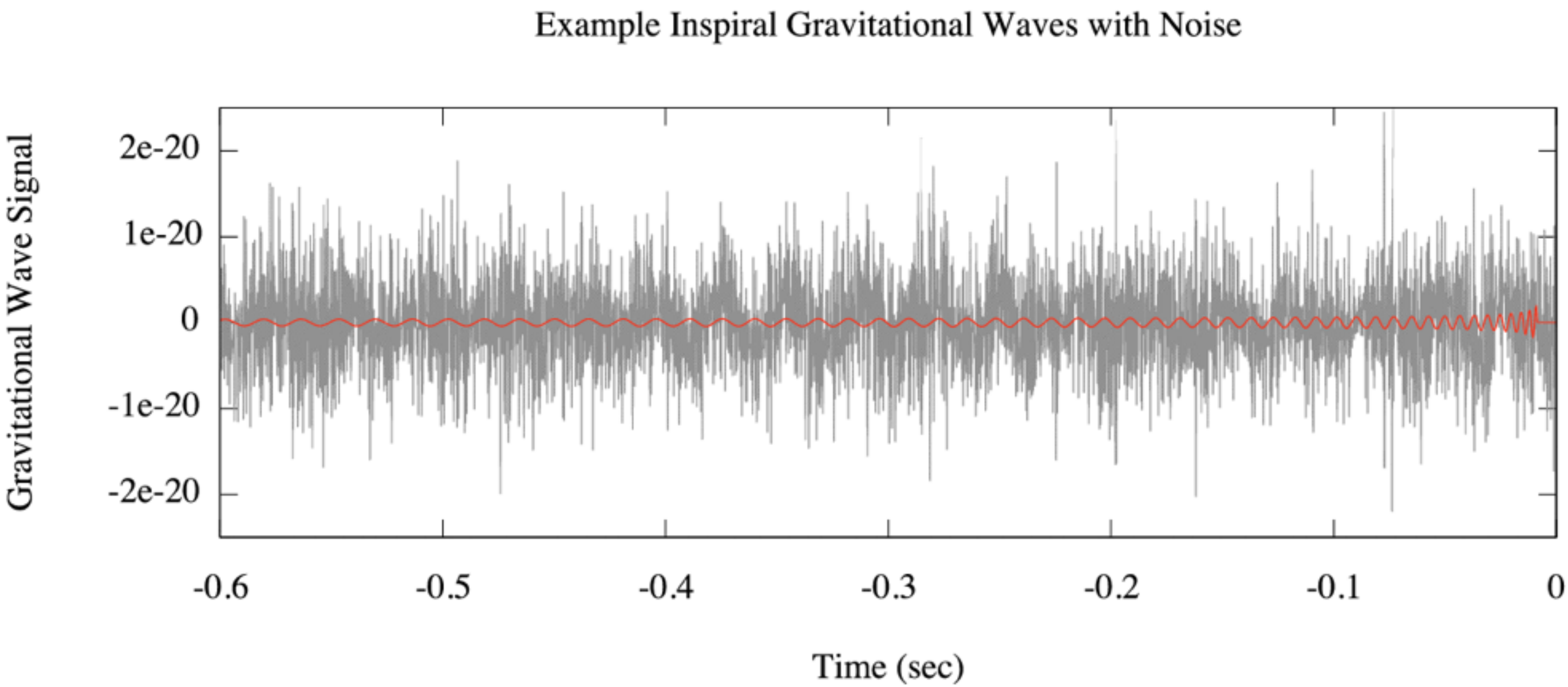
$$posterior = \frac{prior * likelihood}{evidence}$$

Parameter Estimation

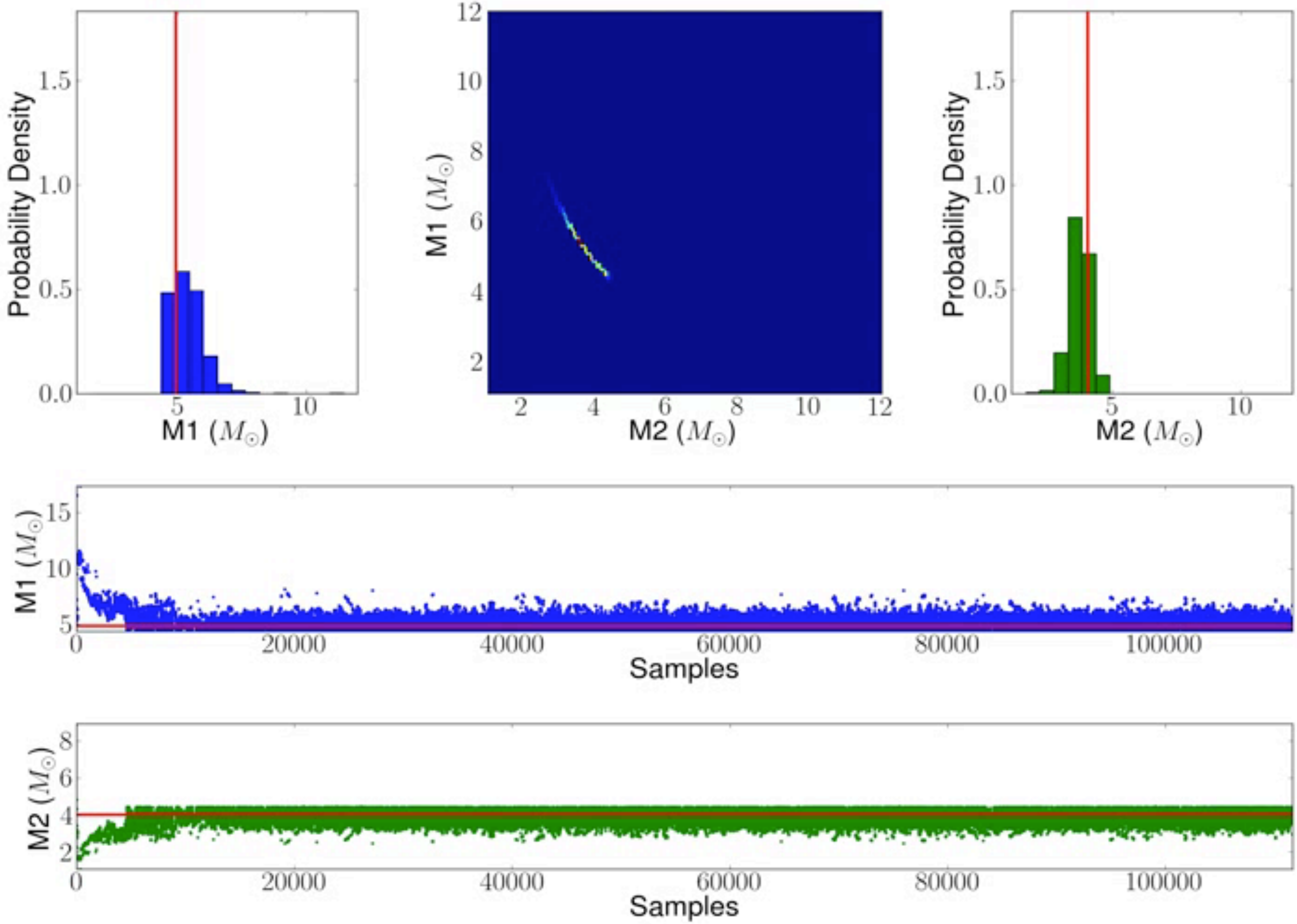


[http://www.ligo.org/science/Publication-S6PE/index.php]

Parameter Estimation



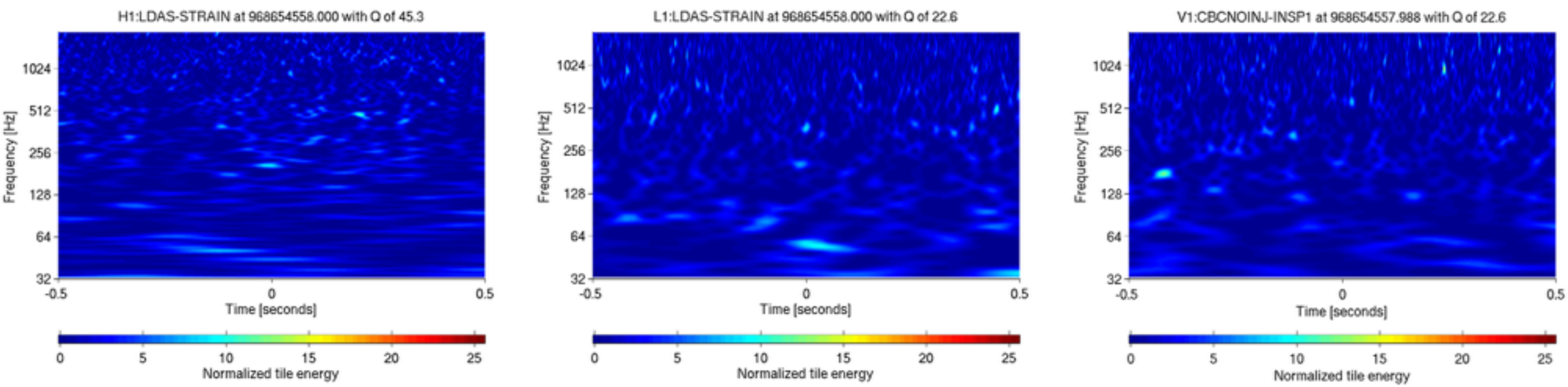
[http://www.ligo.org/science/Publication-S6PE/index.php]



[http://www.ligo.org/science/Publication-S6PE/index.php]

GW100916

- On a nice day of September 2010 …



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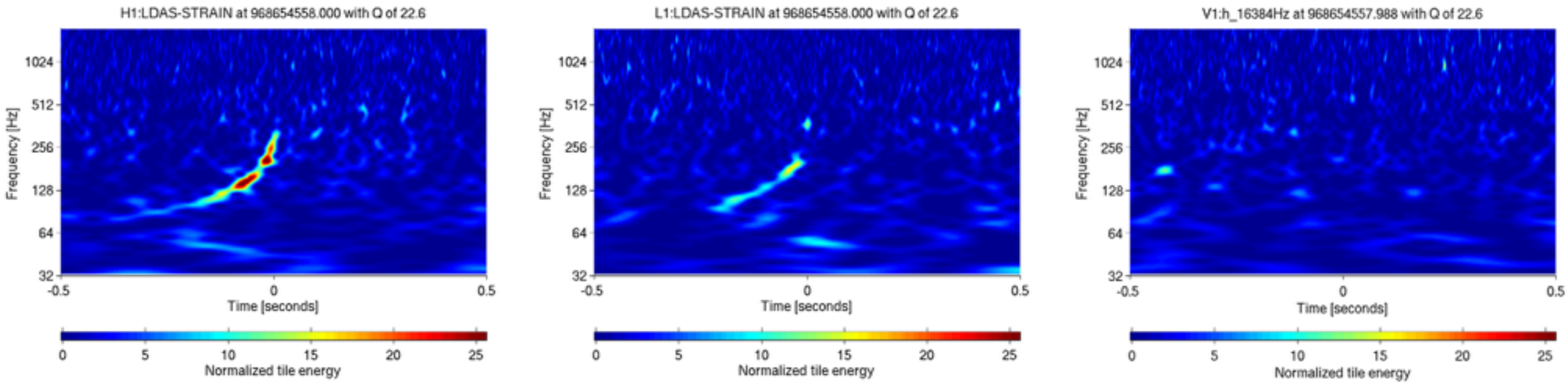

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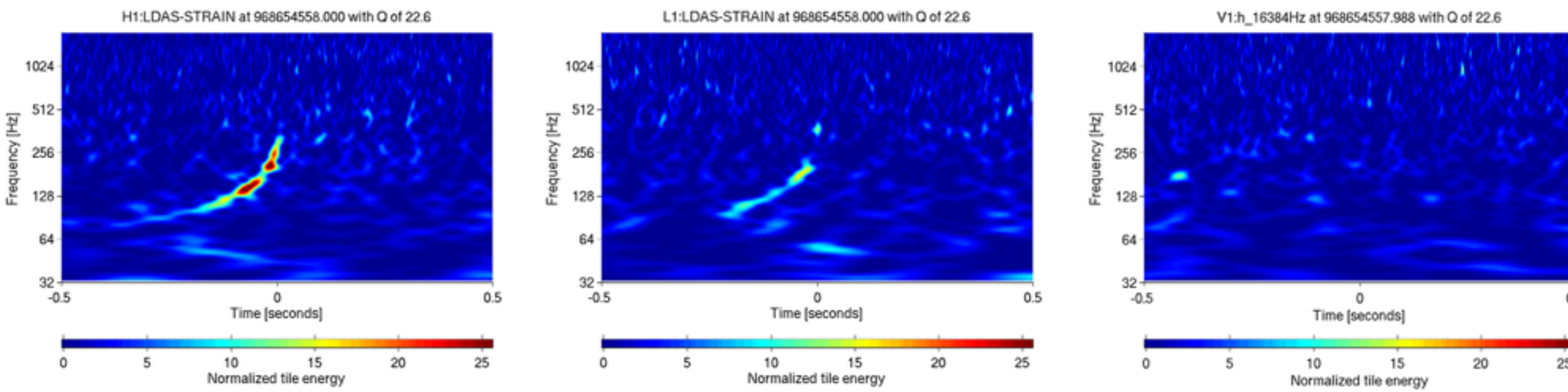
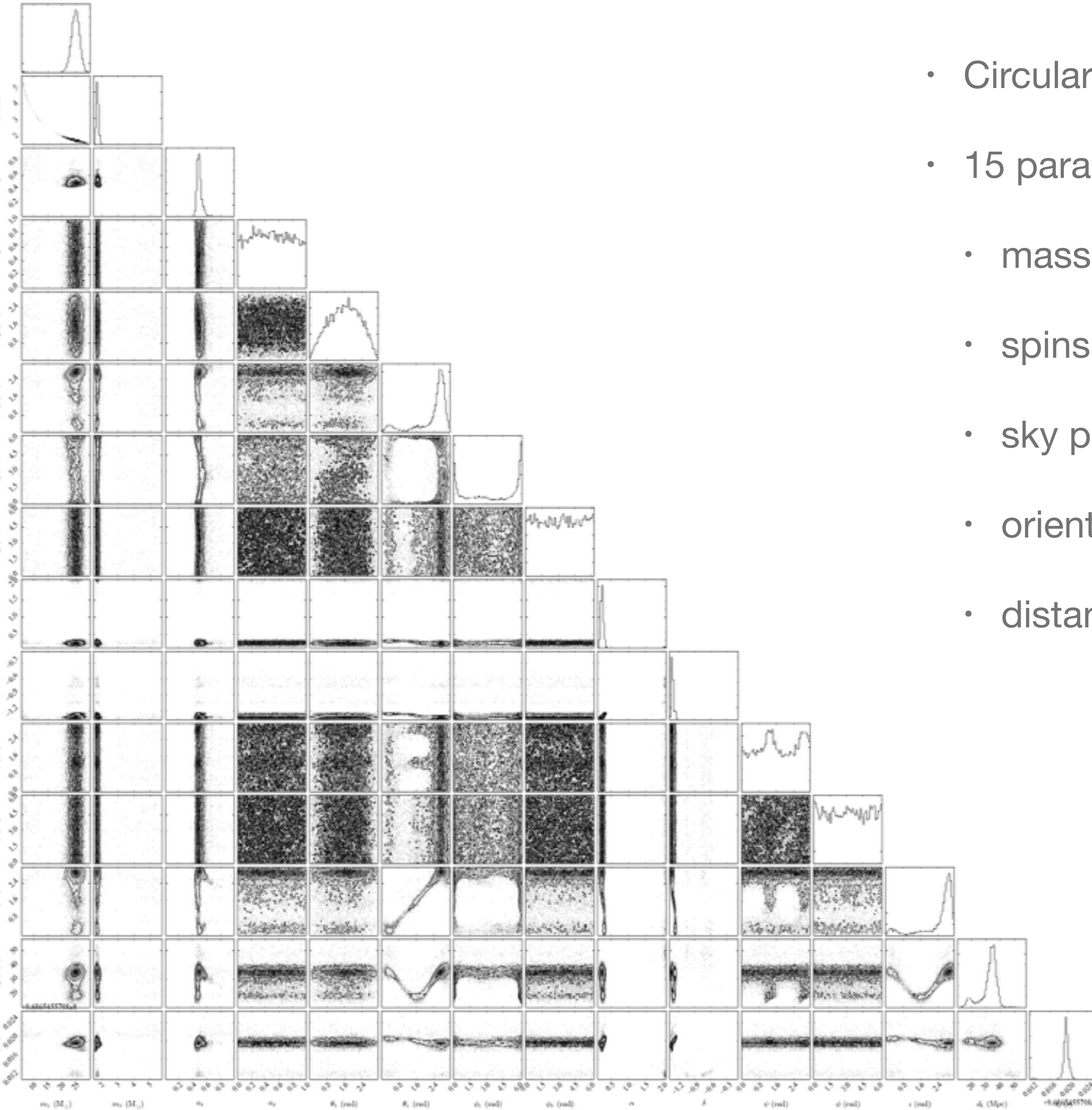


- This event was later reveled to be a “blind injection”

http://www.ligo.org/news/blind-injection.php
http://www.ligo.org/science/GW100916/index.php

- Multi-Messenger Astronomy (see talk by Chris Pankow)



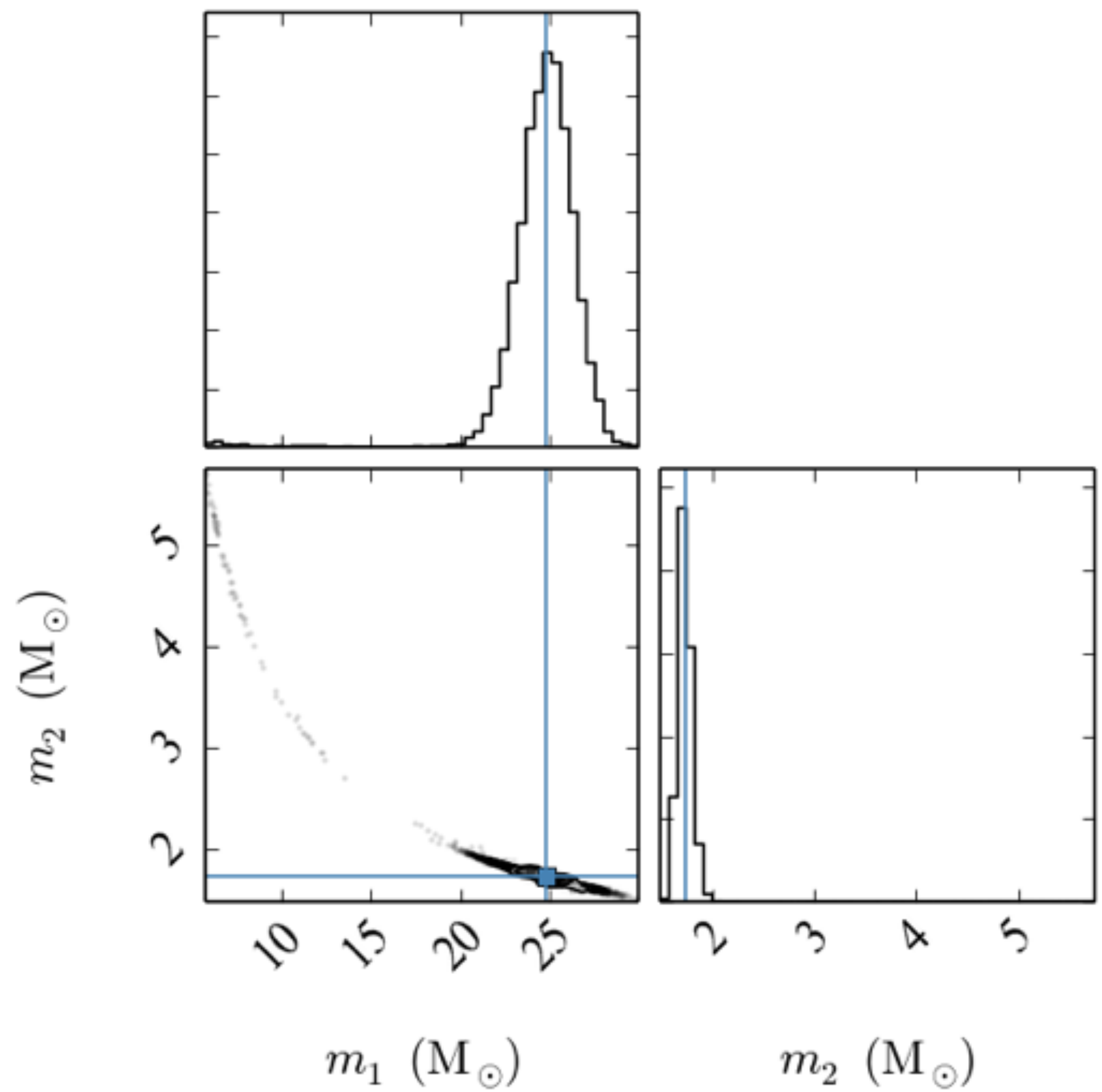
- Circular binary signal model
- 15 parameters:
    - masses (2)
    - spins (6)
    - sky position (2)
    - orientation (3)
    - distance and time (2)

Masses estimation

- Masses are estimated primarily by the "chirp mass":

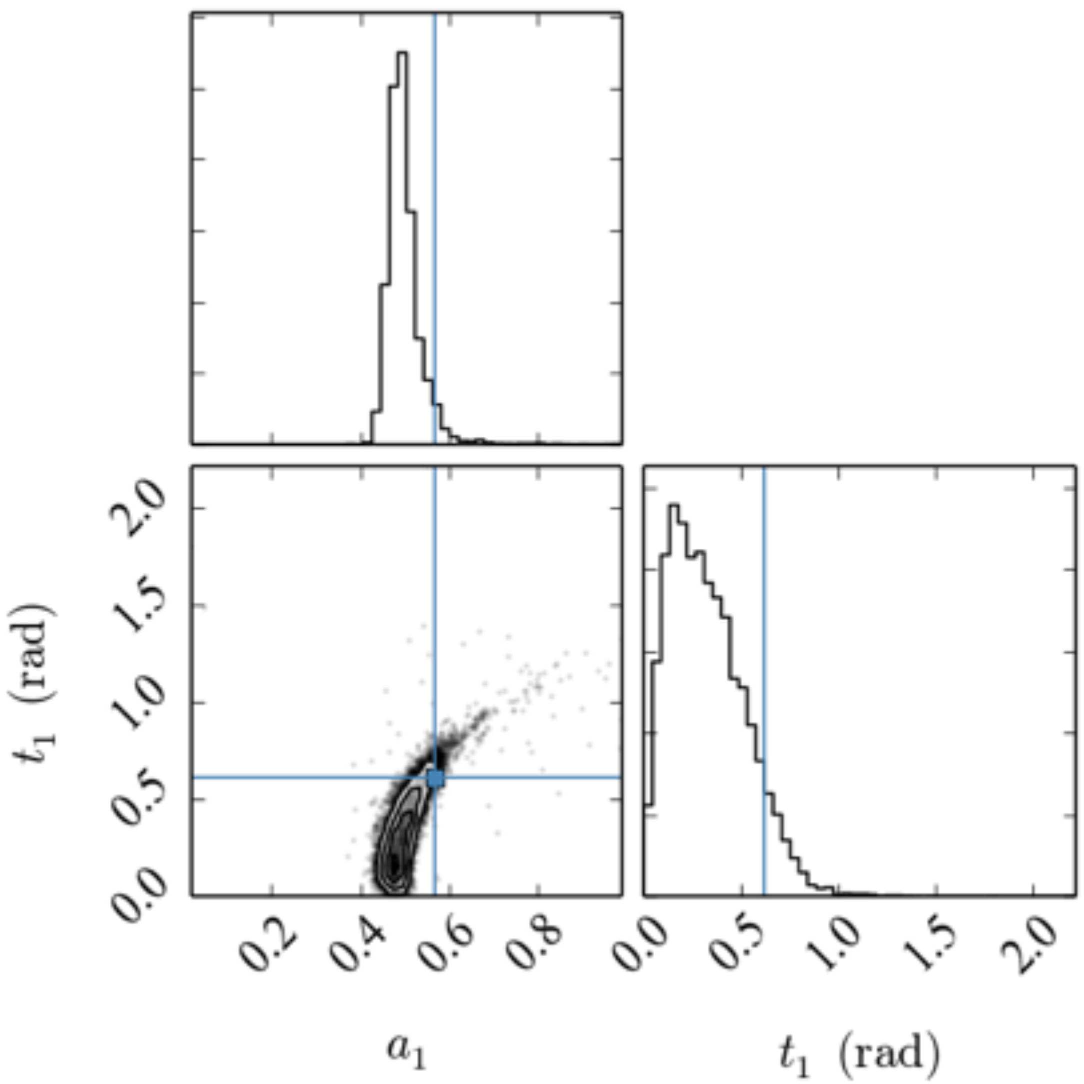
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

- (Leading term in the post-Newtonian expansion)
- Results in a strong degeneracy

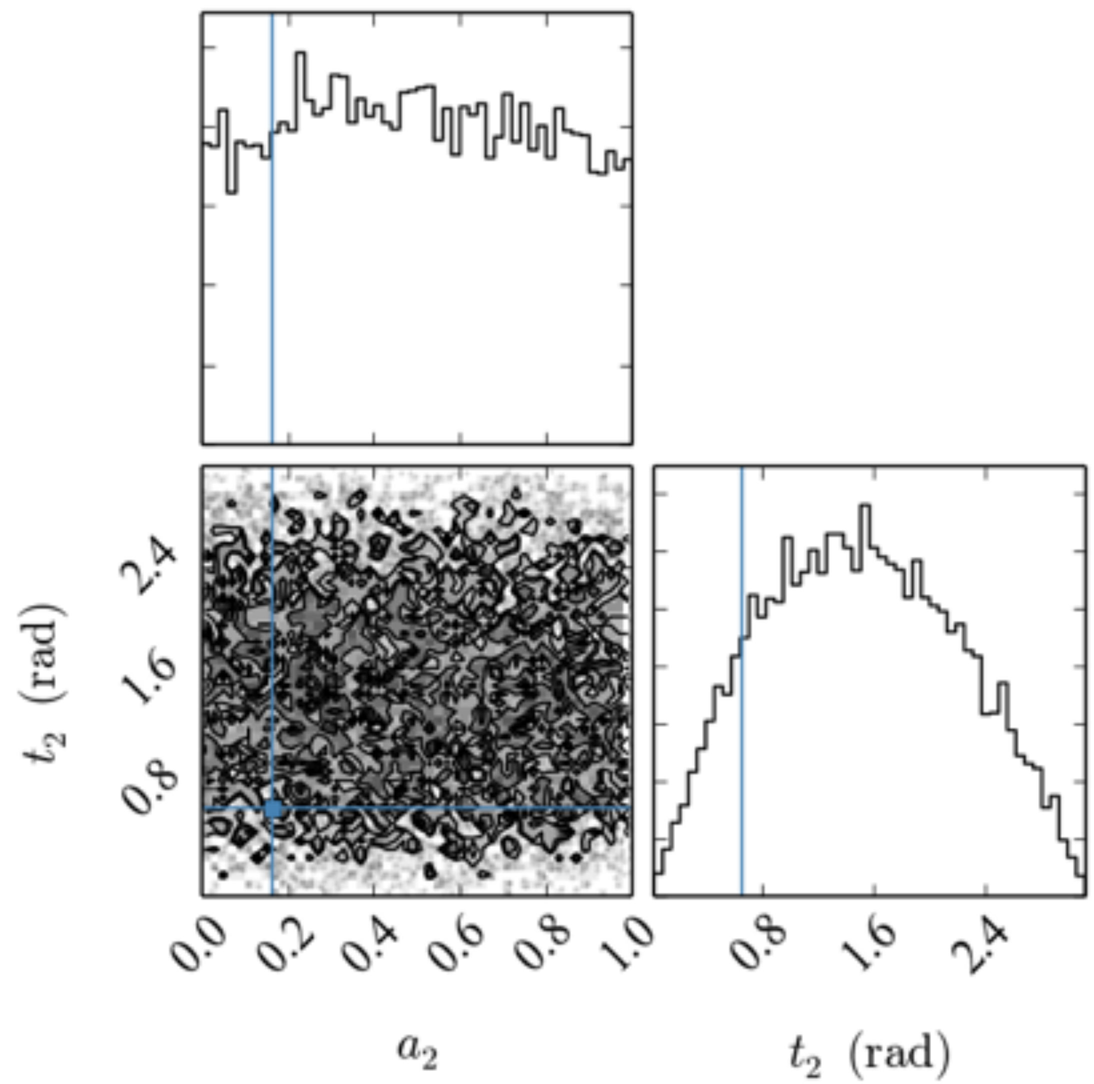


Spin parameters estimation

- spin1 constrained (black-hole)



- spin2 unconstrained (neutron-star)

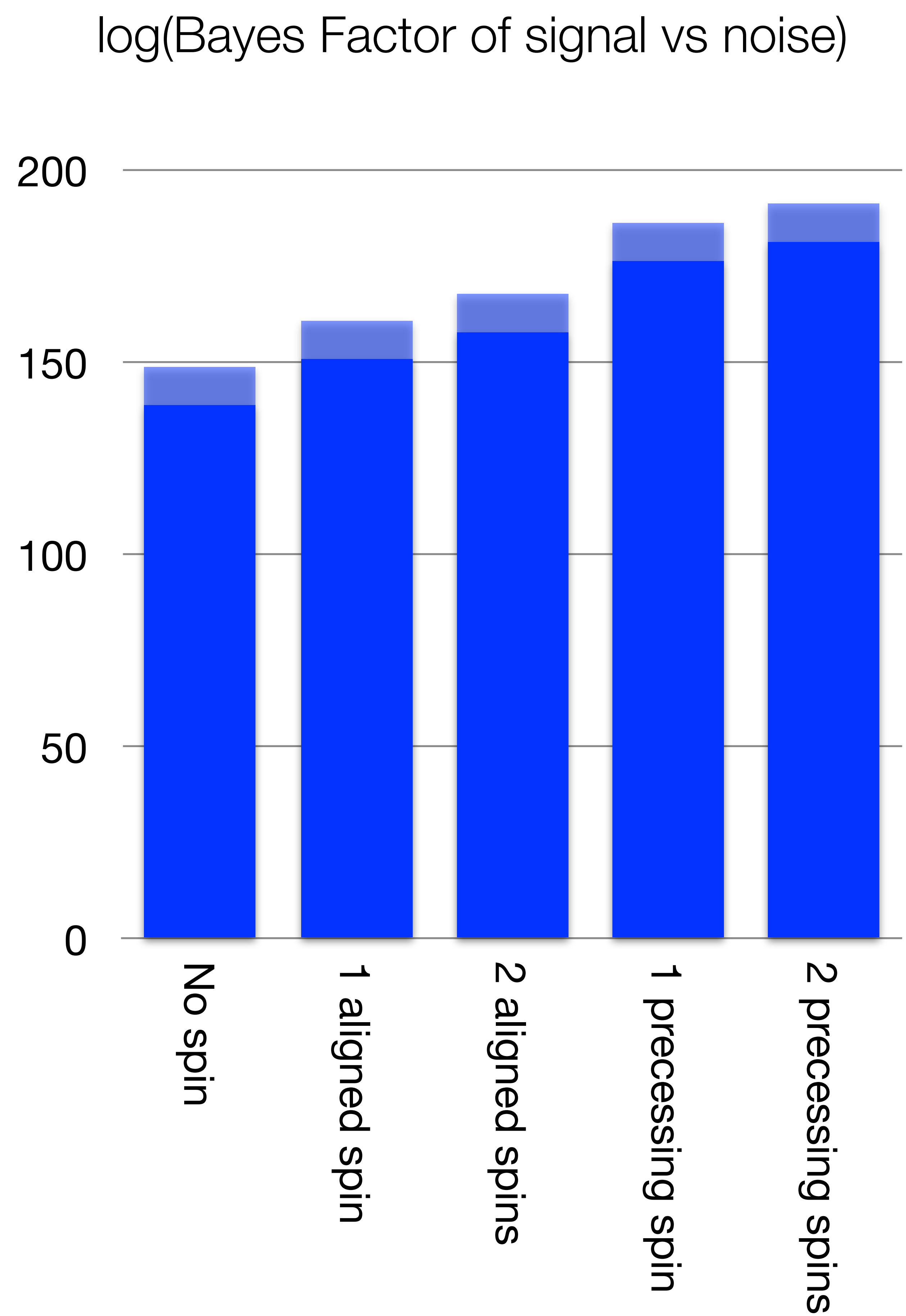


a: dimentionless spin parameter (∈[0;1])

t: tilt angle between the orbital angular momentum and spin

Model selection

- Using the **Bayes Factor**
- (Needs inclusion of the **prior odds** to obtain the **Odds ratio**)
- In this example:
  - strong evidence for precession
  - weak evidence for two spins
- The injected signal was a precessing back-hole - neutron-star binary.



Combining triggers

- Astrophysical population statements
  - Inference of the population parameters

(Mandel, I., Phys. Rev. D 81, 084029 (2010); Farr et al. arXiv:1302.5341 (2013))

  - Selection bias from the detector network

(C Messenger and J Veitch *New J. Phys.* **15** 053027 (2013))

- Testing General Relativity

(Agathos et al. Phys. Rev. D 89, 082001 (2014); Chatziioannou et al. Phys. Rev. D 86, 022004 (2012))

- Measuring Neutron Star Equation of State (via tidal parameters)

(Wade et al. Phys. Rev. D 89, 103012 (2014); Pozzo et al. Phys. Rev. L 111, 071101 (2013))

Supernovae

- Template bank from numerical simulations.
- Main parameters:
    - Total angular momentum of the inner core at bounce
    - Inner core's ratio of rotational kinetic energy to gravitational energy

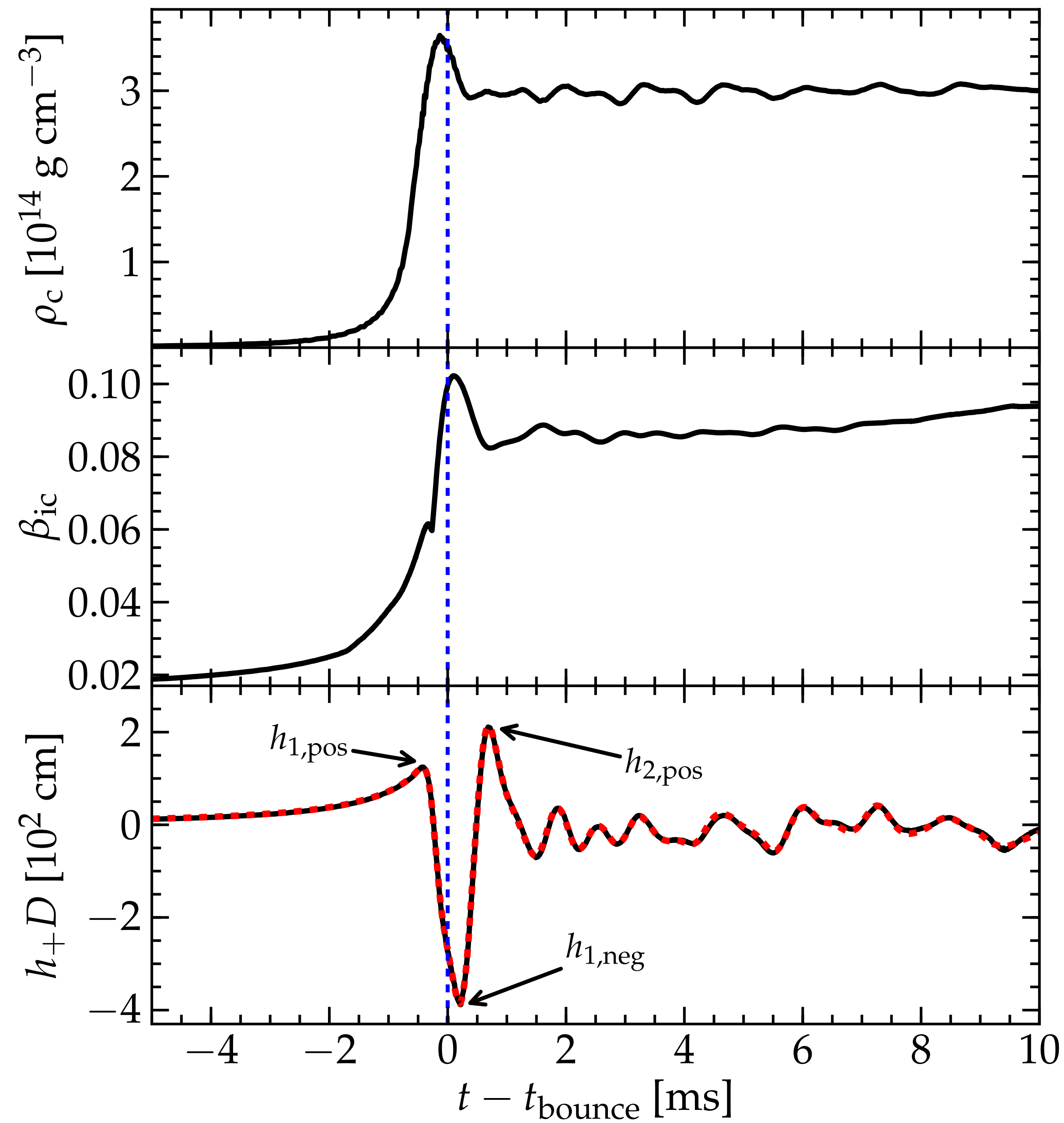


FIG. 2: Time evolution of the central density (top panel), β_{ic} (center panel), and GW strain (bottom panel; rescaled by source distance D) in model $A3O6$.

[Abdikamalov et al. arXiv:1311.3678 (2013)]

Supernovae

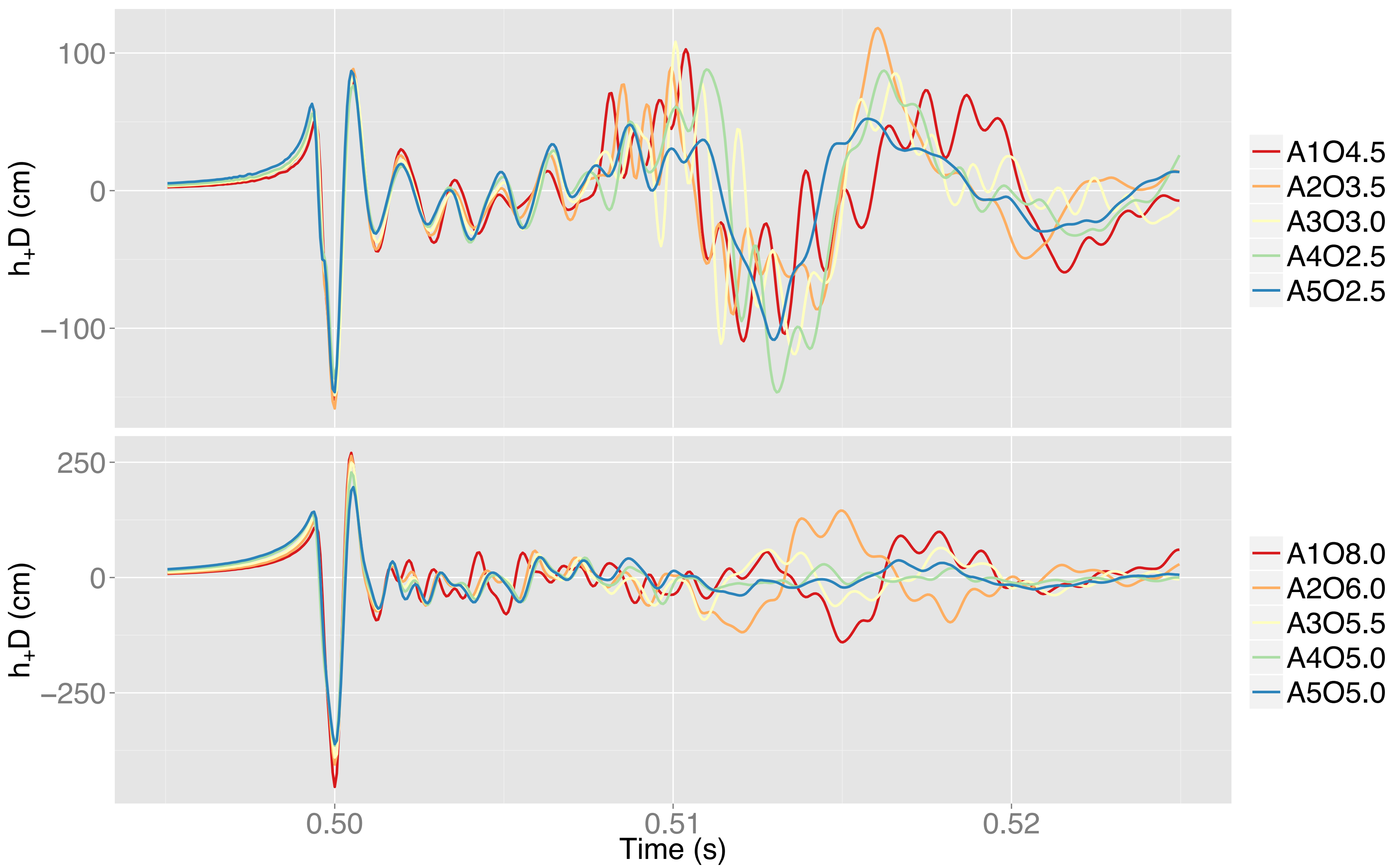


Figure 1: A snapshot of the Abdikamalov *et al* [45] catalogue. The top panel shows the GW strain (scaled by source distance) for five models with different levels of precollapse differential rotation (from strongest differential rotation $A1$ to weakest $A5$), each with $\beta_{ic,b} \sim 0.03$ (i.e., slowly rotating progenitors). The bottom panel is the same, but for rapidly rotating progenitors with $\beta_{ic,b} \sim 0.09$.

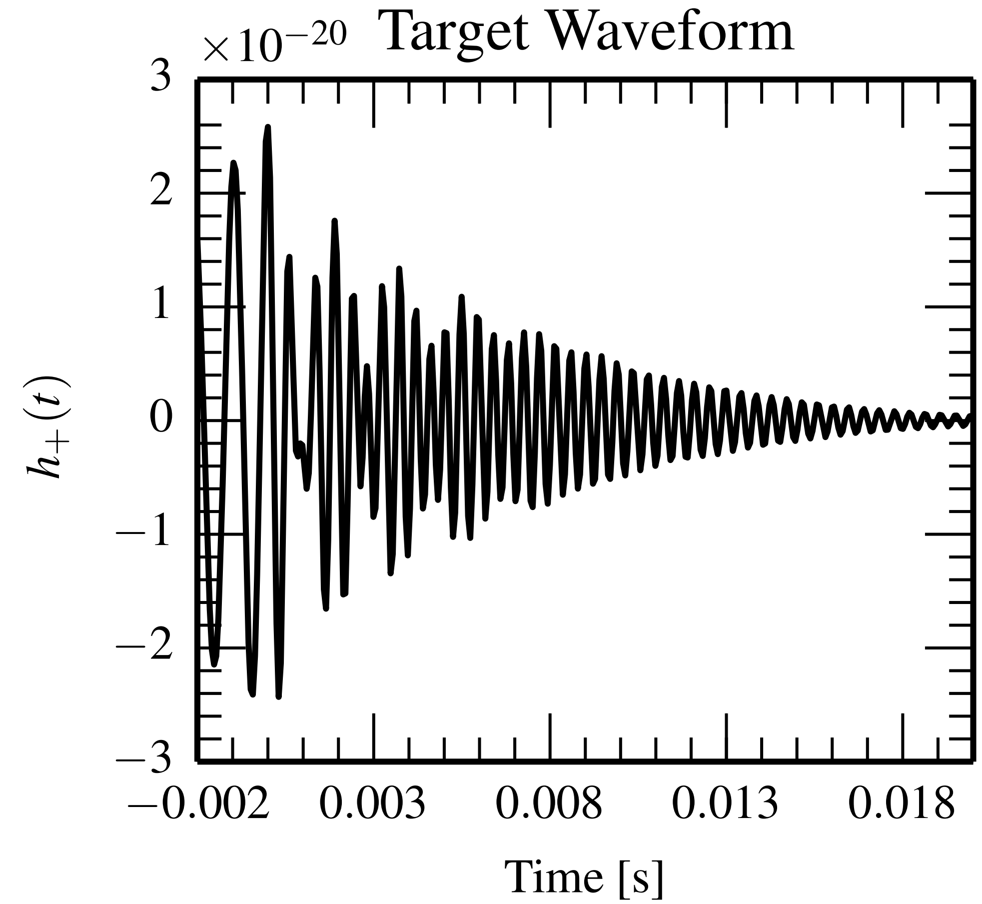
[Edwards et al. arXiv:1407.7549 (2014)]

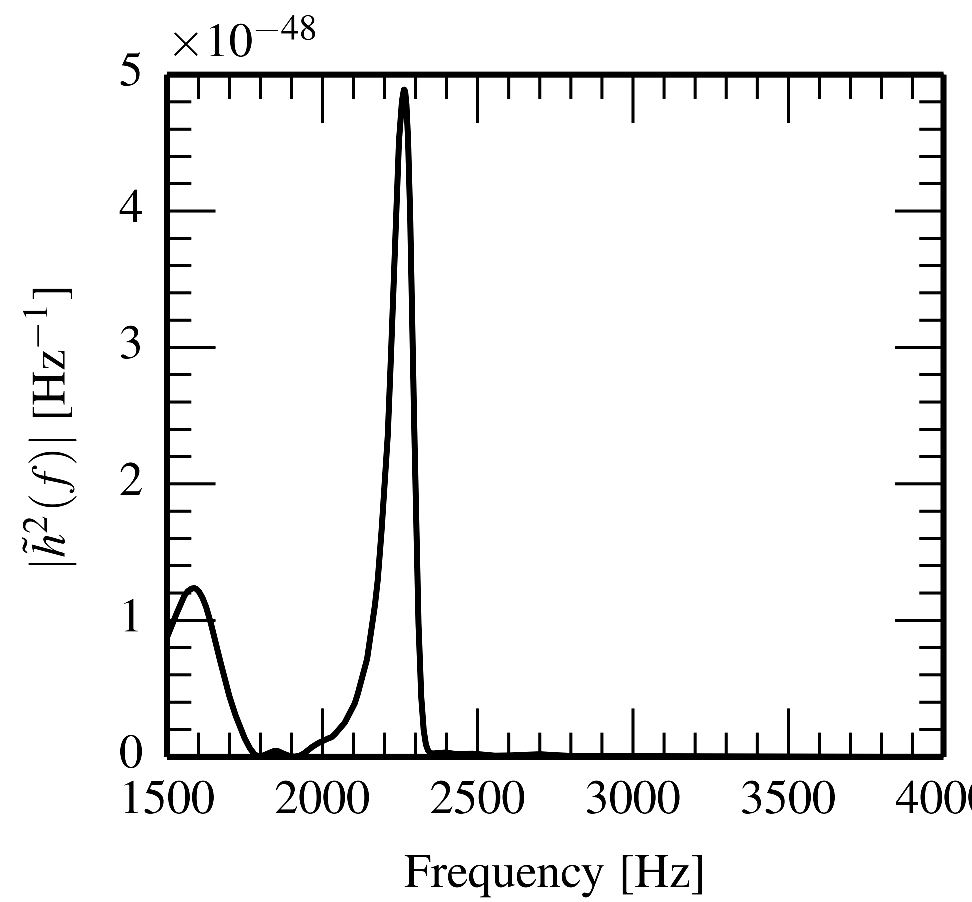
Post-merger neutron star

- Un-modeled, high-frequency search
- Mass-dependent relationship:

$$f_{peak} \Rightarrow R_{1.6}$$

  - Peak frequency
  - Radius of a fiducial 1.6M$_\odot$ neutron star
- Neutron start Equation of State signature





[Clark et al. arXiv:1406.5444 (2014)]

Bursts

- Gamma-Ray Bursts (see the talk by Michał Wąs)
- Do Intermediate Mass Black Holes exist?

(Aasi et al. Phys. Rev. D 89, 122003 (2014))

- Targets:
    - Intermediate mass ratio inspirals
    - Eccentric binary black holes
    - Chirp mass reconstruction

Bursts

- **Un-modelled** searches: the unexpected in gravitational-wave astronomy !
    - Flux, amplitude, frequency profile, duration, sky localisation, polarisation, …

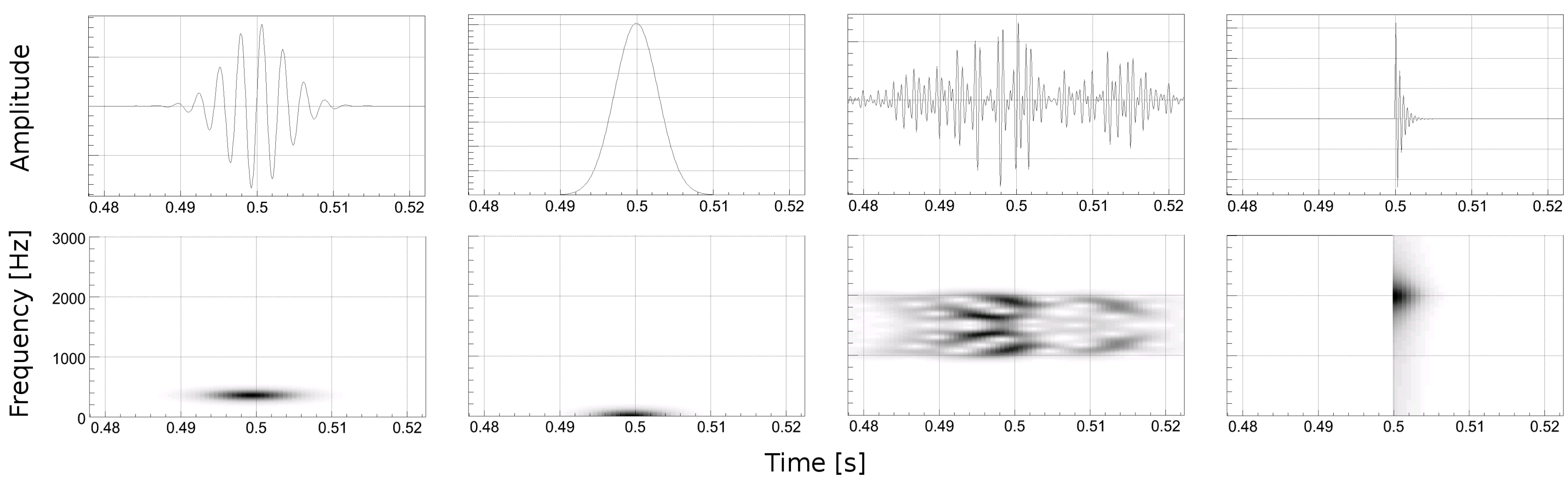


FIG. 2: Representative waveforms injected into data for simulation studies. The top row is the time domain and the bottom row is a time-frequency domain representation of the waveform. From left to right: a 361 Hz $Q = 9$ sine-Gaussian, a $\tau = 4.0$ ms Gaussian waveform, a white noise burst with a bandwidth of 1000–2000 Hz and characteristic duration of $\tau = 20$ ms and, finally, a ringdown waveform with a frequency of 2000 Hz and $\tau = 1$ ms.

[Abadie et al. Phys. Rev. D 85,122007 (2012)]