

# Direct observation of gravitational waves from the merger and inspiral of two black holes

**Alex Nielsen**  
**Max Planck Institute (AEI) – Hanover**  
**on behalf of the LVC**  
**EMMI/GSI Darmstadt**  
**15th November 2016**



MAX-PLANCK-GESELLSCHAFT





# What was seen 2015

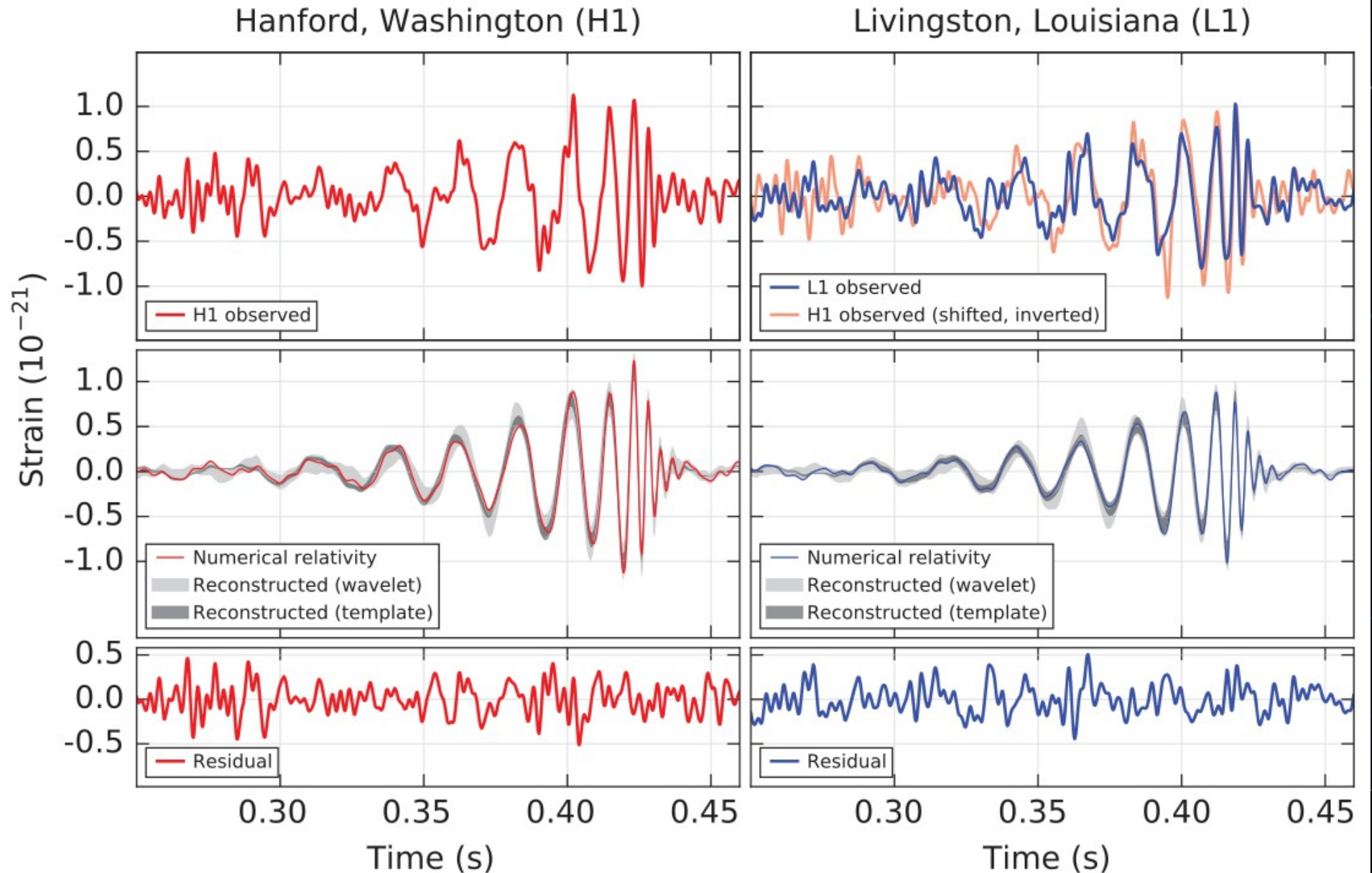


Fig 1. (top) Abbott et al. PRL 116 (2016) 6, 061102



# Gravitational waves

- What are gravitational waves?
- Why are they detectable now?
- What have we learnt?
- Where are we going in the future?



# What are gravitational waves?

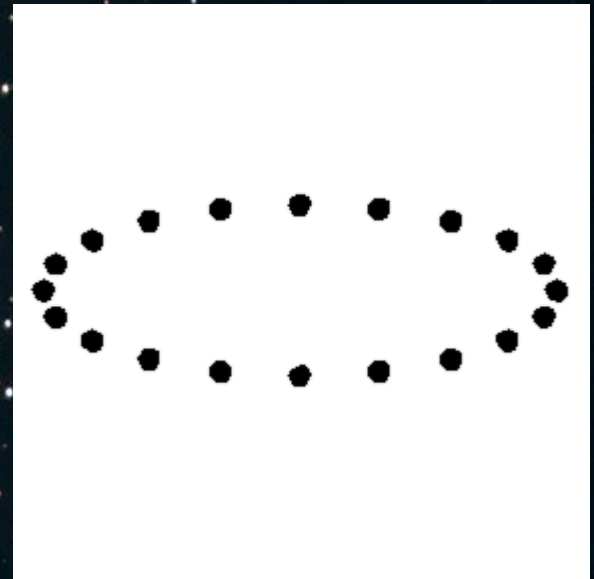
$$G_{ab} = \frac{8\pi G}{c^4} T_{ab} \quad \text{Einstein equation}$$

Small linear perturbation  $g_{ab} = \eta_{ab} + h_{ab}$

$$\nabla^2 \bar{h}_{ab} = 0 \quad \text{Wave equation}$$

$$Q_{ij} \equiv \int d^3x \rho \left( x_i x_j - \frac{1}{3} r^2 \delta_{ij} \right)$$

Einstein quadrupole formula  $h_{ij} = \frac{2}{d_L} \frac{G}{c^4} \frac{d^2 Q_{ij}}{dt^2}$





# Einstein 1916

688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

## Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. EINSTEIN.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die  $g_{\mu\nu}$  in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable  $x_4 = it$  aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$

definierten Größen  $\gamma_{\mu\nu}$ , welche linearen orthogonalen Transformationen gegenüber Tensorcharakter besitzen, gegen 1 als kleine Größen behandelt werden können, deren Quadrate und Produkte gegen die ersten Potenzen vernachlässigt werden dürfen. Dabei ist  $\delta_{\mu\nu} = 1$  bzw.  $\delta_{\mu\nu} = 0$ , je nachdem  $\mu = \nu$  oder  $\mu \neq \nu$ .

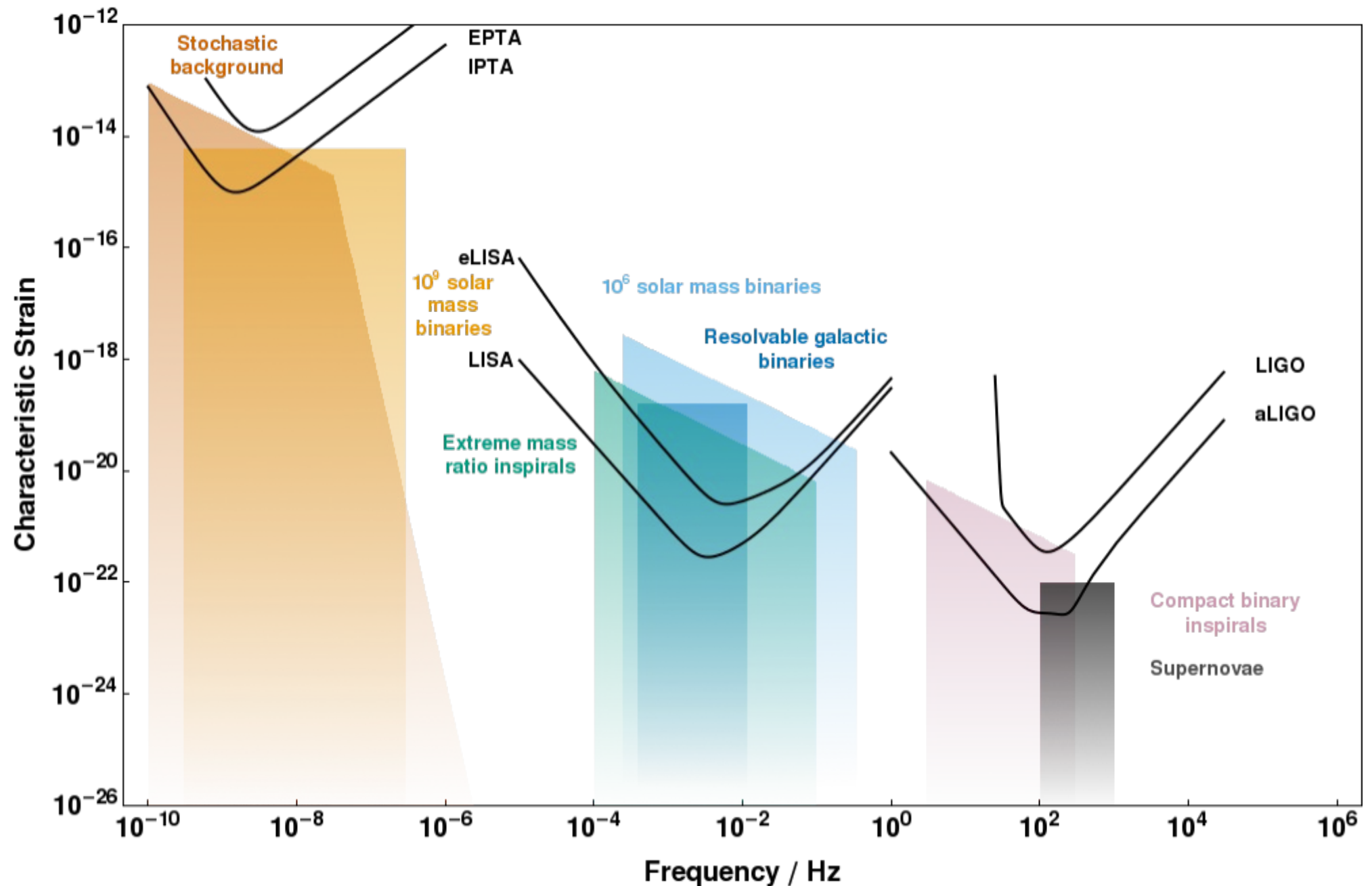
Wir werden zeigen, daß diese  $\gamma_{\mu\nu}$  in analoger Weise berechnet werden können wie die retardierten Potentiale der Elektrodynamik. Daraus folgt dann zunächst, daß sich die Gravitationsfelder mit Lichtgeschwindigkeit ausbreiten. Wir werden im Anschluß an diese allgemeine Lösung die Gravitationswellen und deren Entstehungsweise untersuchen. Es hat sich gezeigt, daß die von mir vorgeschlagene Wahl des Bezugssystems gemäß der Bedingung  $g = |g_{\mu\nu}| = -1$  für die Berechnung der Felder in erster Näherung nicht vorteilhaft ist. Ich wurde hierauf aufmerksam durch eine briefliche Mitteilung des Astronomen DE SITTER, der fand, daß man durch eine andere Wahl des Bezugssystems zu einem einfacheren Ausdruck des Gravitationsfeldes eines ruhenden Massenpunktes gelangen kann, als ich ihn früher gegeben hatte<sup>1</sup>. Ich stütze mich daher im folgenden auf die allgemein invarianten Feldgleichungen.

<sup>1</sup> Sitzungsber. XLVII, 1915, S. 833.

*“...so sieht man, daß A (die Ausstrahlung des Systems durch Gravitationswellen pro Zeiteinheit) in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.”*

A. Einstein, Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften (Berlin), 1916 688

# Full GW spectra



Source: Wikimedia; C. Moore, R. Cole and C. Berry

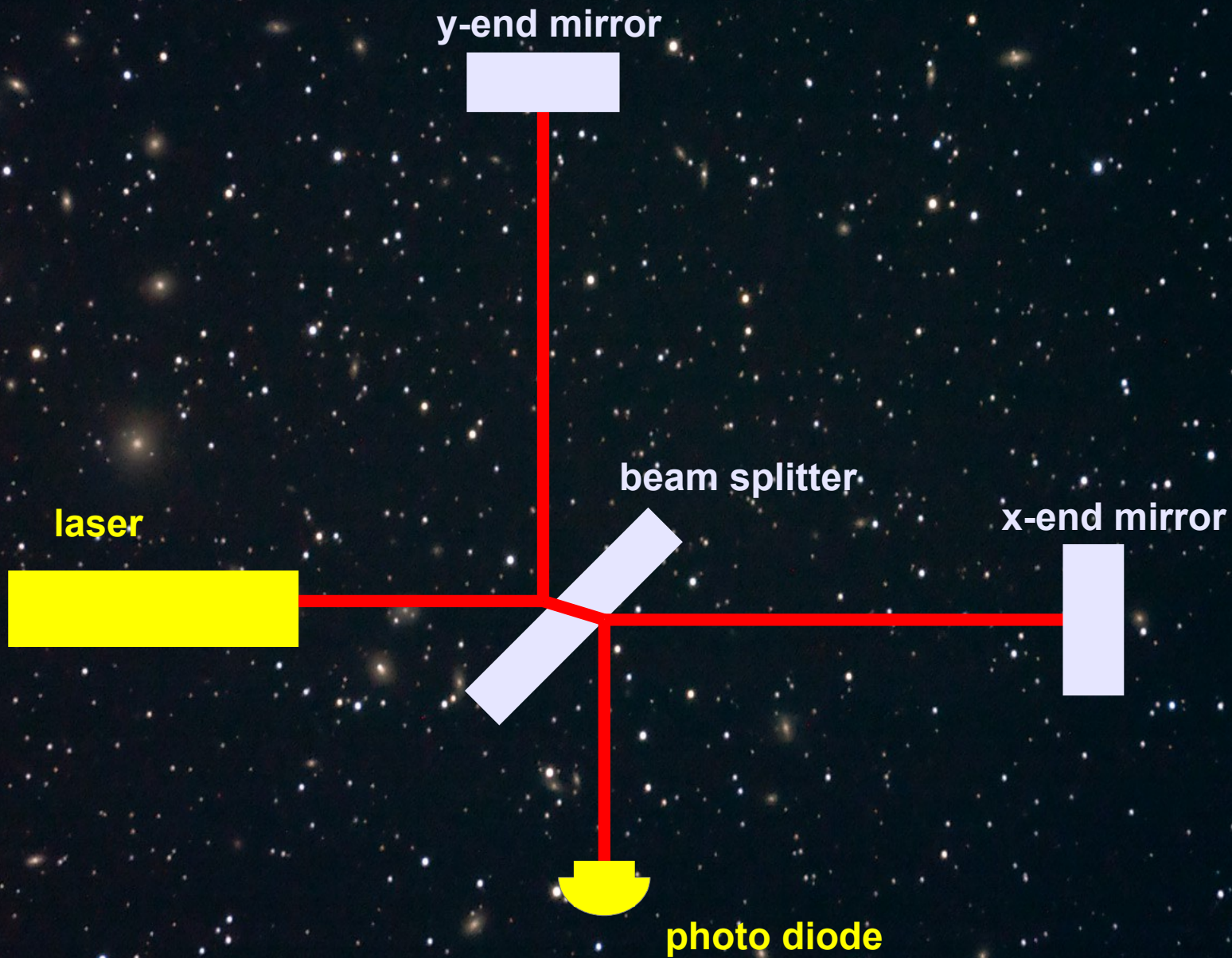




Source: LIGO Lab

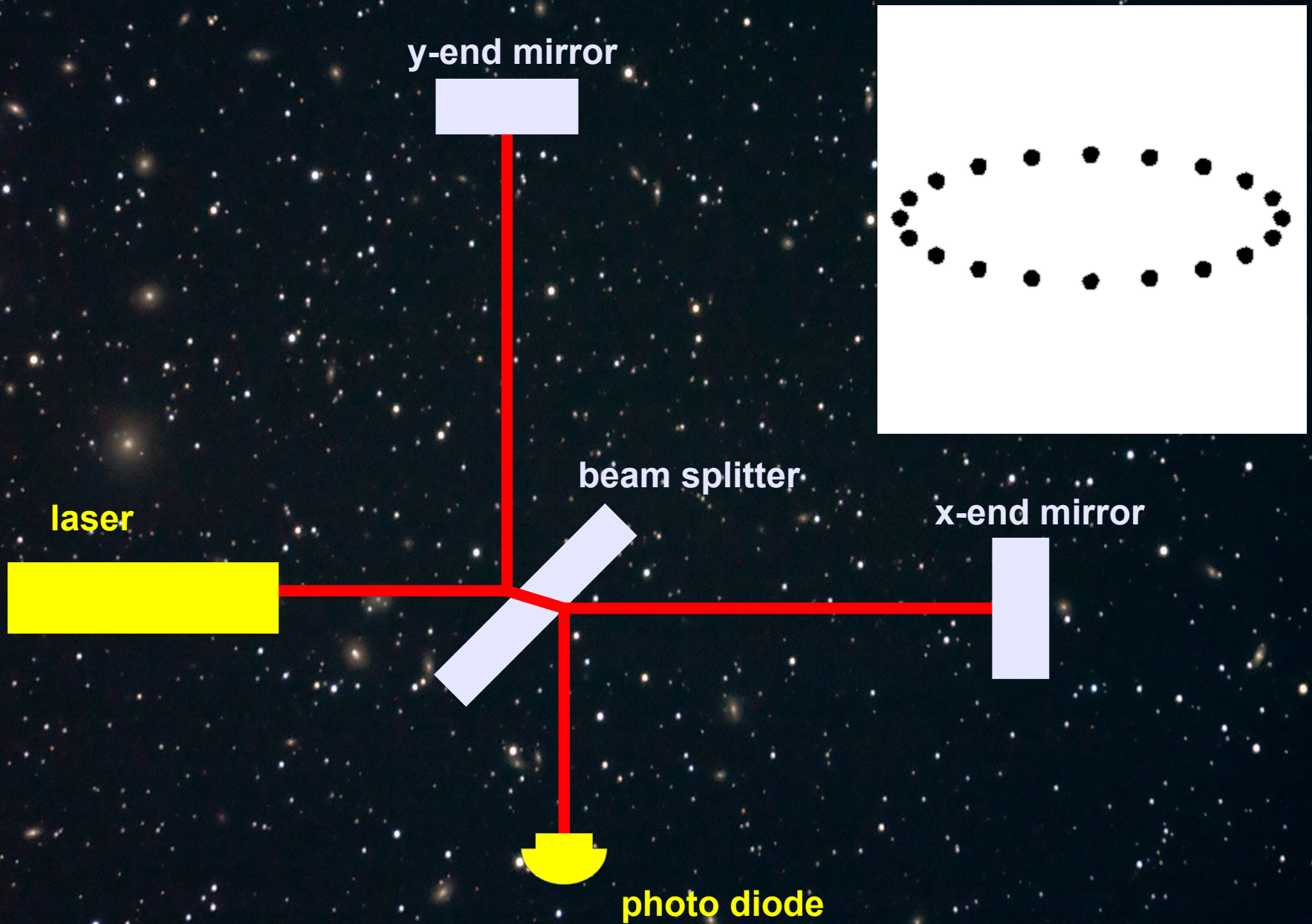


# Interferometers





# Interferometers





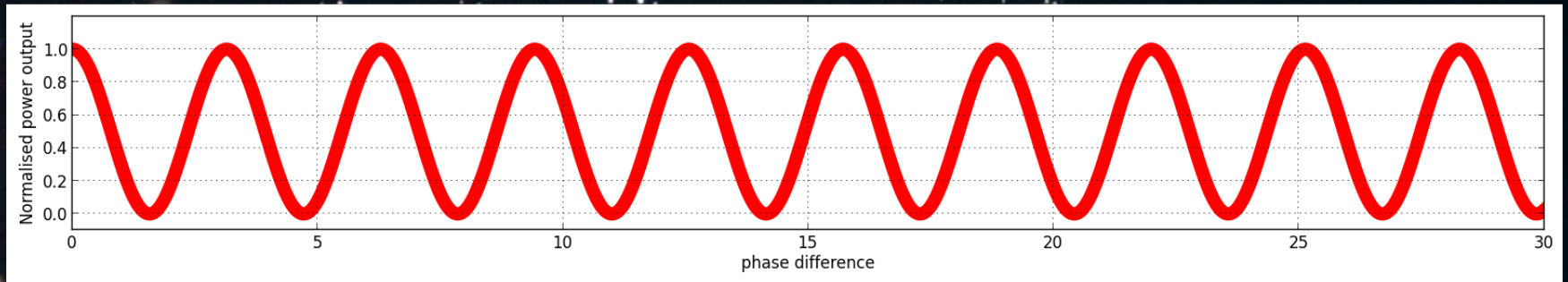
# How LIGO really works

- **Long arms:** Earth's curvature over 4km is  $\sim 1\text{m}$
- **High vacuum:** One trillionth atm,  $10^{-9}$  torr in  $10,000\text{m}^3$
- **High power laser:** 20W 1064 nm Nd:YAG (neodymium-doped yttrium aluminium garnet) (will be up to 200W)
- **Higher power beams:** Fabry-Perot cavities, 100kW, power and signal recycling



# Reading between the lines

Interference pattern:  $P_{out} = P_{max} \cos^2 \Delta \phi$



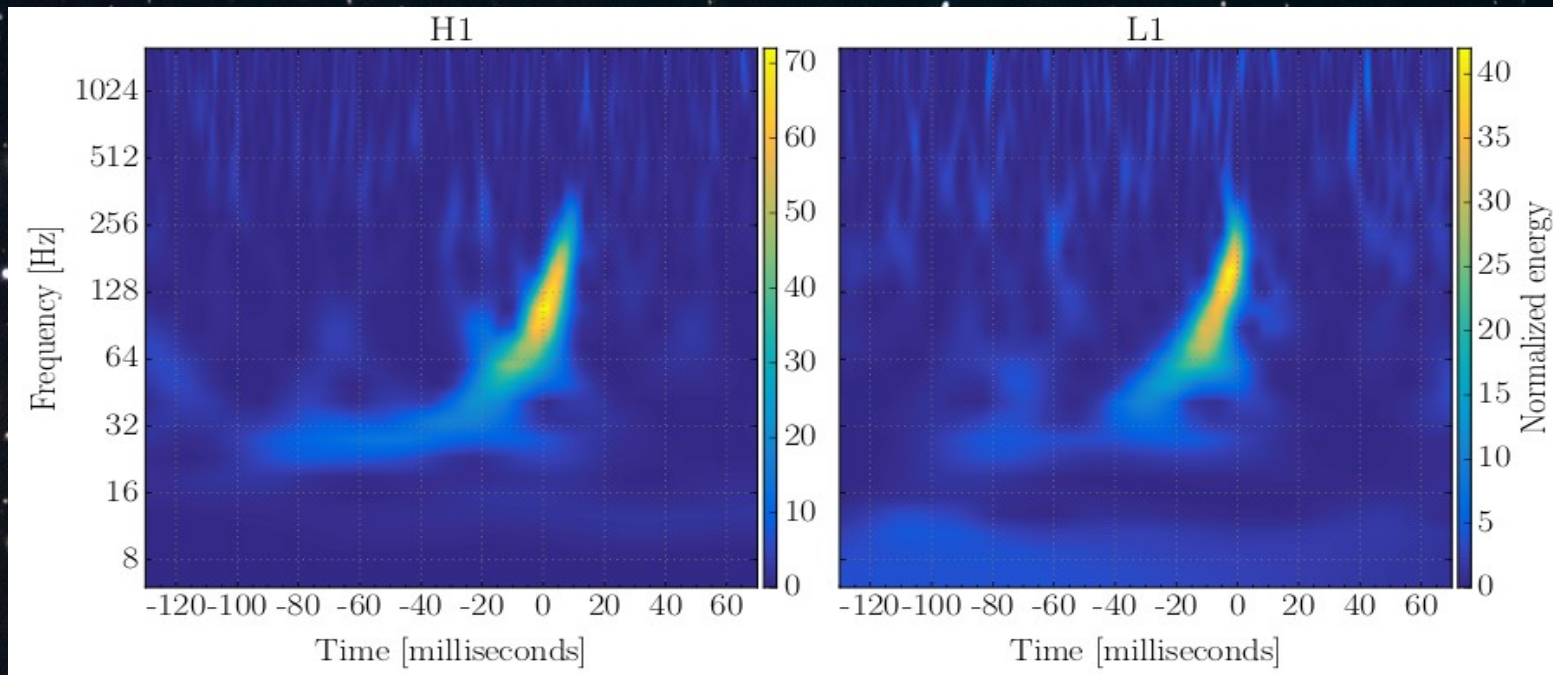
$\Delta \phi = \frac{\pi}{2} + B \frac{c \Delta T}{\lambda}$  : Accumulated phase difference

Displacement sensitivity:

$$\Delta L = \frac{\lambda}{B} \sqrt{\frac{P_{out}}{P_{max}}}$$



# What was seen II



*Fig. 10 Abbott et al. CQG33 (2016) 134001*

**Frequency ~30 Hz to ~250 Hz**

**Wavelength ~10,000 km to ~1,000 km**

**Visible duration ~ 0.1 secs**

**Increasing amplitude, increasing frequency = chirp**

**0.007 secs earlier in Livingston**

**The same signal in both detectors!**



# LVT151012

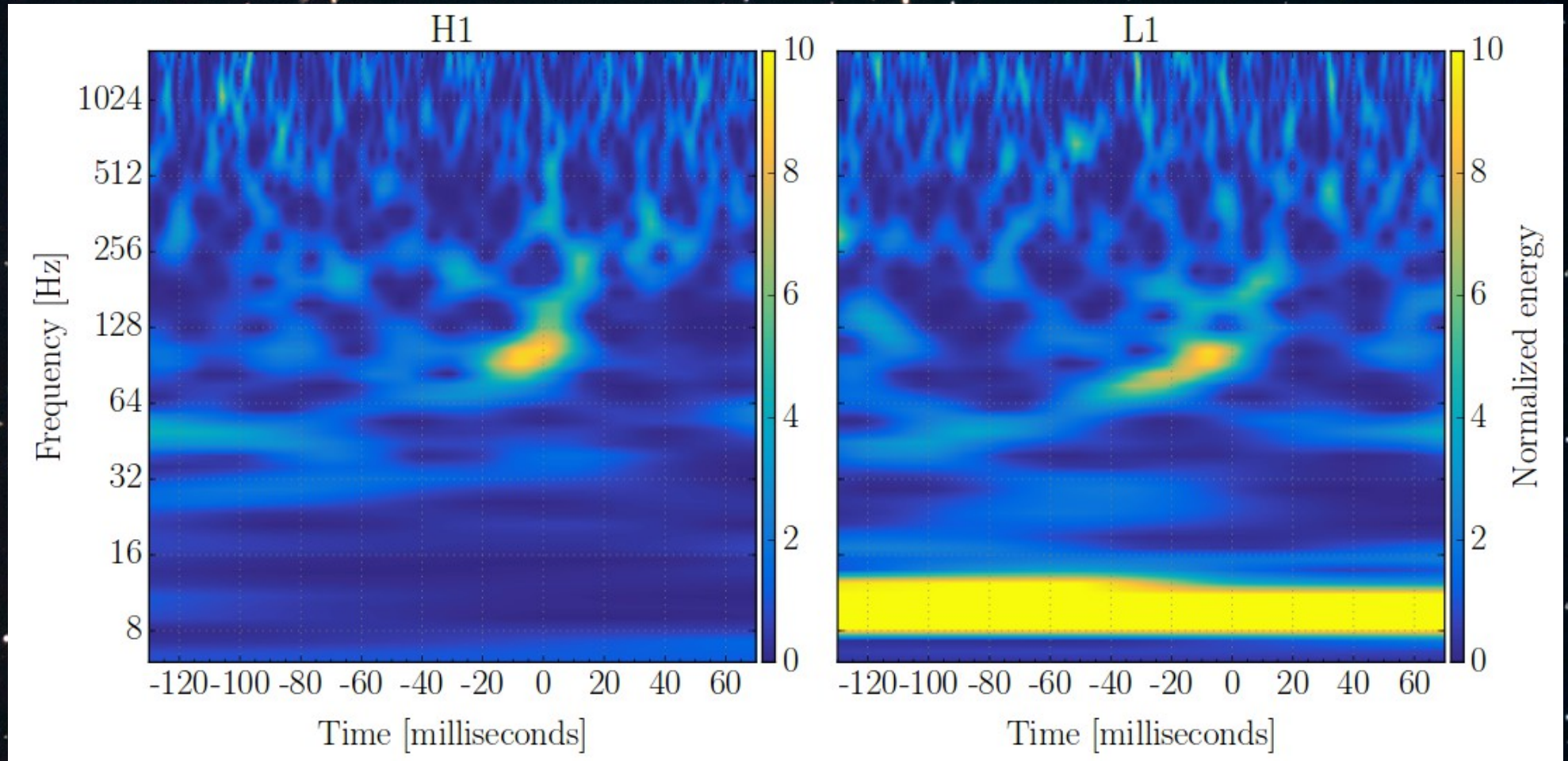


Fig. 13 Abbott et al. CQG33 (2016) 134001

**False Alarm Rate, 1 per 2.3 years**



[illegible]

<http://pem.ligo.org/>



# Non-Gaussian transients

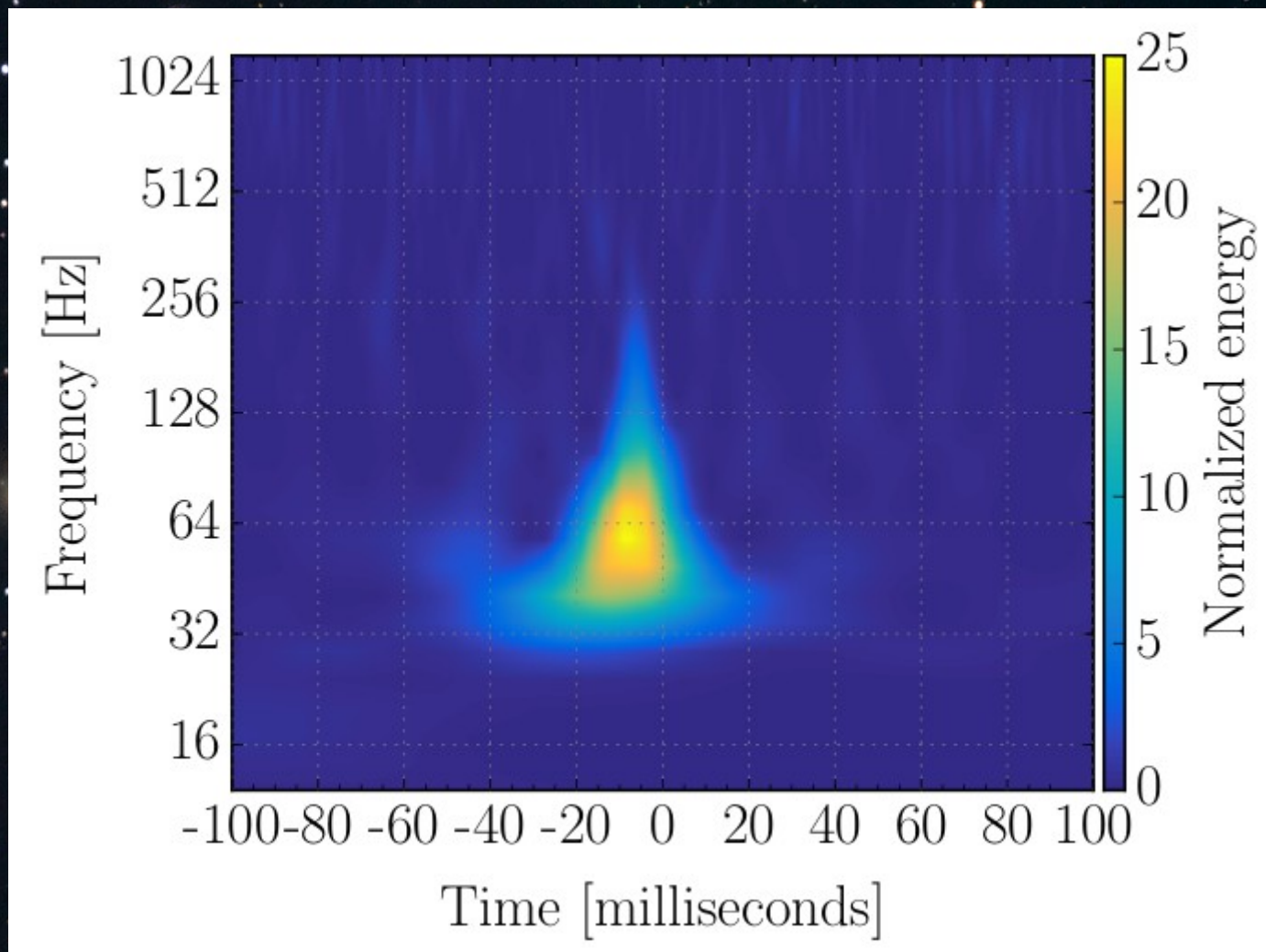


Fig. 3 Abbott et al. CQG33 (2016) 134001



# Search significance

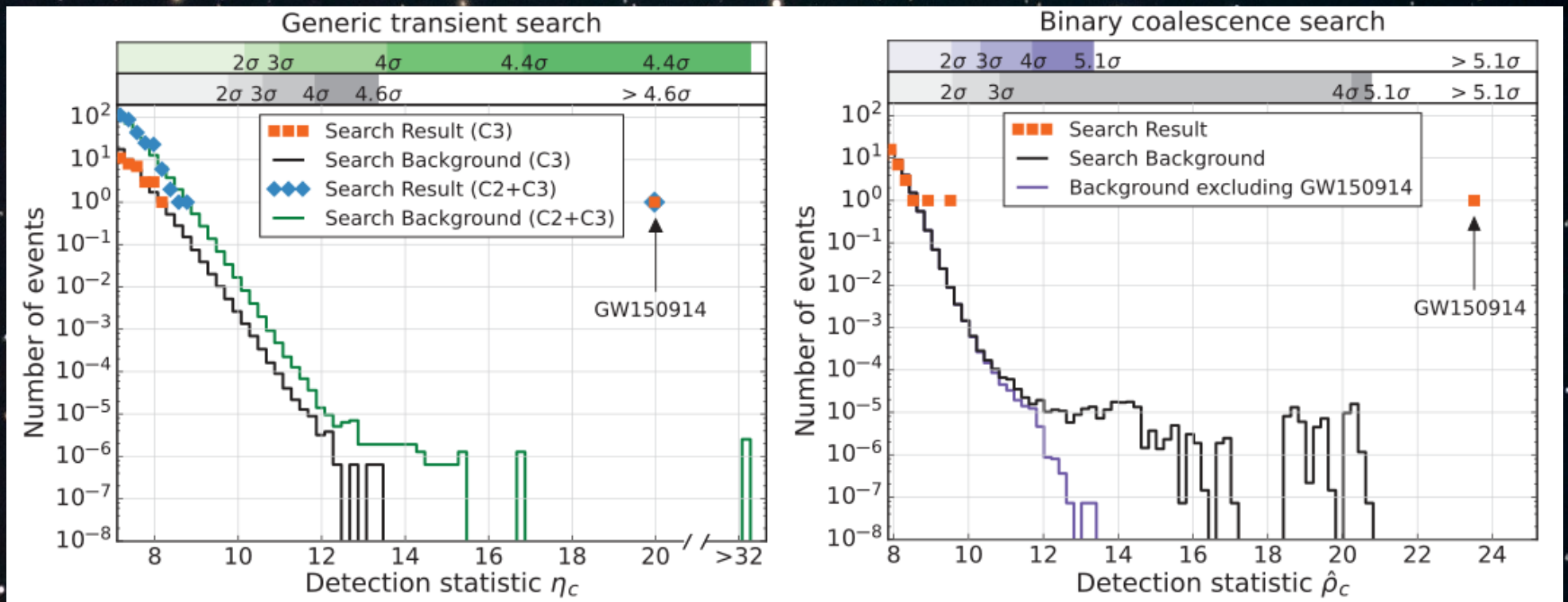


Fig 4 Abbott et al. PRL 116 (2016) 6, 061102



# Binary inspiral

- Quadrupole formula

$$\frac{dE_{GW}}{dt} = \frac{G}{c^5} \frac{d^3 Q_{ij}}{dt^3} \frac{d^3 Q_{ij}}{dt^3}$$

- Newtonian order, chirp mass

$$f(t) = \frac{5^{3/8}}{8\pi} \left( \frac{c^3}{GM_c} \right)^{5/8} (t_0 - t)^{-3/8}$$

- Increase of frequency determined by “chirp mass”

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



# What was seen

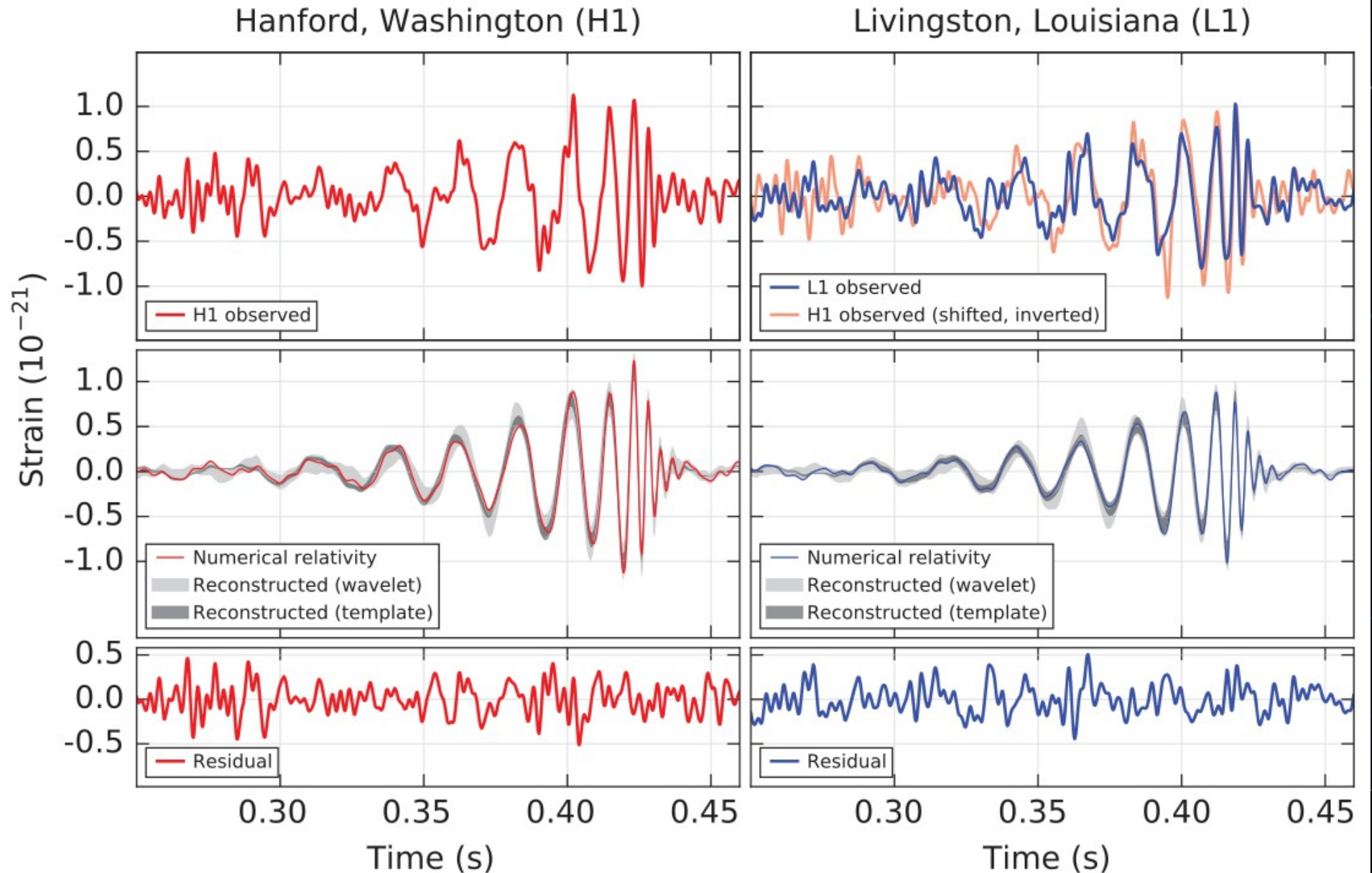


Fig 1. (top) Abbott et al. PRL 116 (2016) 6, 061102



# Three binary black hole events

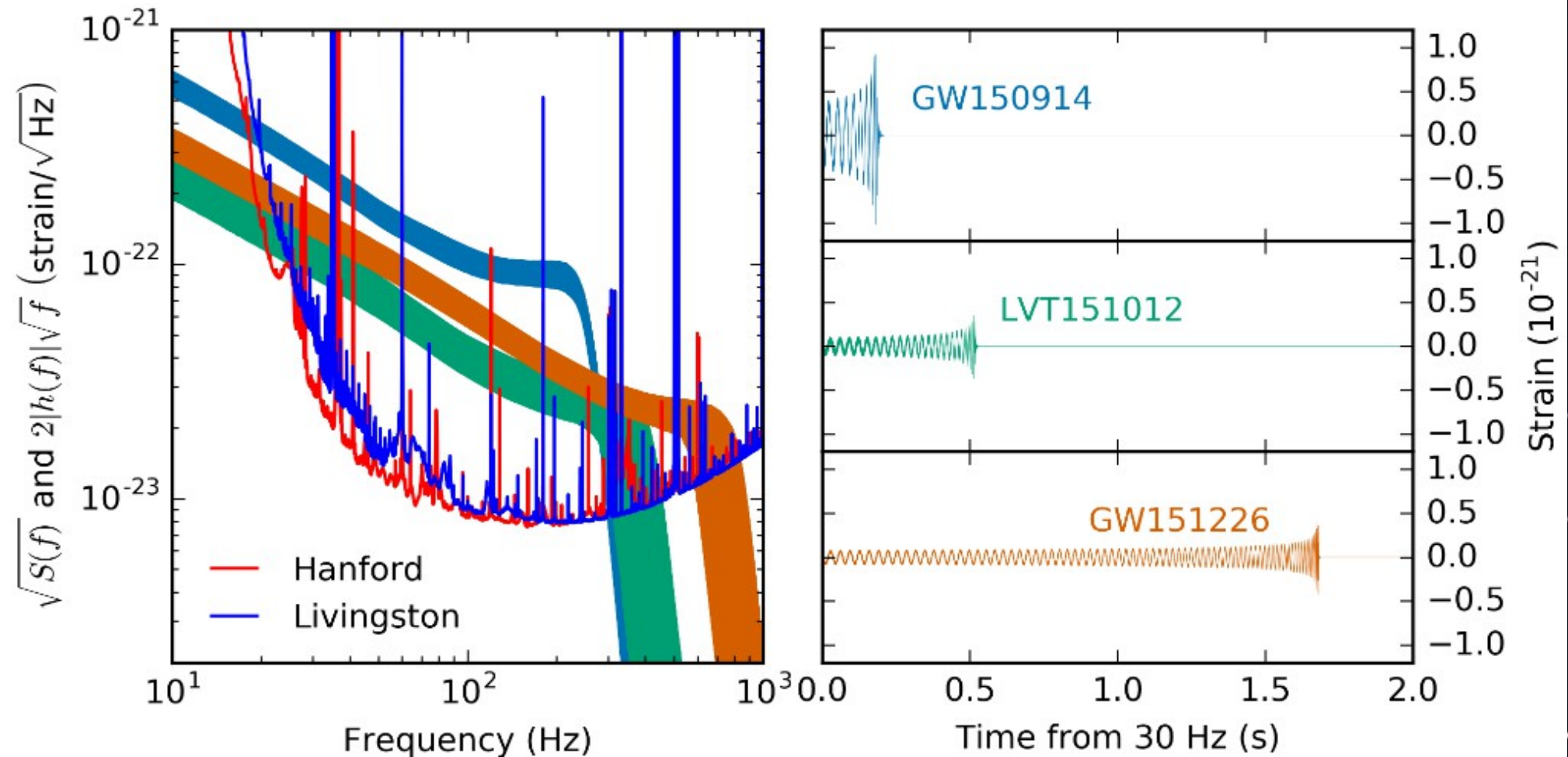


Fig 1 of Abbott et al. 1606.04856



# Source parameters

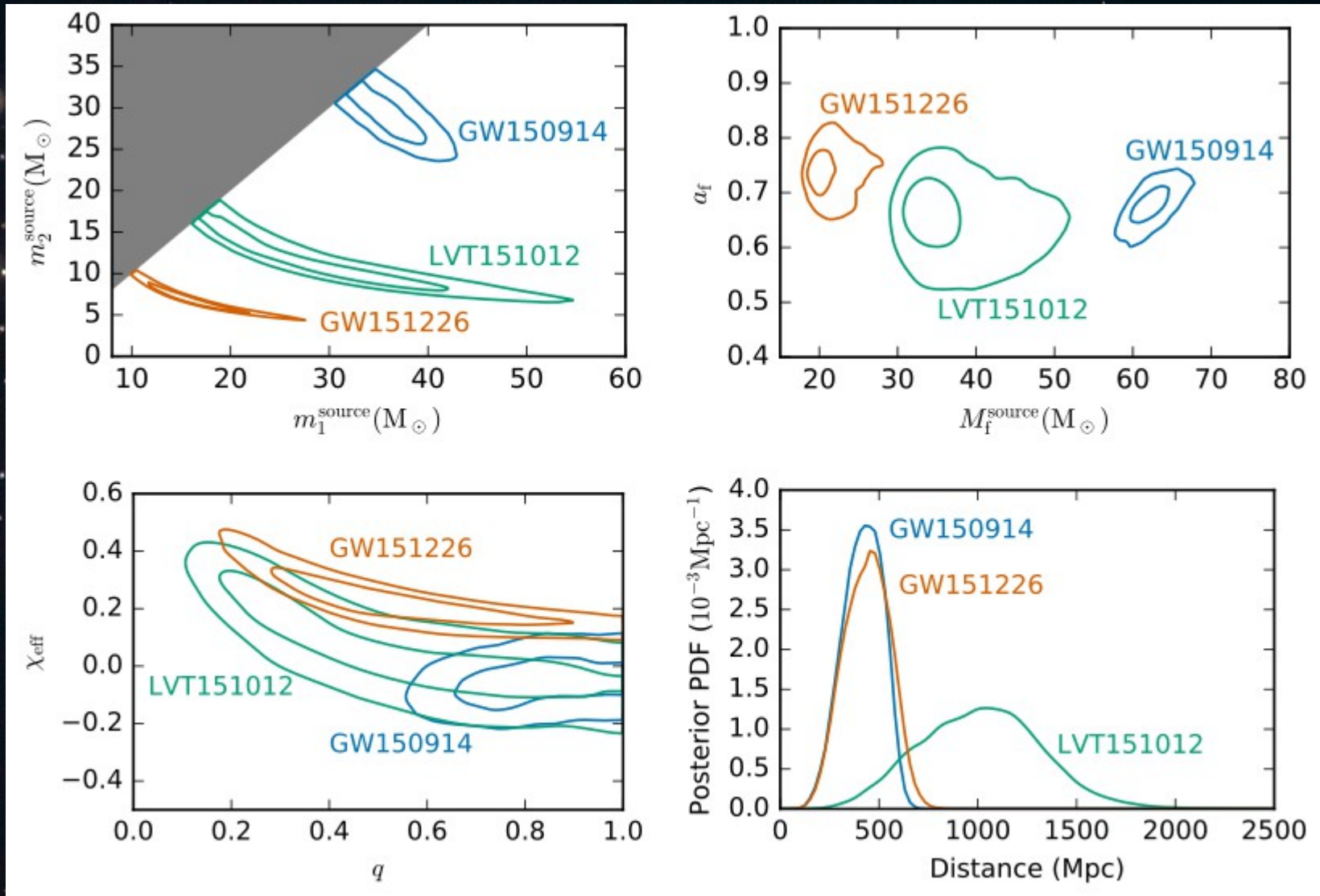
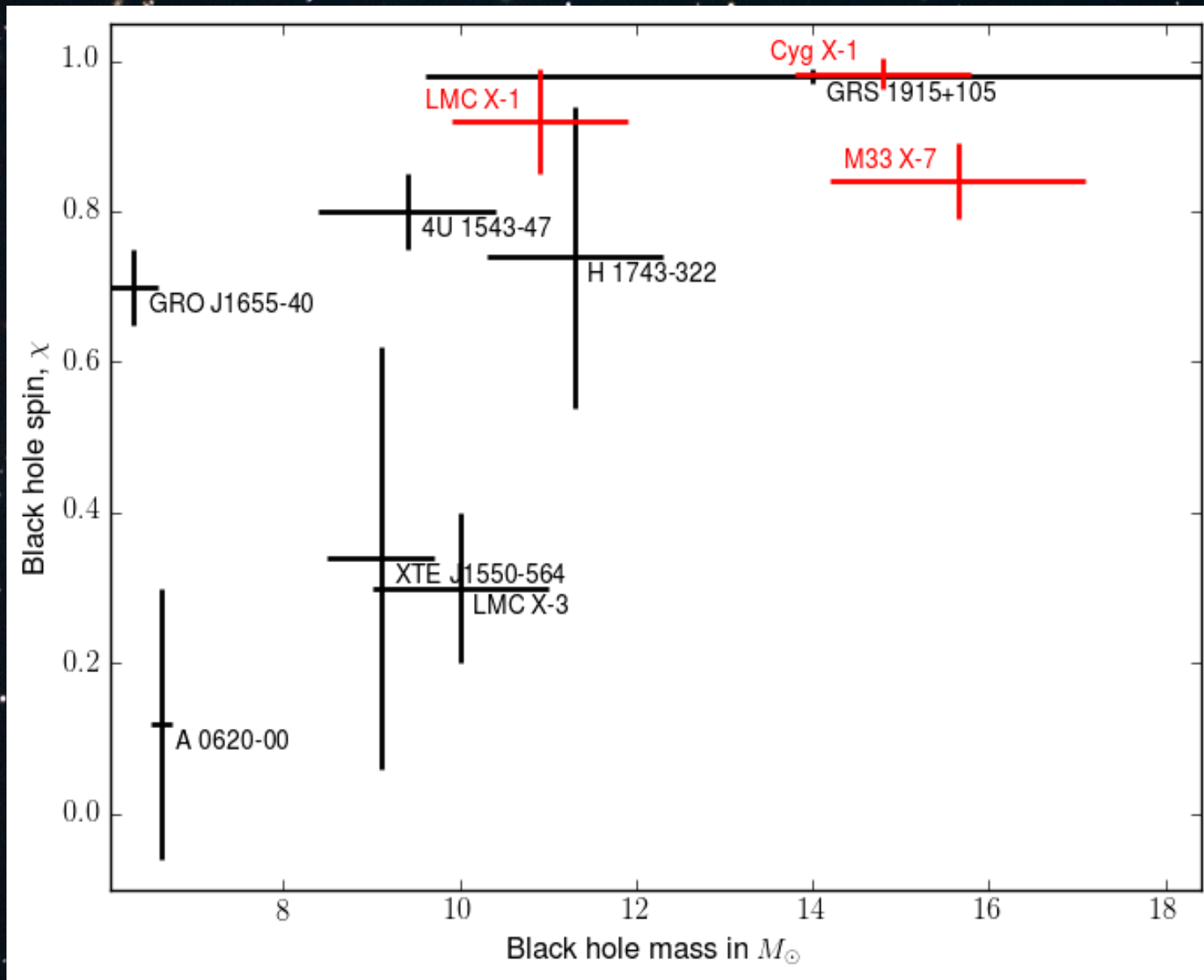


Fig 4 of Abbott et al. 1606.04856

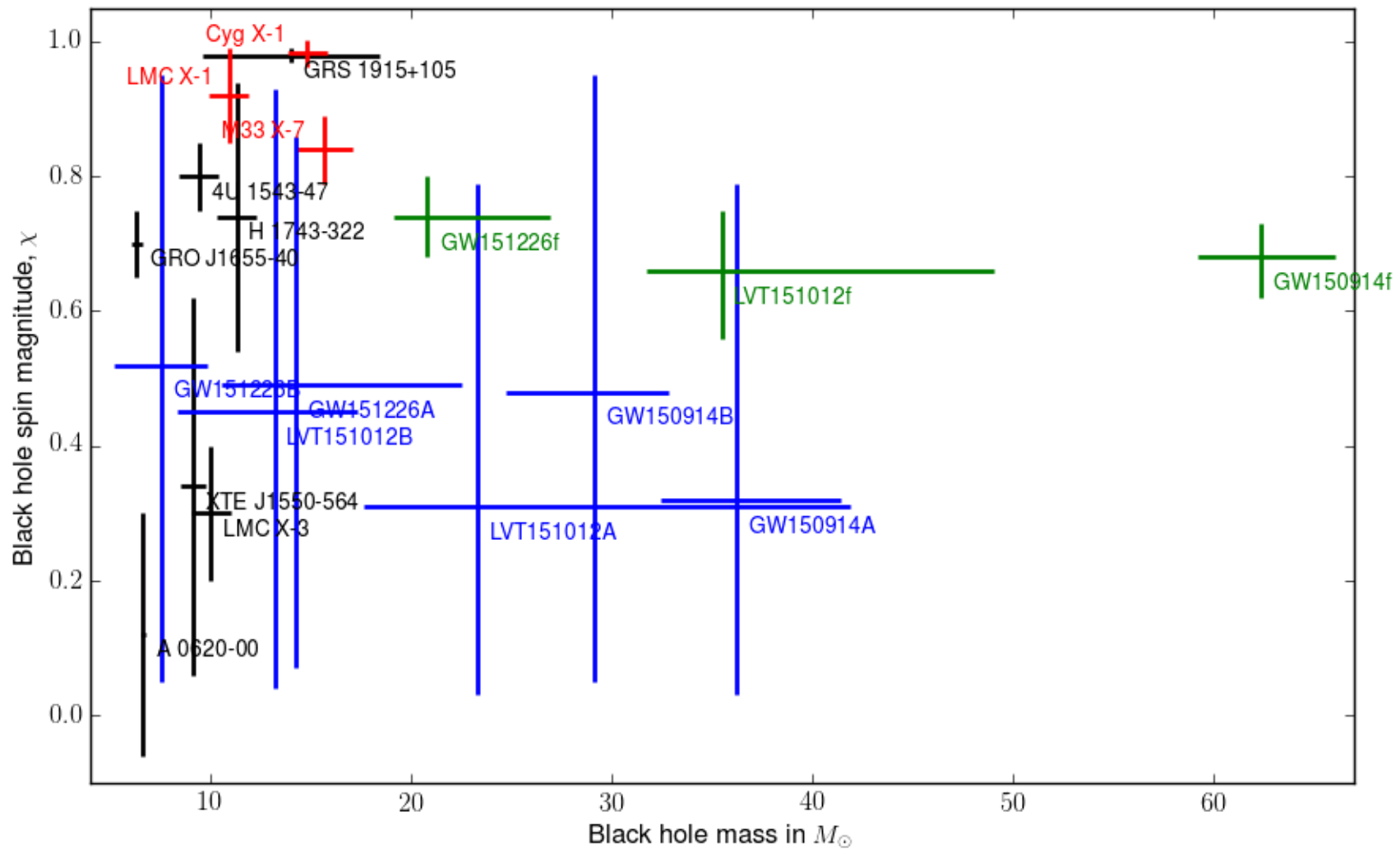


# X-ray binaries masses and spin





# X-ray + GW masses and spins





# Astrophysics

- Formation of heavy black holes – **direct collapse?**
- Time to merge from 1AU by GW alone,  
~ 100x age of universe - **common envelope?**
- Formation of binary still open – **cluster or field?**
- Peak energy flux  $200^{+30}_{-20}$  solar masses per second



# Signal consistency test

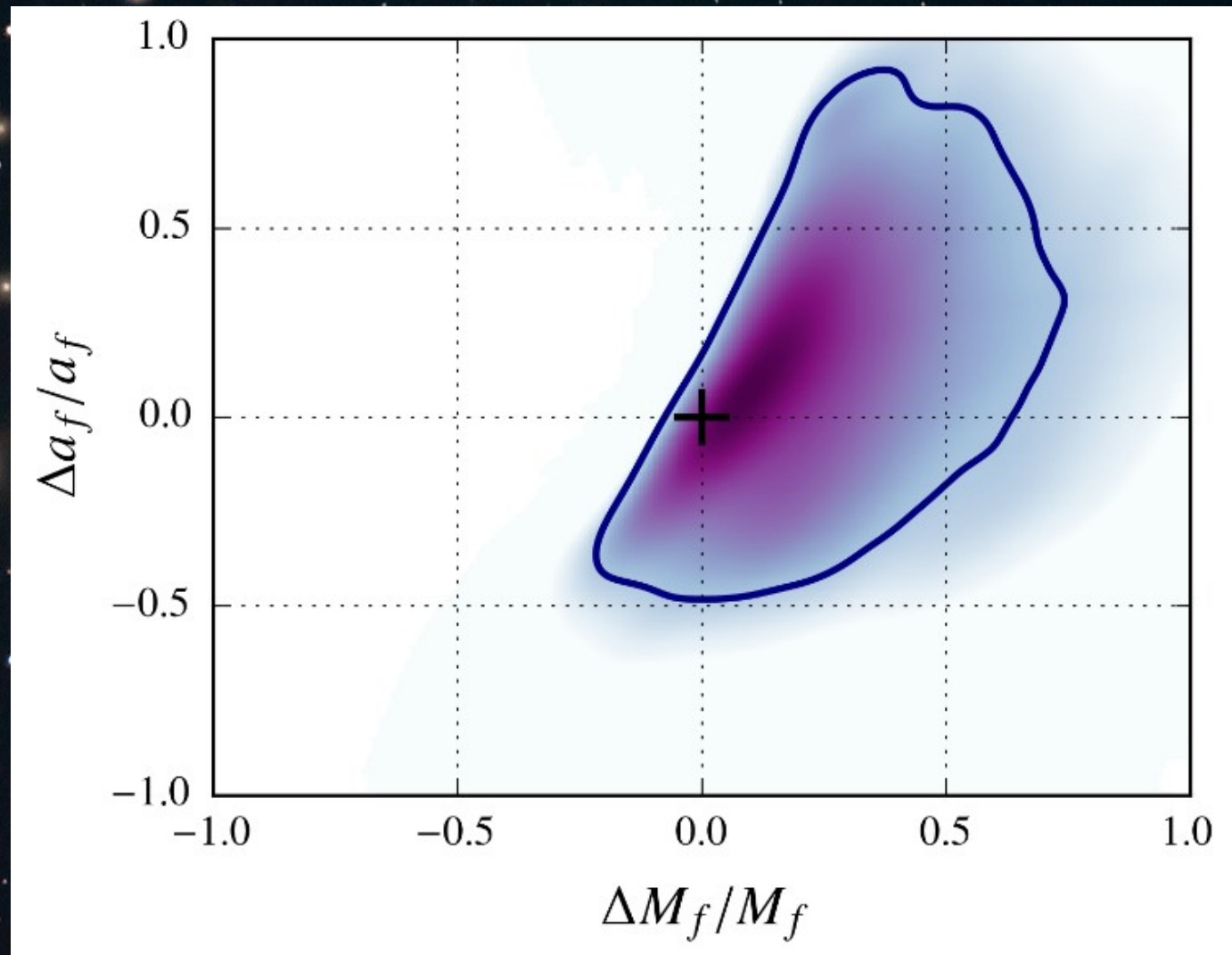
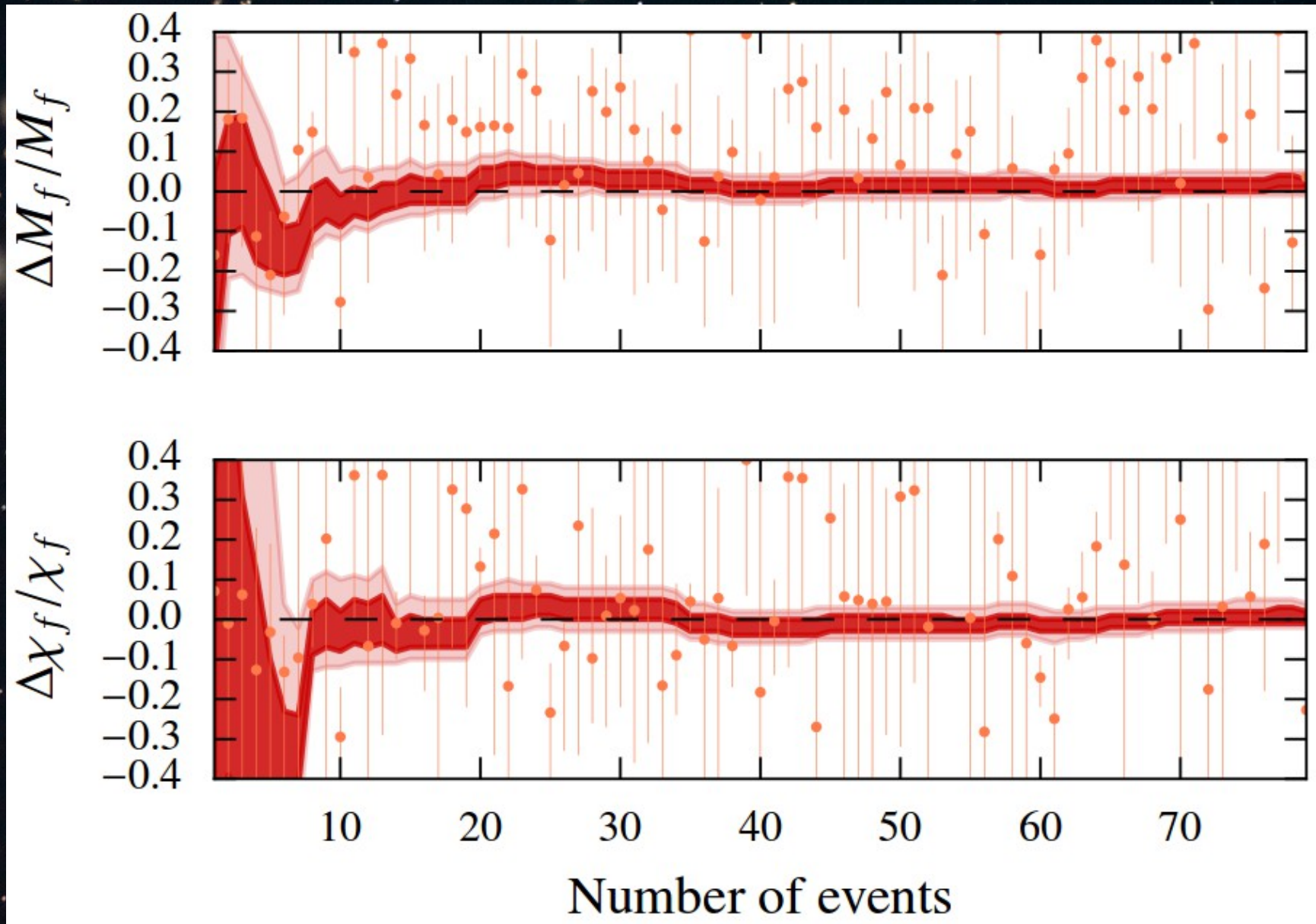


Fig. 3 (bot) of Abbott et al. PRL 16 (2016) 221101

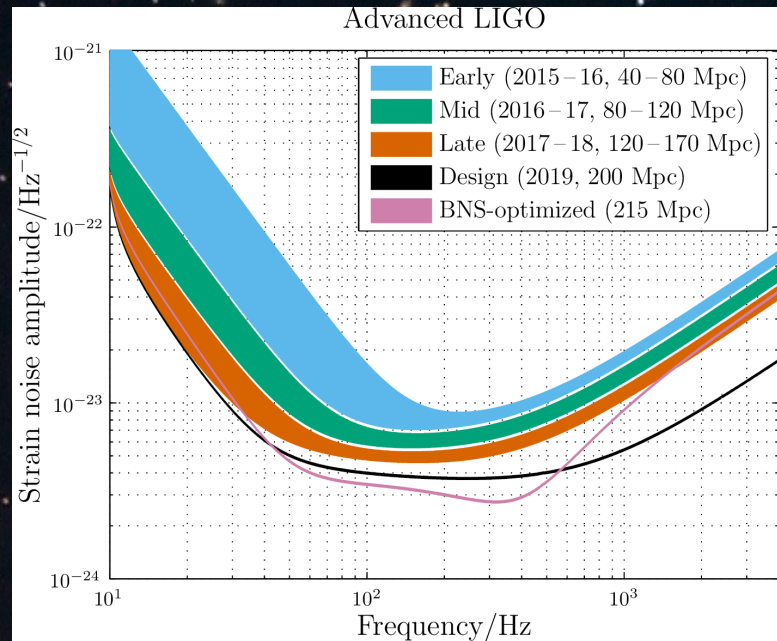


# IMR consistency going forward





# Event rate estimates



**Ten or more  
detections by the end  
of O2 is quite likely**

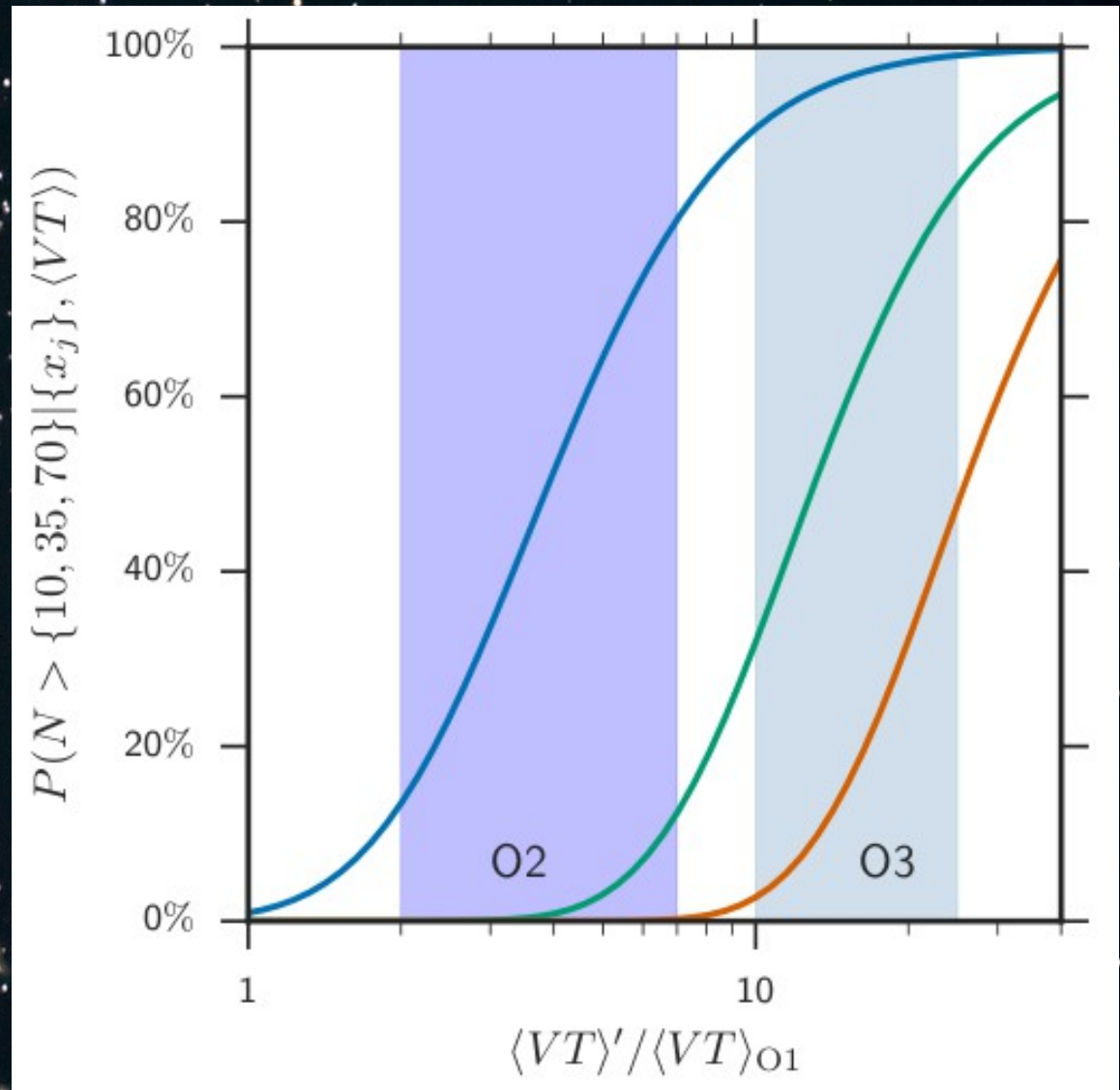
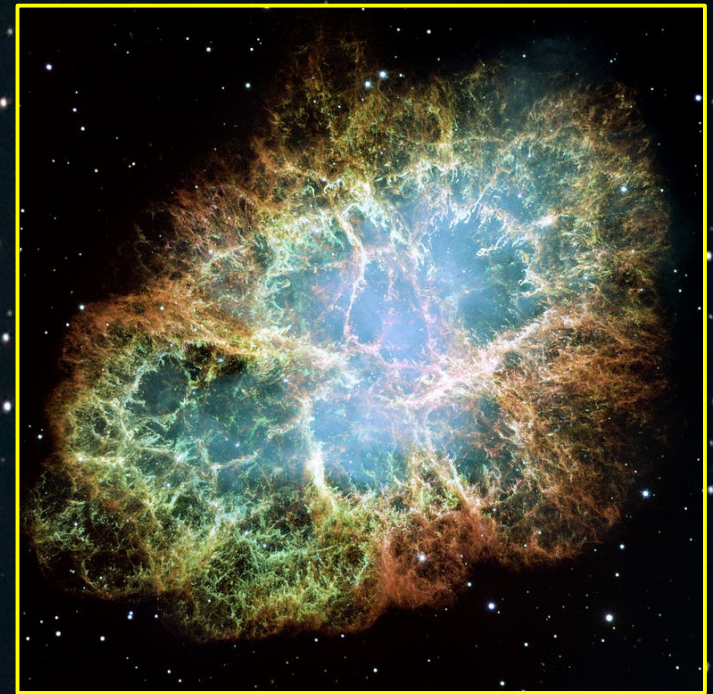


Fig 12 of Abbott et al. 1606.04856



# Other potential aLIGO sources

- Neutron stars – tidally disrupting
- Deformed rotating neutron stars
- Galactic supernovae
- Astrophysical background
- Cosmic strings
- First-order phase transitions
- Inflationary particle production
- Non-perturbative preheating
- Inflationary vacuum fluctuations



Source: NASA/HST



# Squeezed light

- Heisenberg uncertainty in amplitude, phase
- Inject phase-locked squeezed vacuum state into output port
- Periodically poled potassium titanyl phosphate
- Hoped for ~30% gain in sensitivity



# Squeezed light

- Heisenberg uncertainty in amplitude, phase
- Inject phase-locked squeezed vacuum state into output port
- Periodically poled potassium titanyl phosphate
- Hoped for ~30% gain in sensitivity

PRL 117, 110801 (2016)

PHYSICAL REVIEW LETTERS

week ending  
9 SEPTEMBER 2016



## Detection of 15 dB Squeezed States of Light and their Application for the Absolute Calibration of Photoelectric Quantum Efficiency

Henning Vahlbruch,<sup>1,\*</sup> Moritz Mehmet,<sup>1,†</sup> Karsten Danzmann,<sup>1</sup> and Roman Schnabel<sup>1,2</sup>

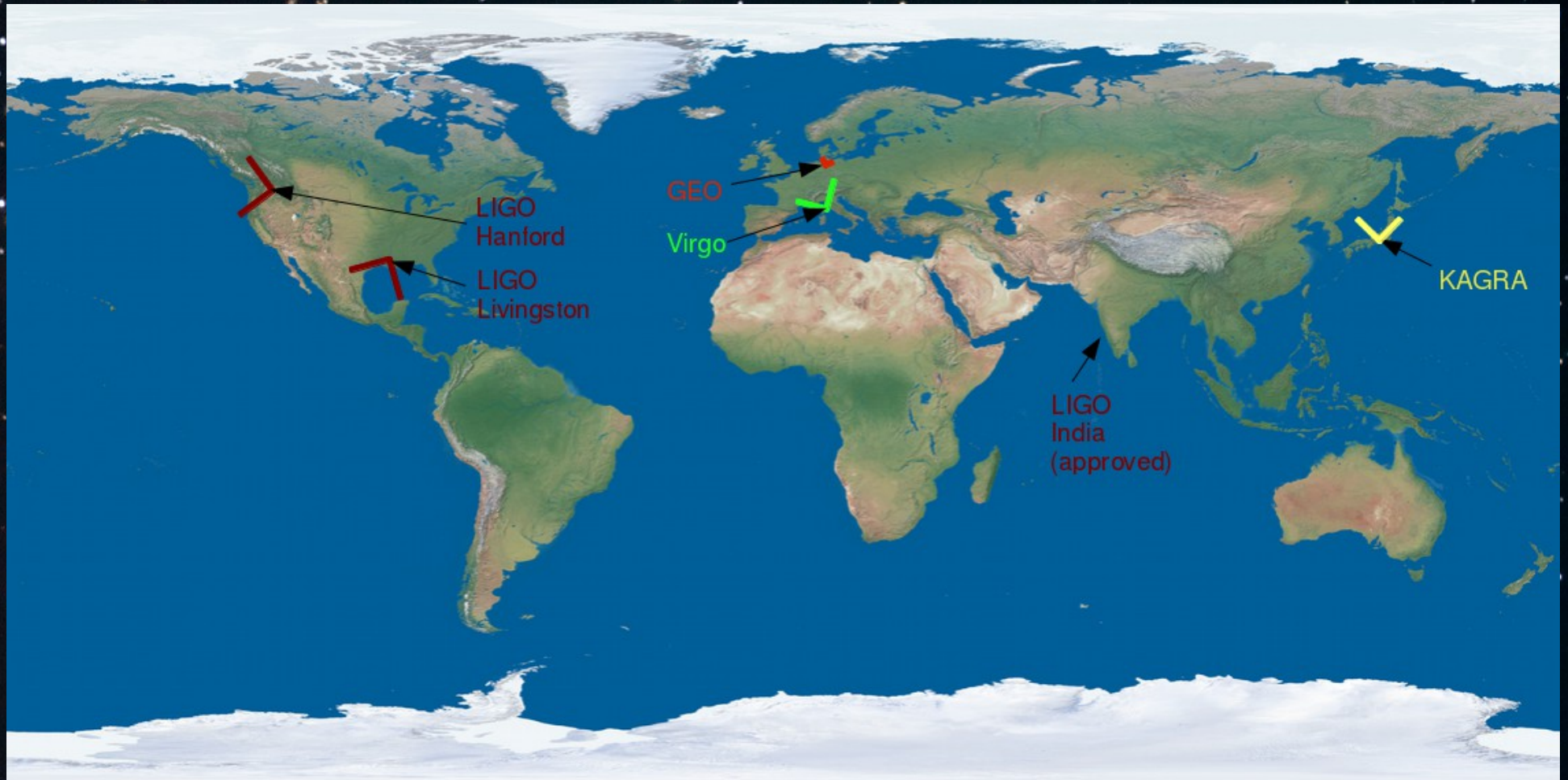
<sup>1</sup>*Institut für Gravitationsphysik, Leibniz Universität Hannover and Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), Callinstraße 38, 30167 Hannover, Germany*

<sup>2</sup>*Institut für Laserphysik and Zentrum für Optische Quantentechnologien, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany*

(Received 15 June 2016; published 6 September 2016)



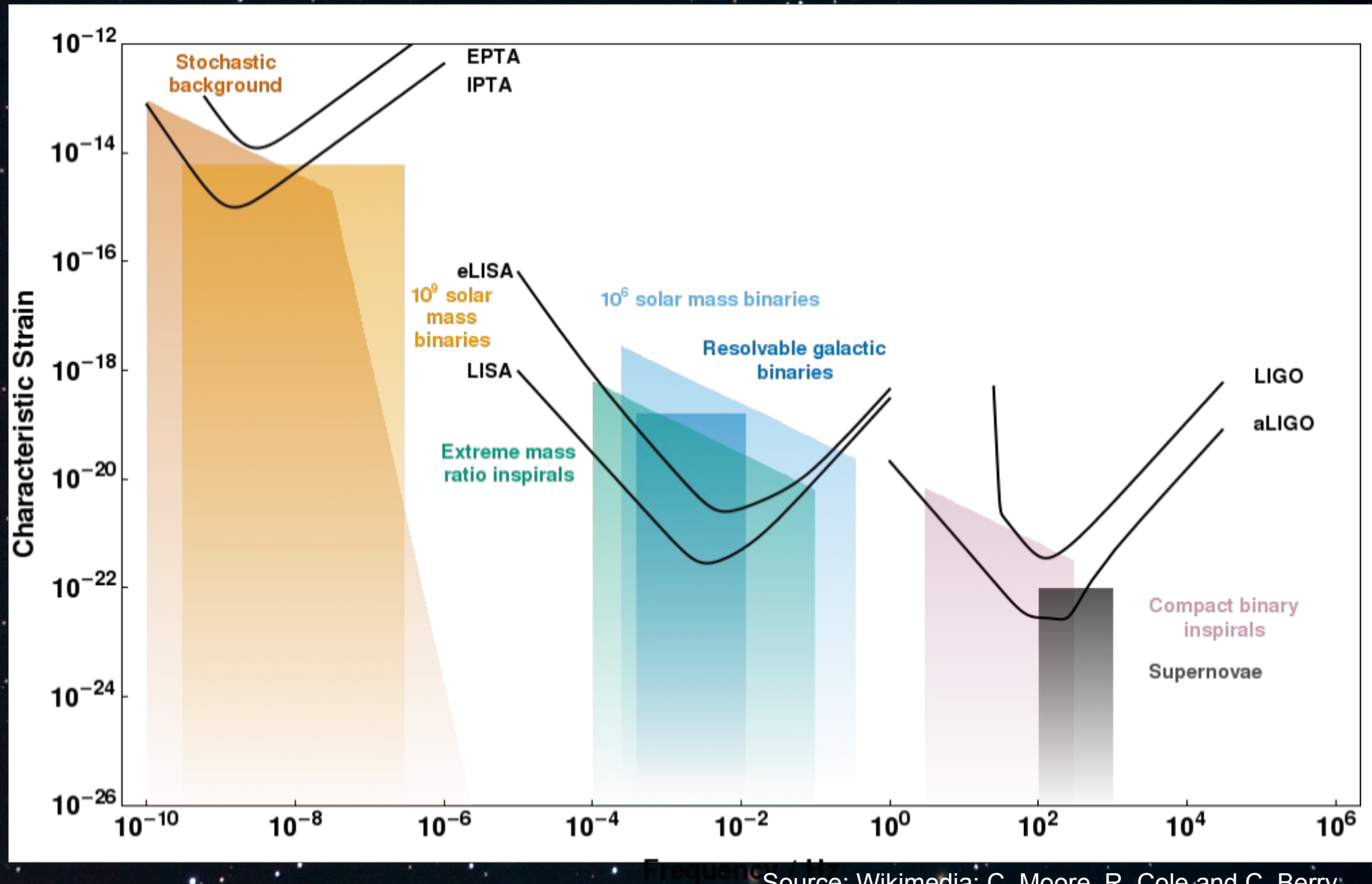
# Worldwide network



Source: Virgo/LAPP, T. Patterson



# Full GW spectra

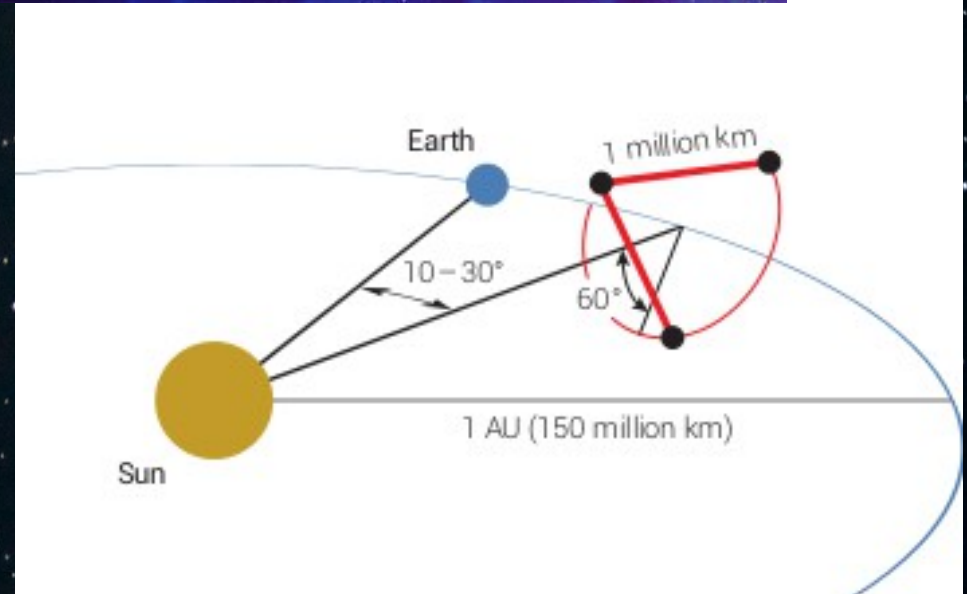
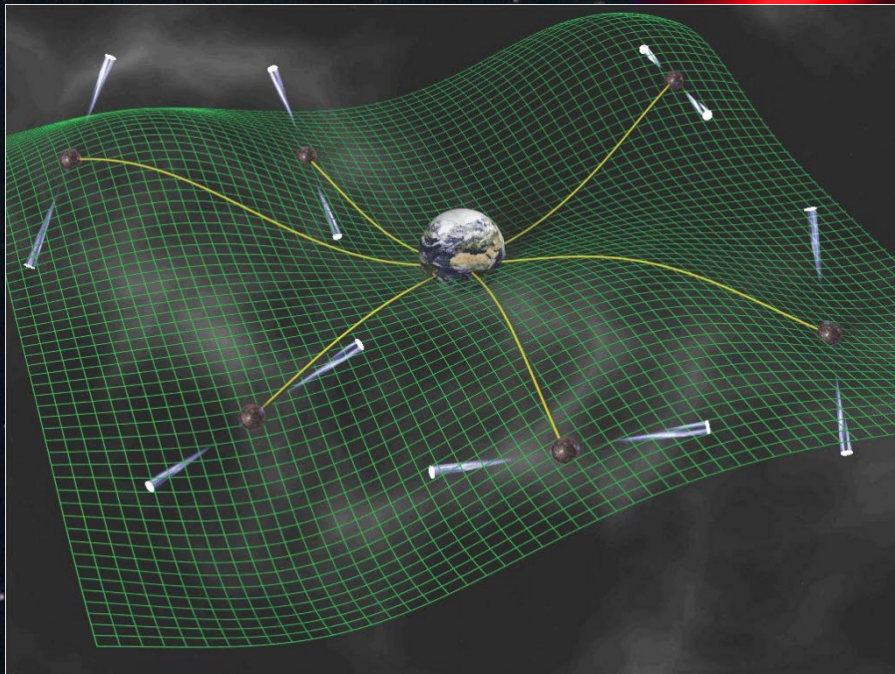




# Pulsar Timing Arrays and LISA



Source: David Champion/MPIfR



Source: Amaro-Seoane et al 1201.3621



# Summary

- **LIGO has detected gravitational waves**
- **Binary black hole systems exist**
- **Binary black holes merge**
- **The future is likely to bring more**



The background of the image is a deep space photograph filled with numerous stars and distant galaxies. The stars appear as small, bright points of light in various colors (white, yellow, blue) against a dark, black background. Some galaxies are visible as faint, elongated structures. The overall effect is a sense of vastness and cosmic scale.

**Thank you**



# References and links

- Abbott et al. “*The basic physics of the binary black hole merger GW150914*” arXiv:1608.01940, Annalen der Physik
- Abbott et al. “*Binary Black Hole Mergers in the first Advanced LIGO Observing Run*” arXiv: 1606.04856, PRX
- Abbott et al. “*Properties of the Binary Black Hole Merger GW150914*” PRL 116 (2016) 241102
- LIGO Open Science Center: <https://losc.ligo.org>
- Logbooks: <https://alog.ligo-la.caltech.edu/aLOG/>
- Physical environment monitors: <https://pem.ligo.org>



# Gravitational Waveforms

- **Numerical relativity**

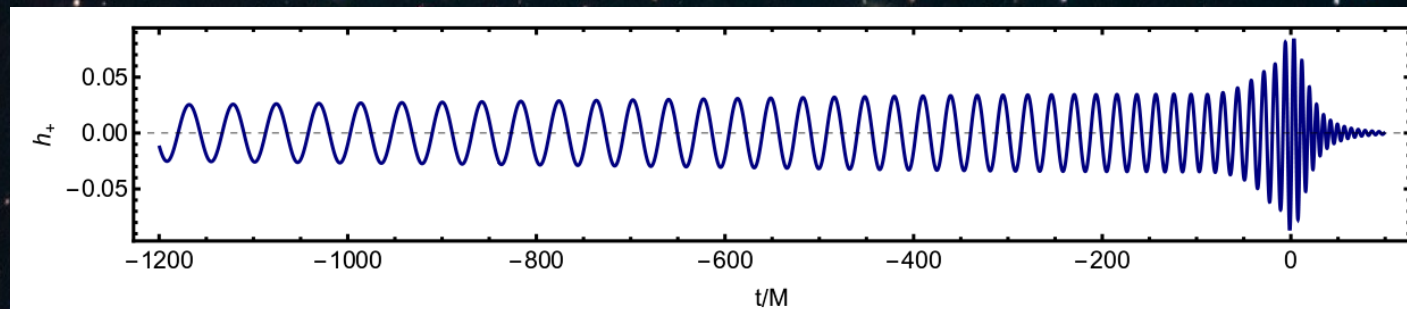
either finite differencing or spectral methods

- **Effective One Body (EOBNR)**

maps two body problem to one body problem via effective Hamiltonian and calibrated to numerical simulations

- **IMRPhenom**

combines post-Newtonian inspiral with phenomenological fit model of numerical simulations of late inspiral and merger, and quasi-analytical ringdown phase



Source: Khan et al. PRD 93 (2016) 044007



# Average Sensitivity

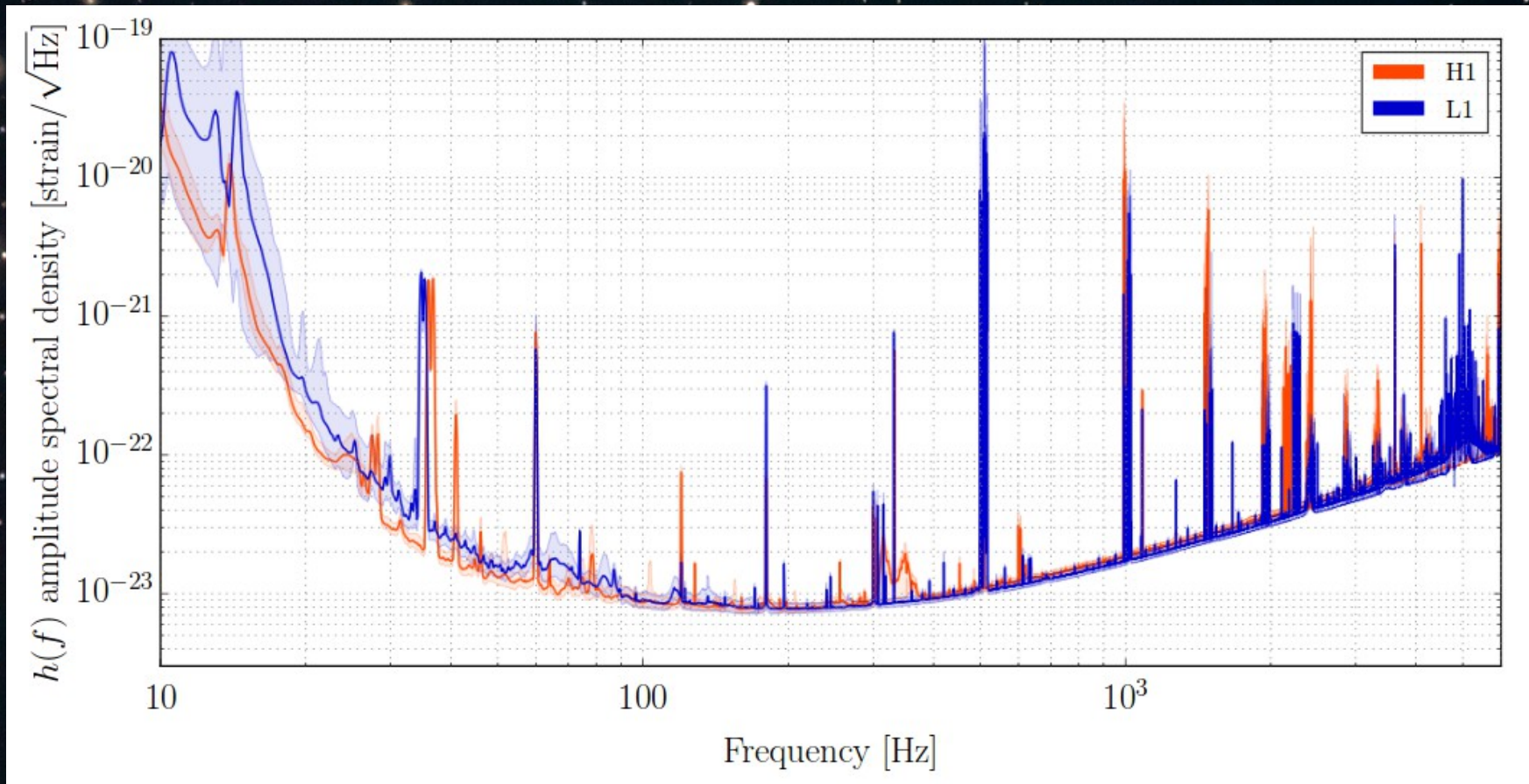


Fig. 1 Abbott et al. CQG33 (2016) 134001



# Spectral lines

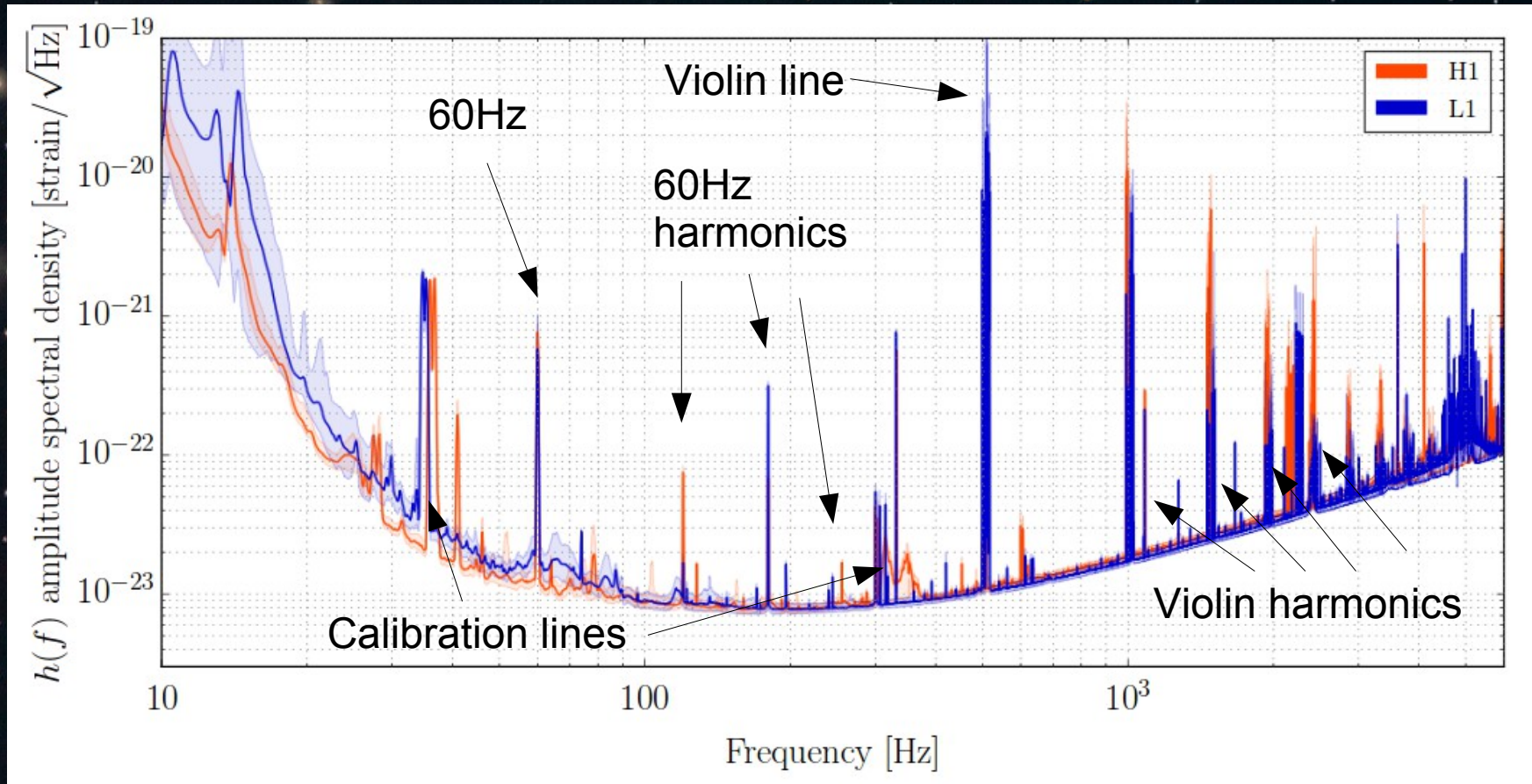


Fig. 1 Abbott et al. CQG33 (2016) 134001