Binary Black Hole Mergers in the first Advanced LIGO Observing Run

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MAX-PLANCK-GESELLSCHAFT

LSC LIGO Scientific Collaboration

Three binary black hole events

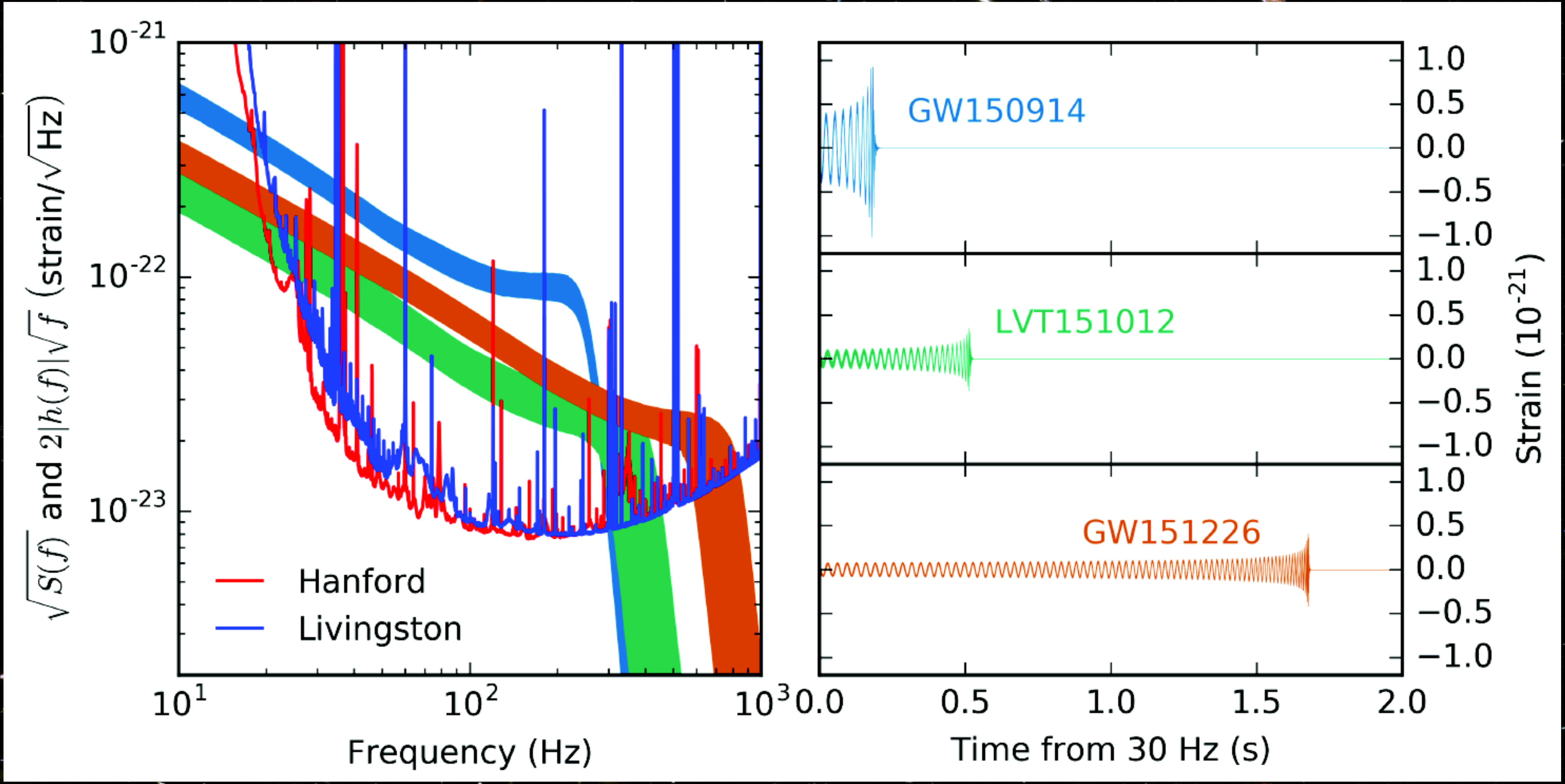


Fig 1 of LVC 1606.04856, PRX6 041015

Update on LIGO's second observing run

28 January 2017 -- The second Advanced LIGO run began on November 30, 2016 and is currently in progress. As of January 23 approximately 12 days of Hanford-Livingston coincident science data have been collected, with a scheduled break between December 22, 2016 and January 4, 2017. Average reach of the LIGO network for binary merger events have been around 70 Mpc for 1.4+1.4 Msun, 300 Mpc for 10+10 Msun and 700 Mpc for 30+30 Msun mergers, with relative variations in time of the order of 10%.

So far, 2 event candidates, identified by online analysis using a loose false-alarm-rate threshold of one per month, have been identified and shared with astronomers who have signed memoranda of understanding with LIGO and Virgo for observational followup. A thorough investigation of the data and offline analysis are in progress; results will be shared when available.

Gravitational waves

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

Einstein’s changing attitude to gravitational waves

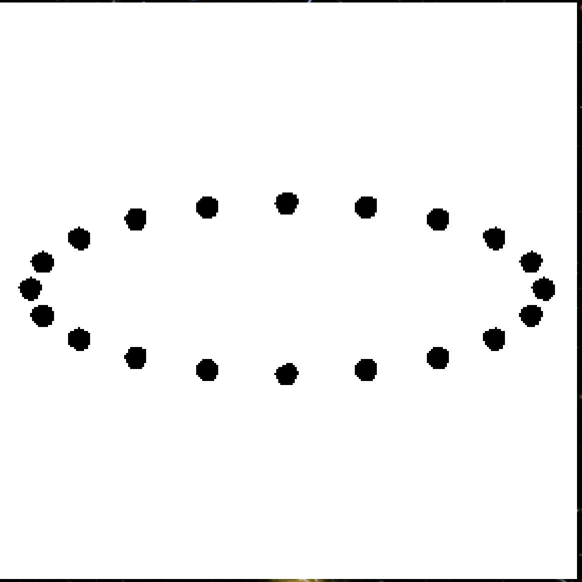
- **19 Feb 1916, letter to Schwarzshild:** *“Es gibt also keine Gravitationswellen, welche Lichtwellen analog wären”*
- **22 Jun 1916, article:** *“...so sieht man, daß A (die Ausstrahlung des Systems durch Gravitationswellen pro Zeiteneinheit) in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.”* *Nährungsweise Integration der Feldgleichungen, Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin), 1916 688*
- **31 Jan 1918, article:** *“Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.”* *Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin), 1916 154*
- **1936 undated letter to Max Born:** *“Together with a young collaborator, I arrived at the interesting result that gravitational waves do not exist, though they have been assumed a certainty to the first approximation.”*
- **1936 Princeton lecture:** *“If you ask me whether there are gravitational waves or not, I must answer that I do not know. But it is a highly interesting problem.”*

What are gravitational waves?

$G_{ab} = 8\pi G T_{ab}$ Einstein equation

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

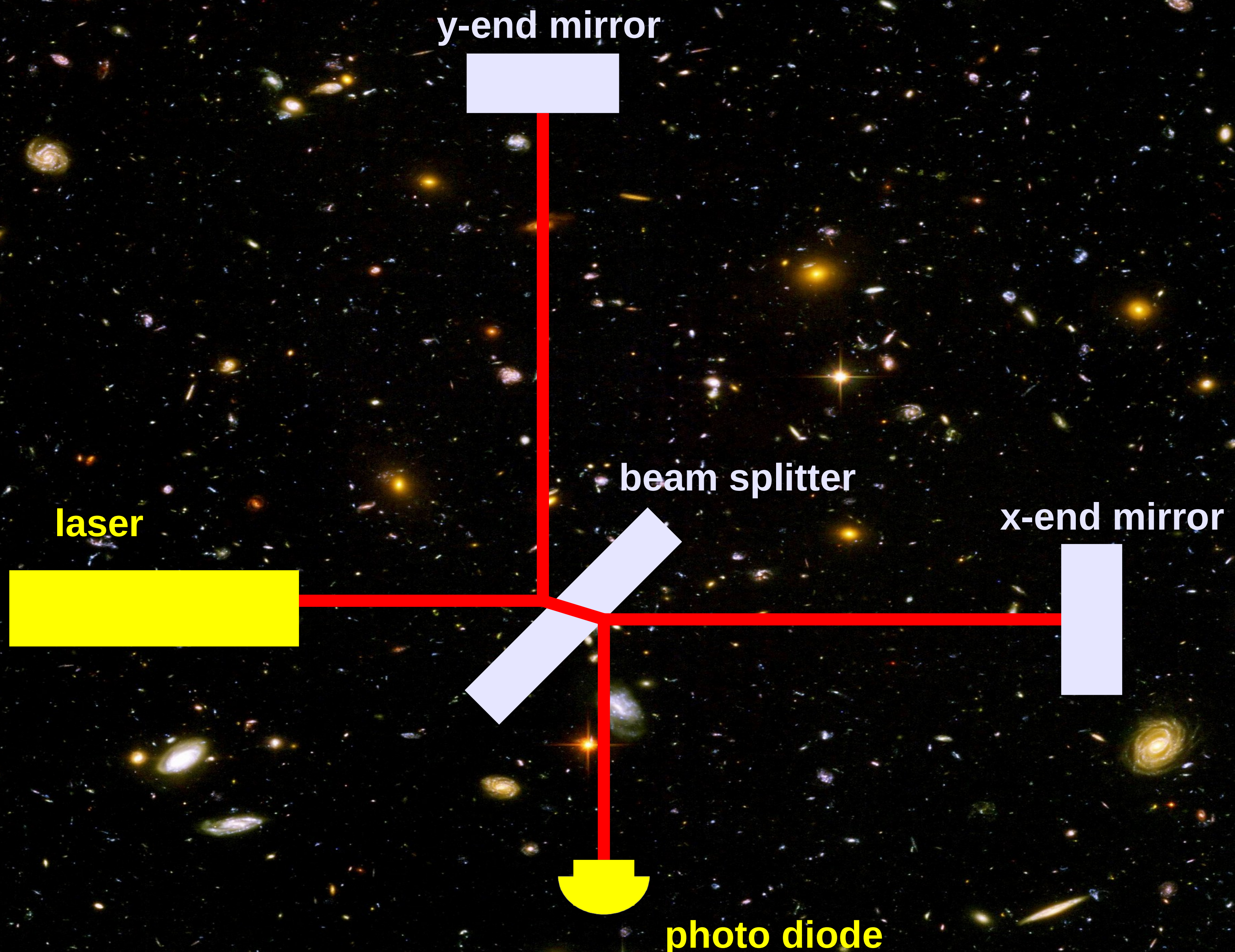
$\nabla^2 \bar{h}_{ab} = 0$ Wave equation



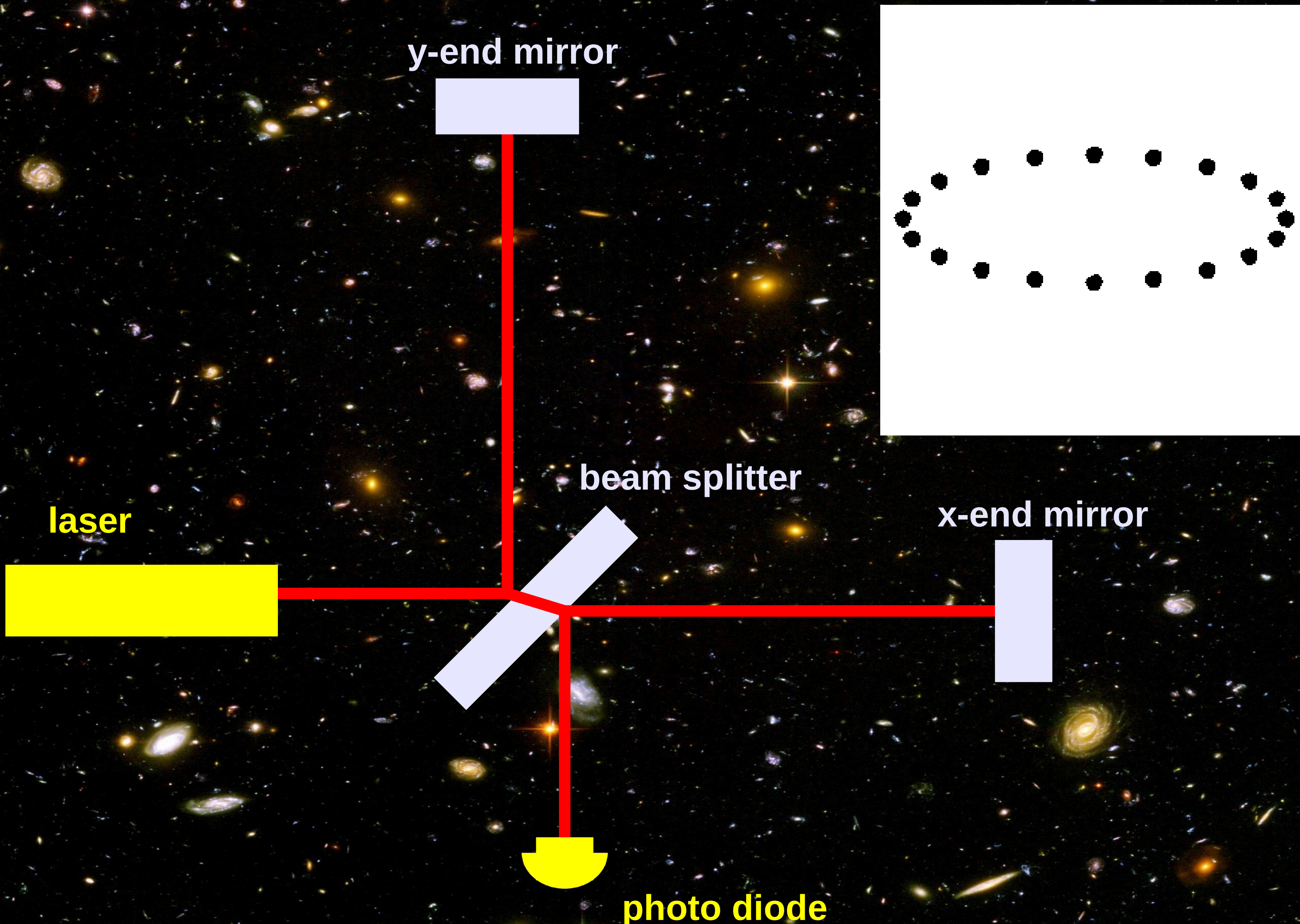
$$Q_{ij} \equiv \int d^3x \rho \left(x_i x_j - \frac{1}{3} r^2 \delta_{ij} \right)$$

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

Interferometers



Interferometers



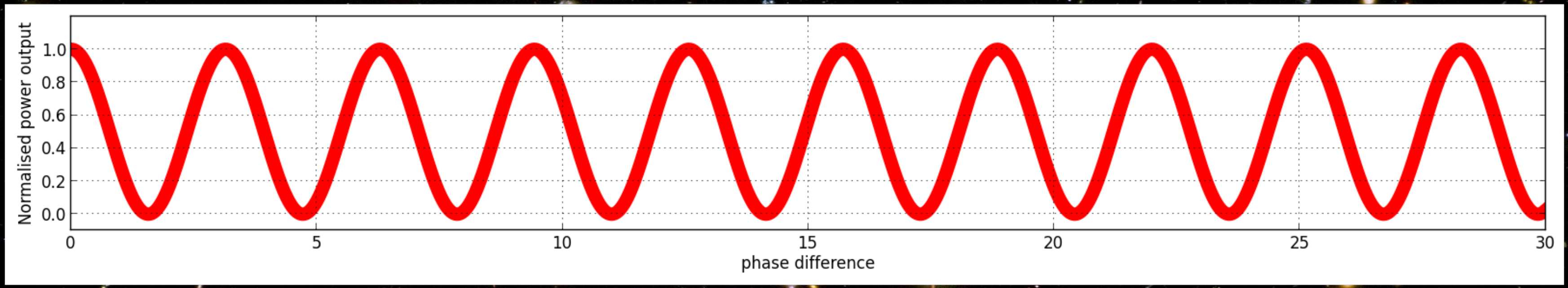
Source: LIGO Lab

How LIGO really works

- **Long arms**: Earth's curvature over 4km is ~1m
- **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
- **Near-dark photo diodes**: 50 mW
- **High vacuum**: One trillionth atm, 10^{-9} torr in $10{,}000 m^3$
- **Active seismic isolation**: at $\sim 10^{-13}$ m
- **Passive suspension**: at $\sim 10^{-19}$ m
- **Heavy test-mass mirrors**: 40kg suspended by fused-silica wires 0.4mm thick

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

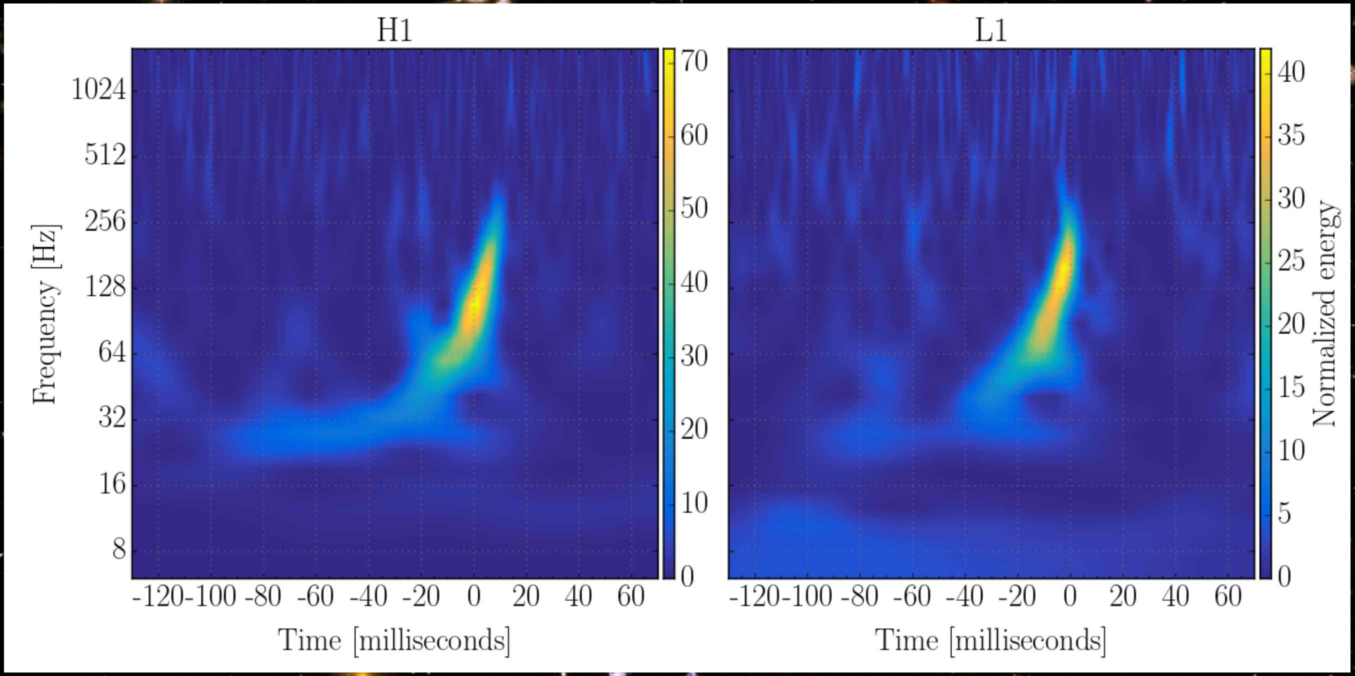


Fig. 10 of LVC CQG33 (2016) 134001

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

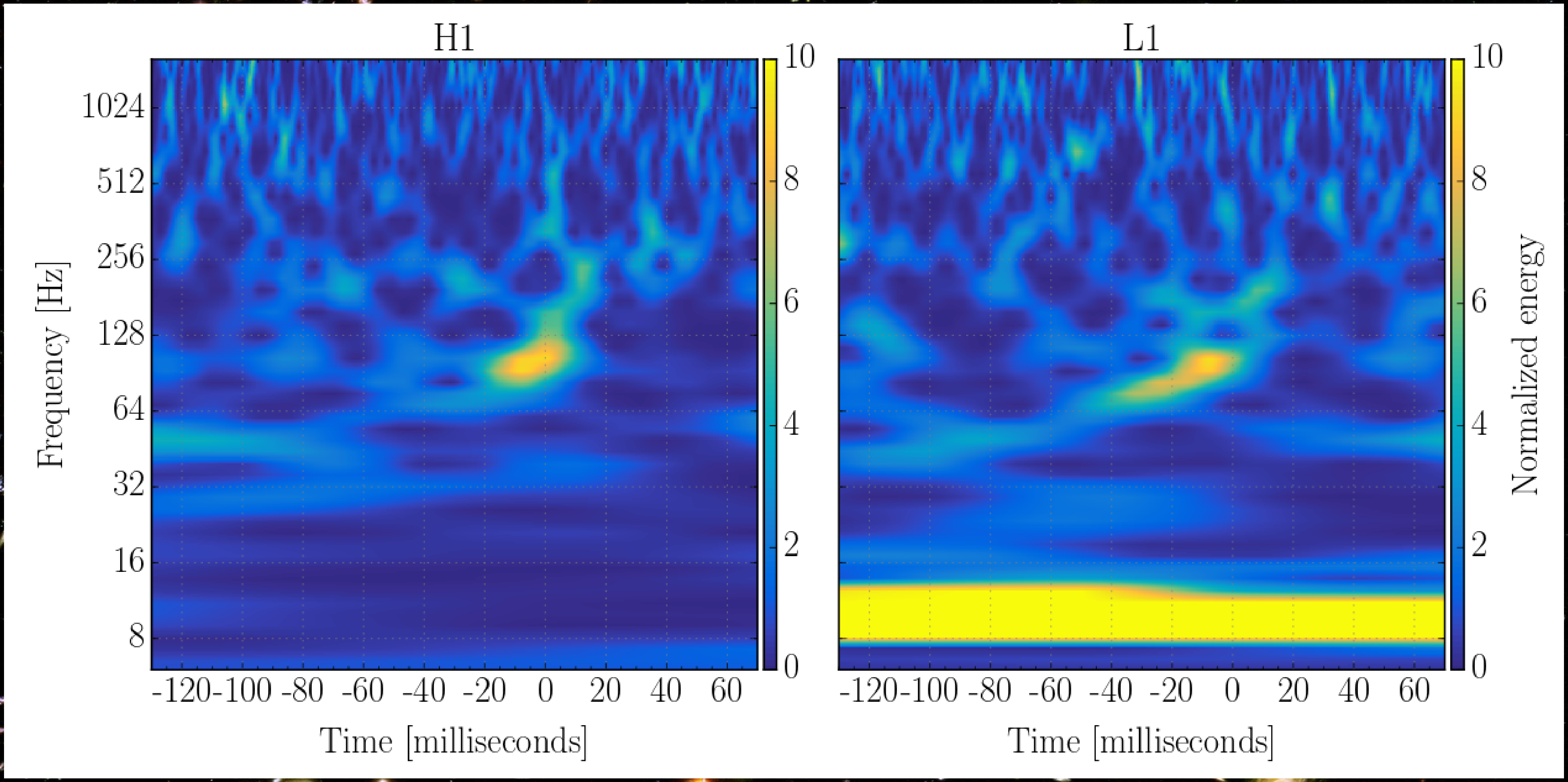


Fig. 13 of LVC CQG33 (2016) 134001

False Alarm Rate, 1 per 2.3 years

Non-Gaussian transients

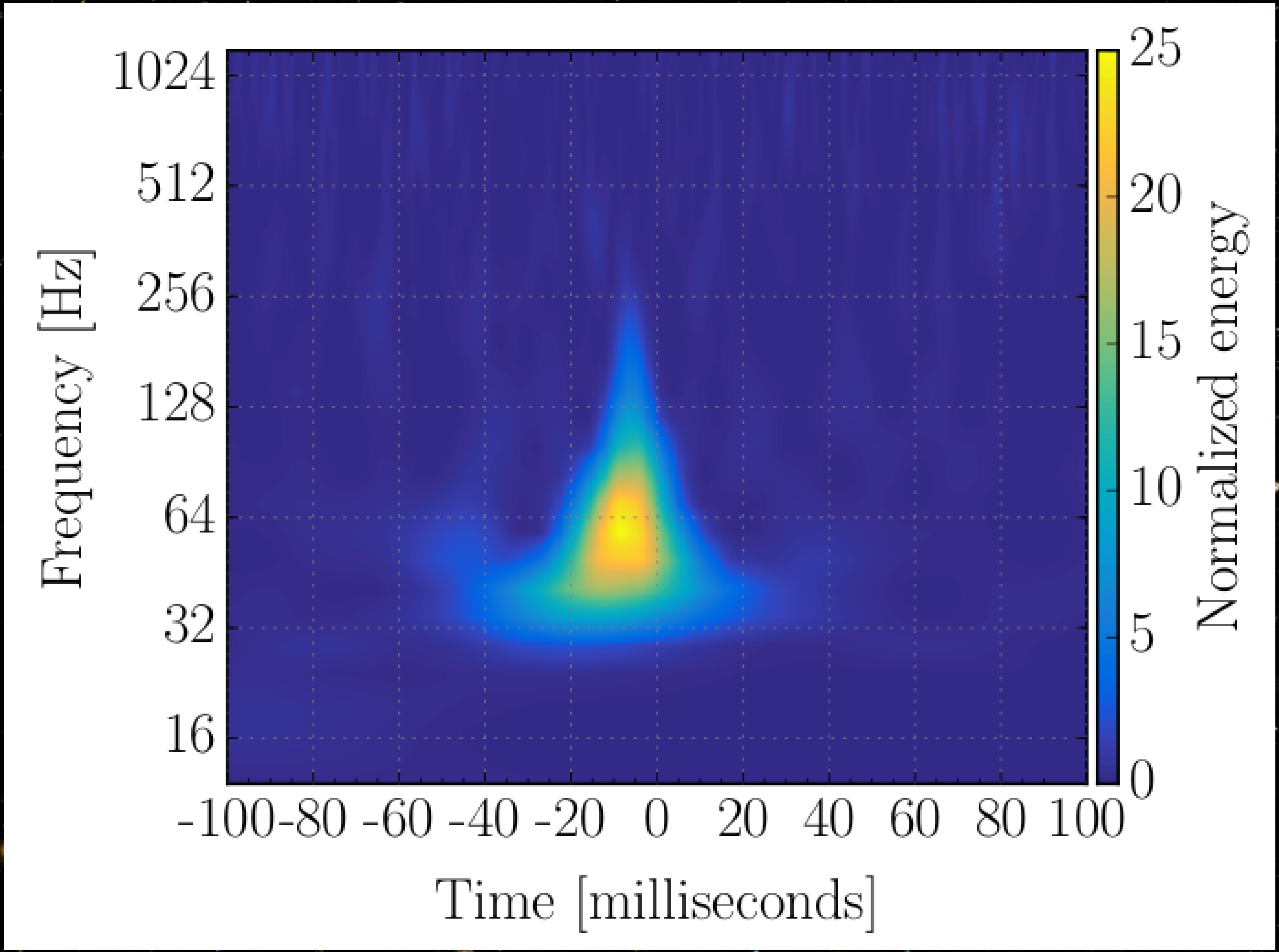
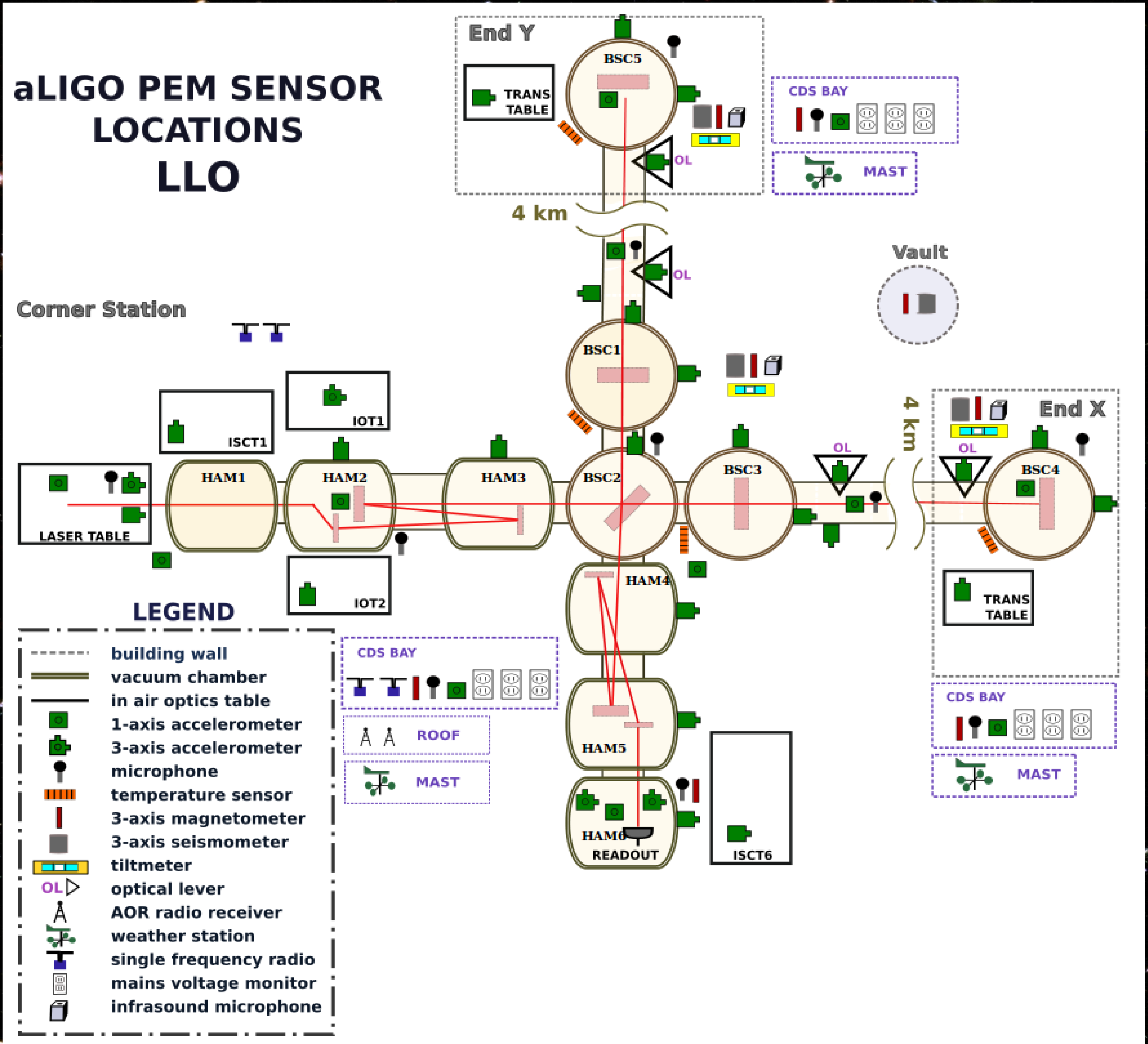


Fig. 3 LVC CQG33 (2016) 134001



http://pem.ligo.org/

Daytime versus nighttime

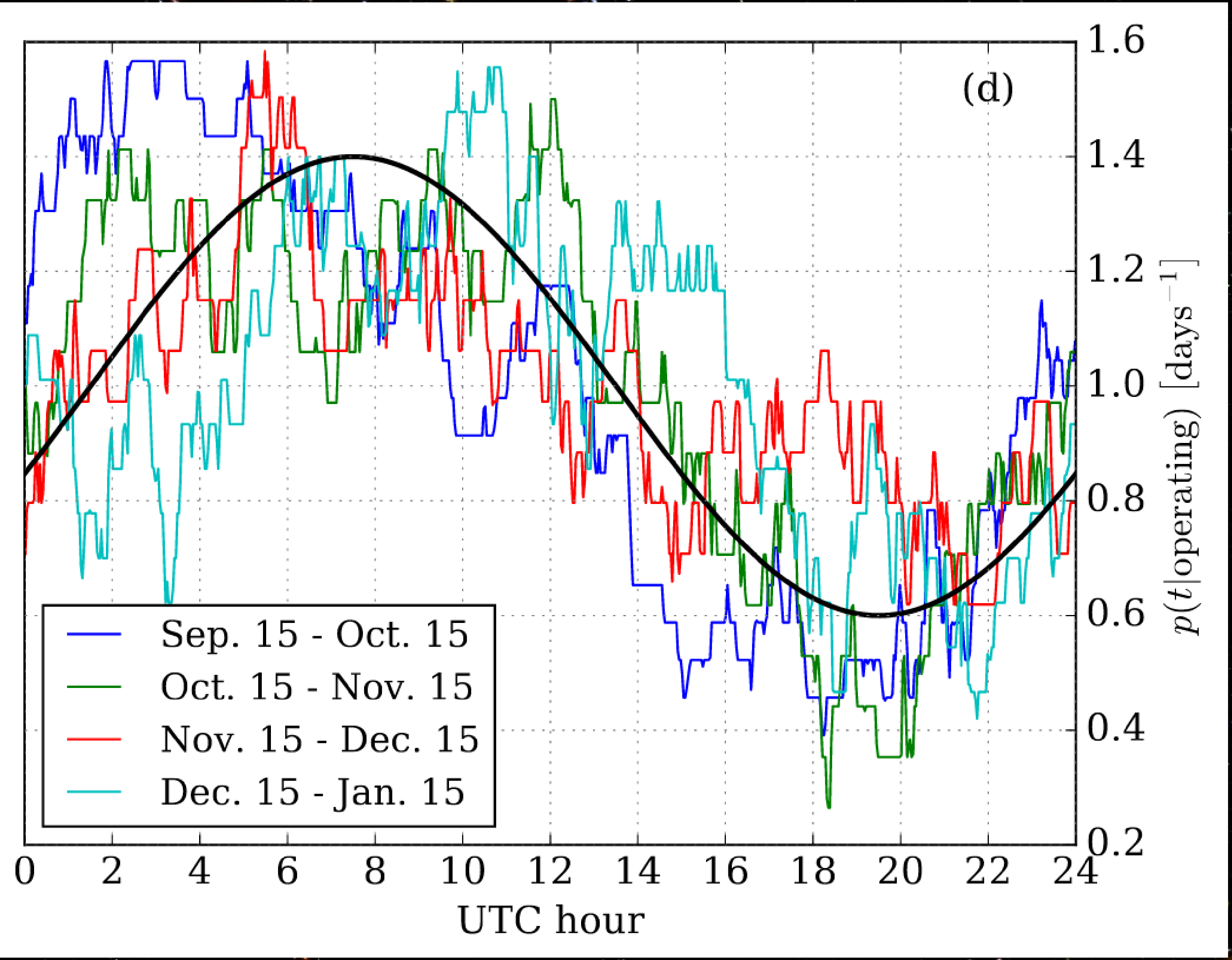


Fig. 1 (right) of Chen et al. 1608.00164

What was seen

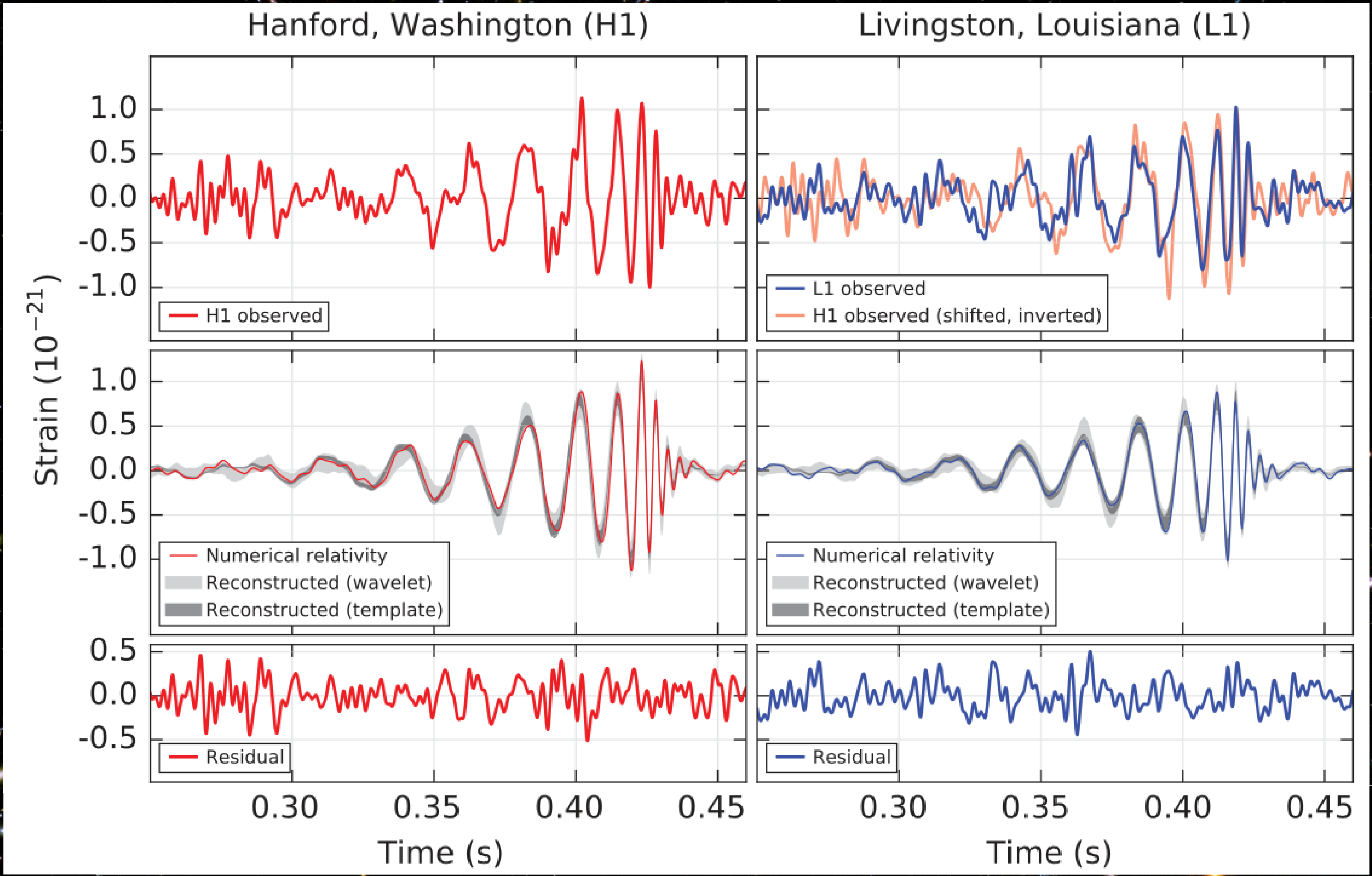


Fig 1. (top) of LVC PRL 116 (2016) 6, 061102

Testing gravity

- Compact and dynamic

$$\left(\frac{\pi G M f}{c^3}\right)^{1/3} \sim \sqrt{\frac{GM}{c^2 r}} \sim \frac{v}{c} \sim 0.5$$

- Curvature scale corrections to gravity?

$$K l_p^4 \sim \frac{3}{4}\frac{\hbar^2 c^2}{G^2 M^4} \ll 1$$

- Horizon scale corrections to gravity?

$$\langle B|\hat{T}_{ab}|B\rangle \Rightarrow \infty$$

Post-Newtonian expansion (2-2 phase)

PN order	Includes (amongst other things)
0PN	Kepler Newtonian Gravity
0.5PN	Zero in GR
1PN	Pericenter advance (cf zero) PPN parameters γ, β, ξ
1.5PN	Spin-orbit couplings Gravitational tails (backscatter)
2PN	Spin-spin couplings (Newtonian) quadrupole-monopole (GR BH) (Newtonian) magnetic dipole-dipole (cf zero)
3PN	Tails of tails
5PN	(Newtonian) Adiabatic tidal deformations

Bounds on PN coefficients from GW150914 and GW151226

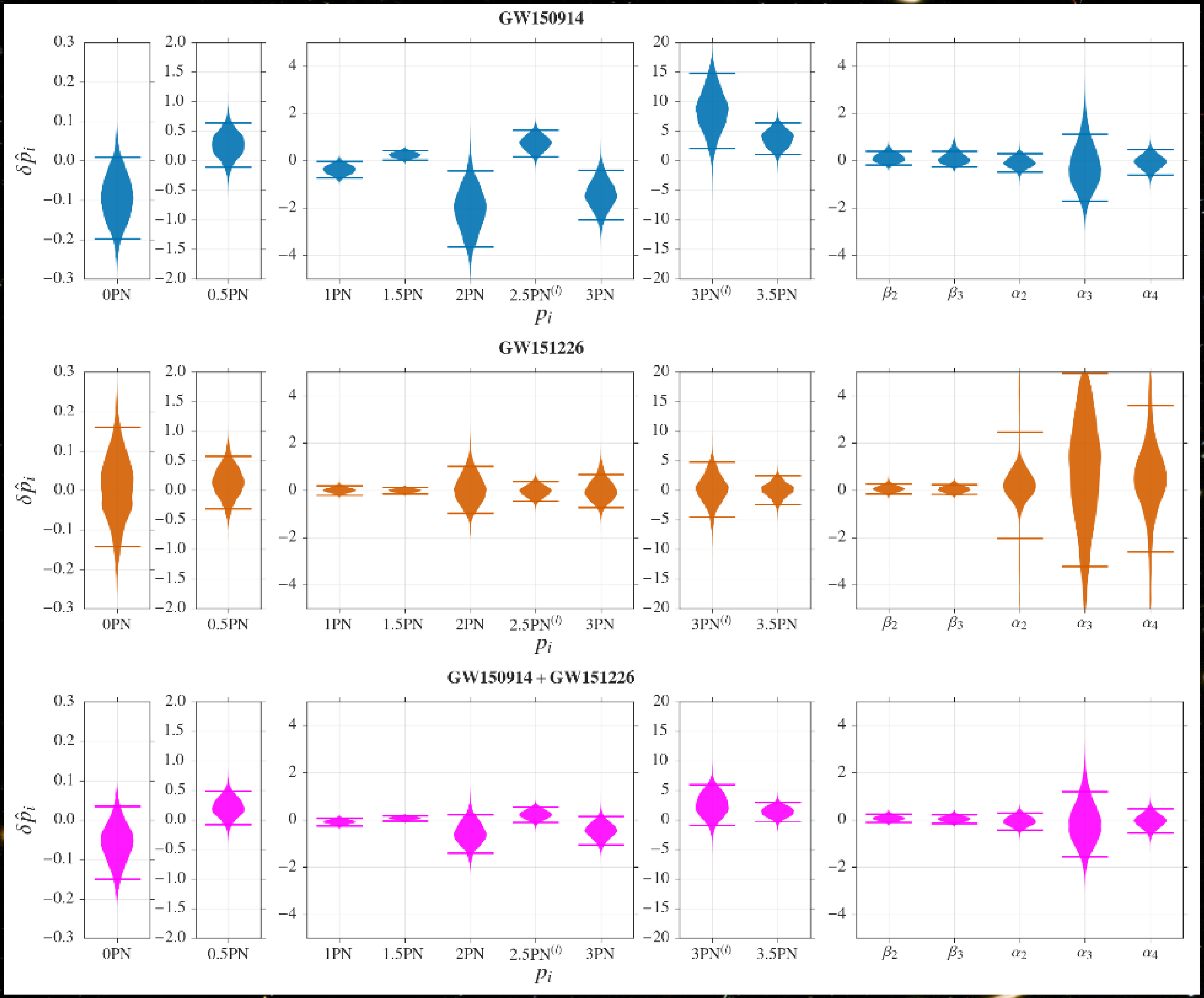


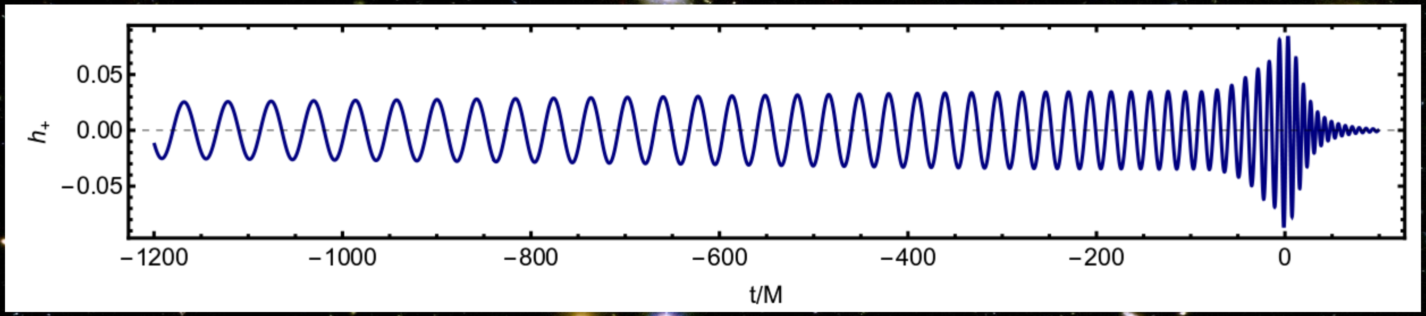
Fig 6 of LVC 1606.04856 PRX6 041015

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

Source parameters

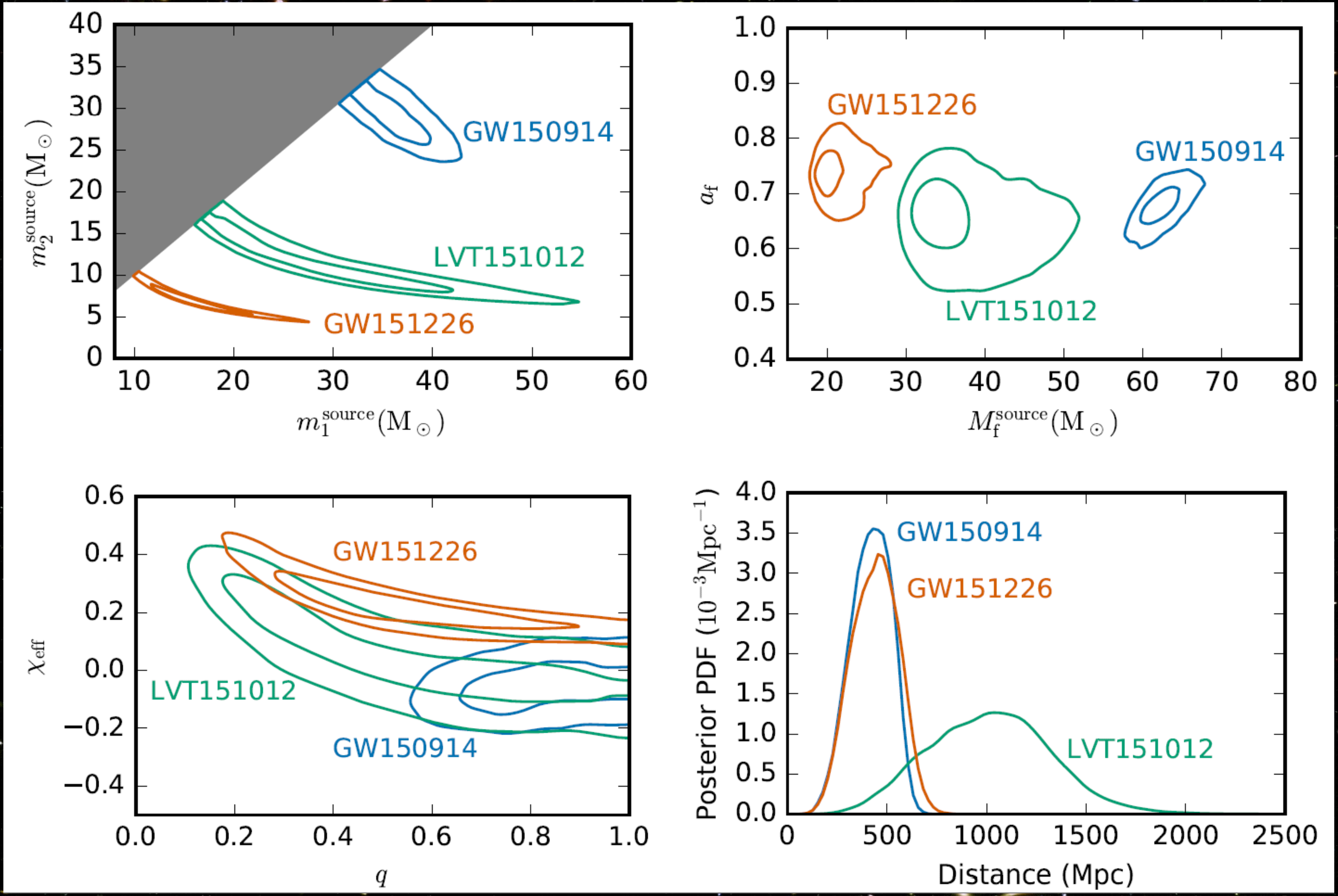


Fig. 4 of LVC 1606.04856, PRX6 041015

Inspiral-merger-ringdown consistency

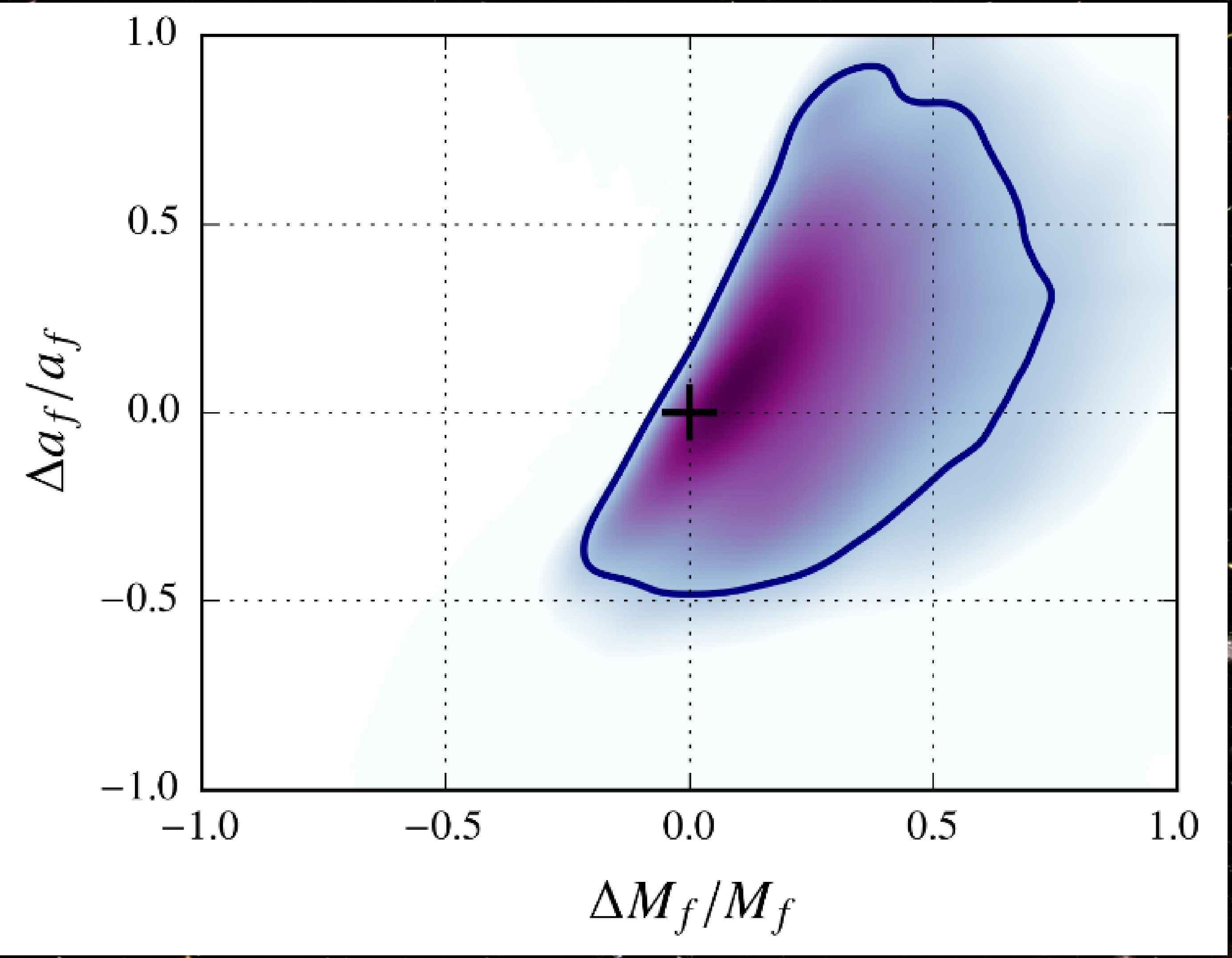
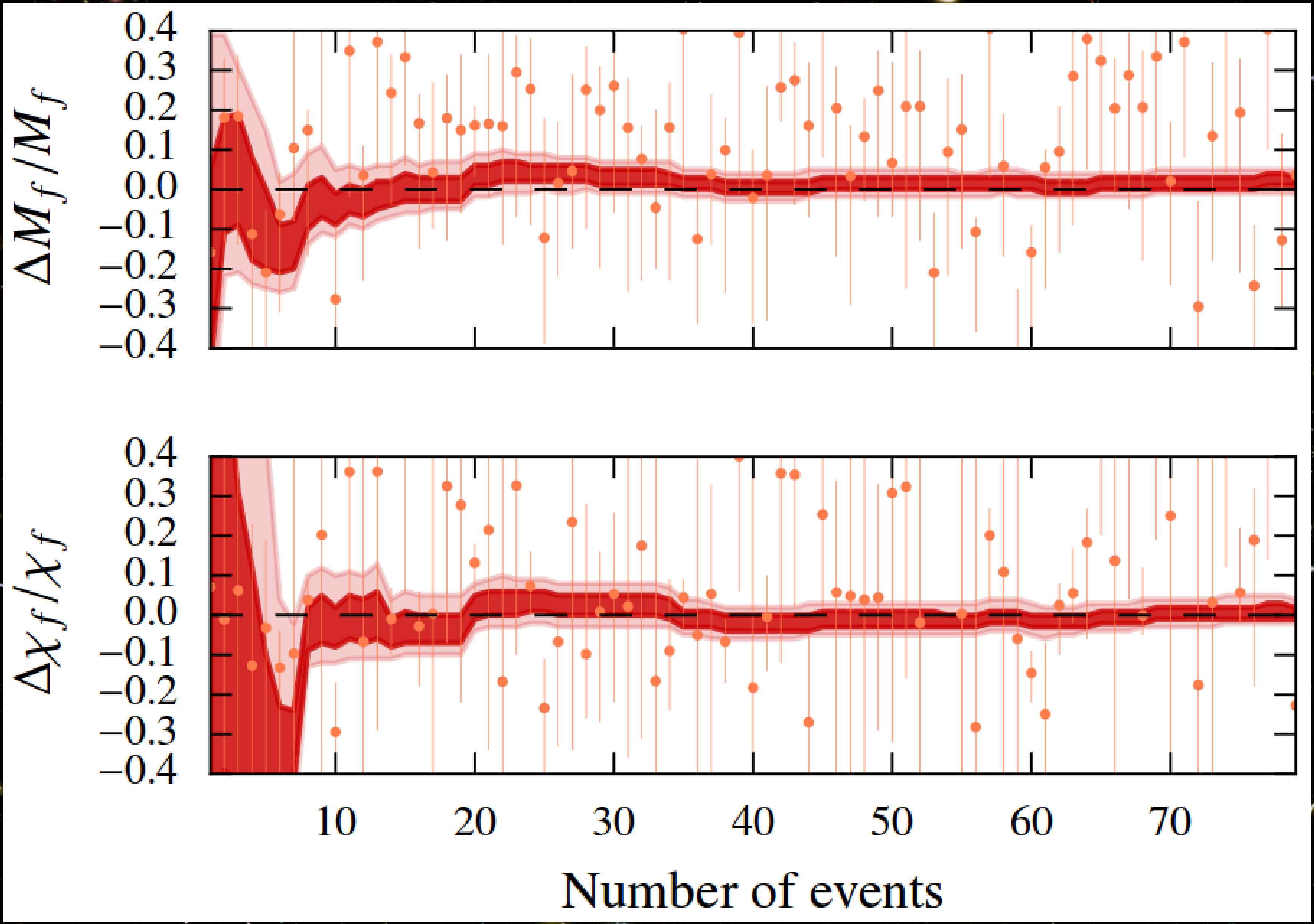


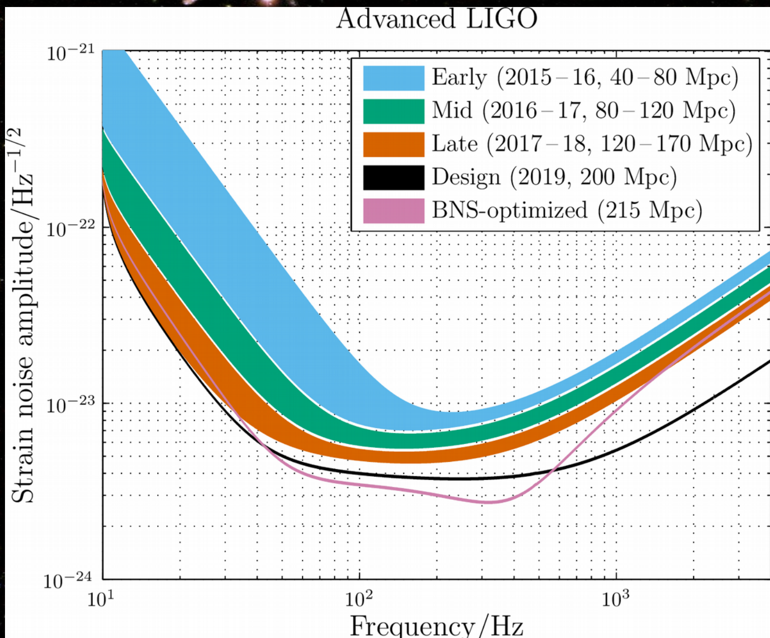
Fig. 3 (bot) of LVC PRL 16 (2016) 221101

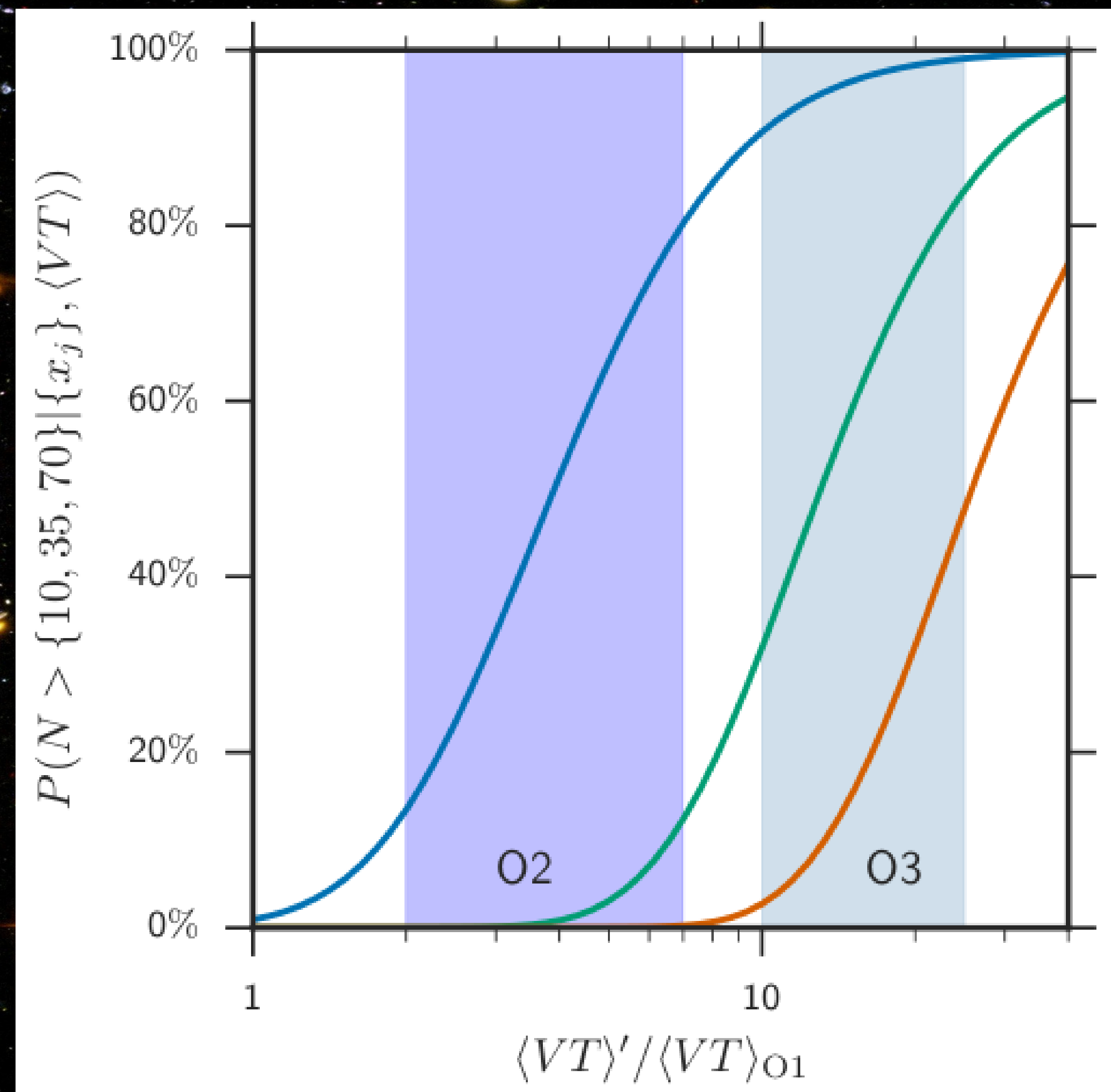
IMR consistency going forward



Source: Ghosh et al PRD94 (2016) 021101

Event rate estimates





Multiple detections by the end of observing run O3 is quite likely

Fig 12 of LVC 1606.04856 PRX6 041015

X-ray binaries masses and spin

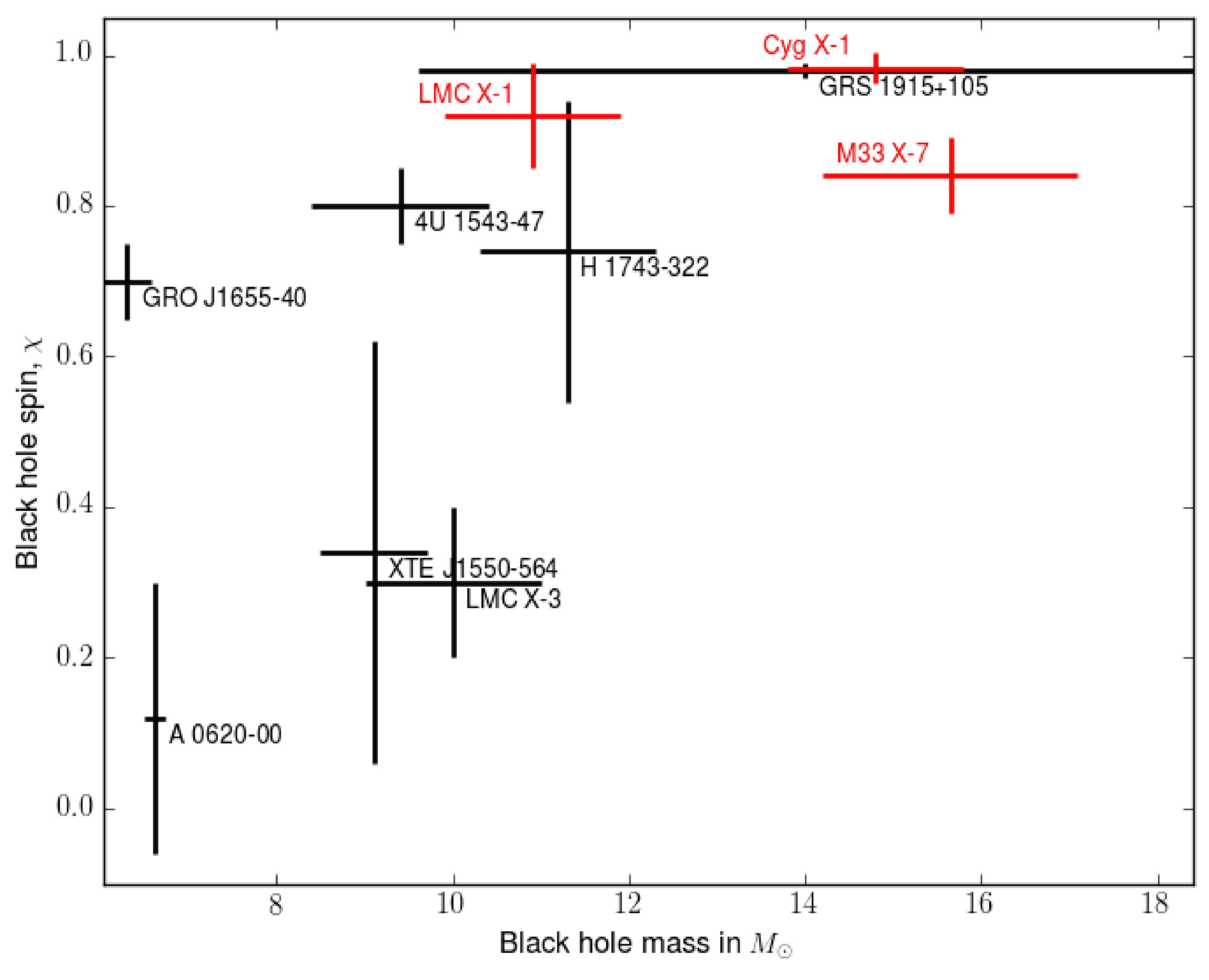
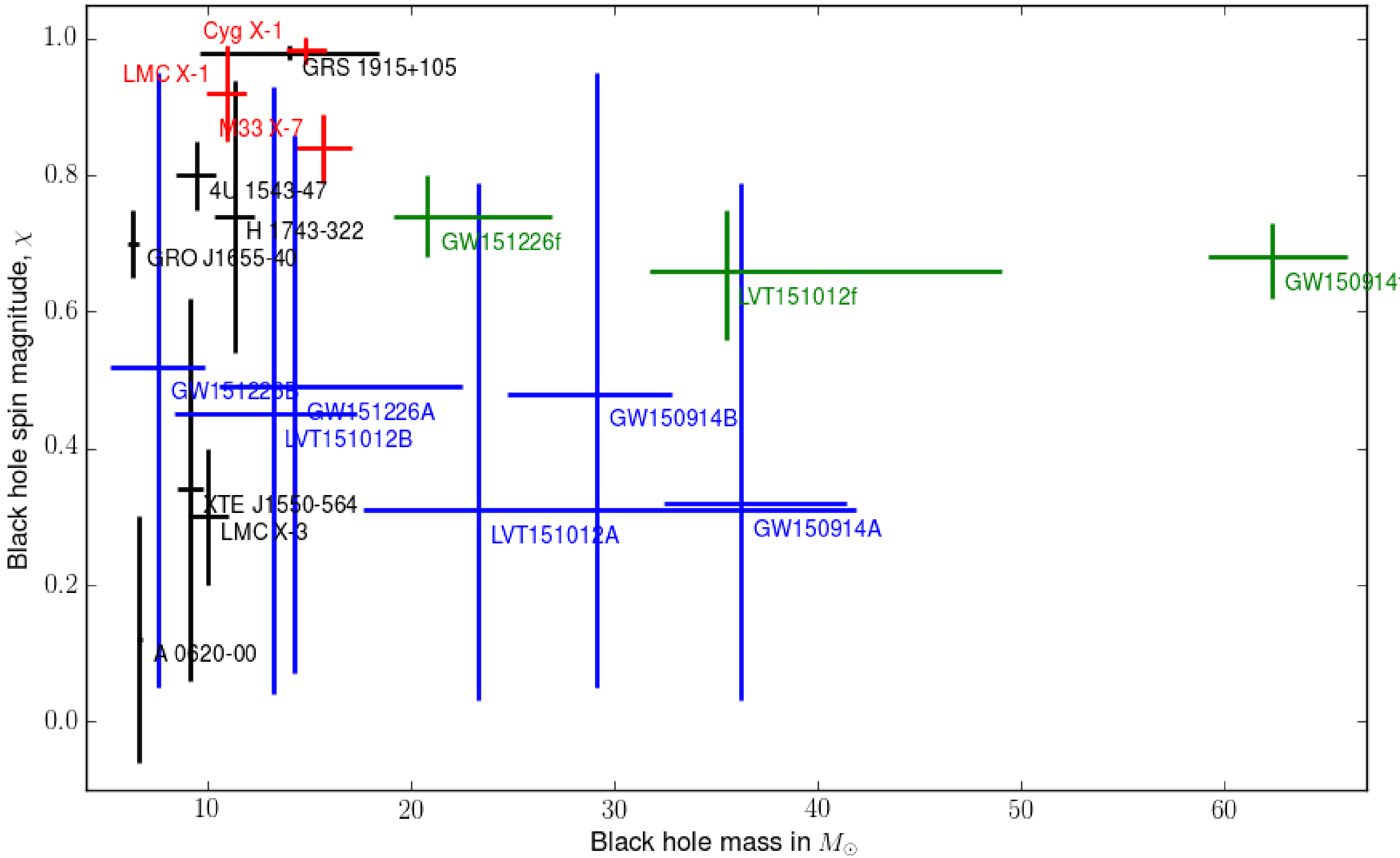


Fig. 1 of Nielsen J.Phys.Conf.Ser. 716 (2016) no.1, 012002

X-ray + GW masses and spins

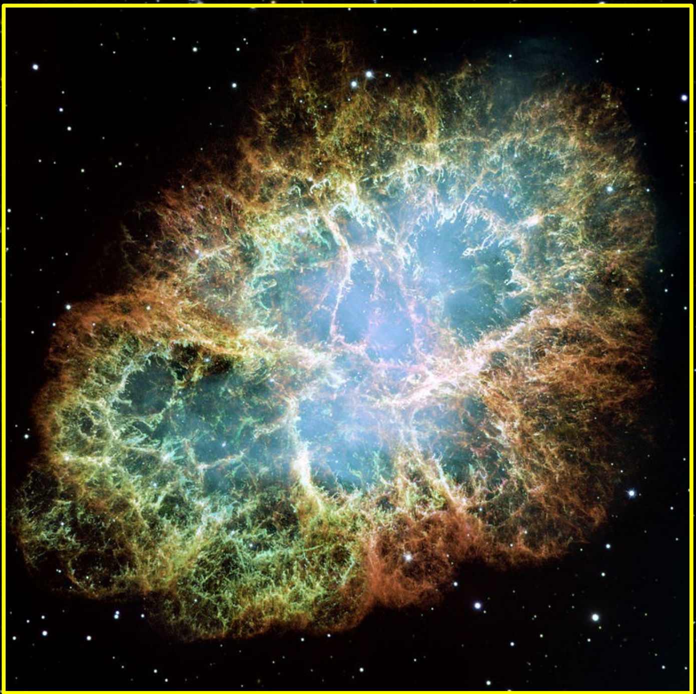


Astrophysics

- 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

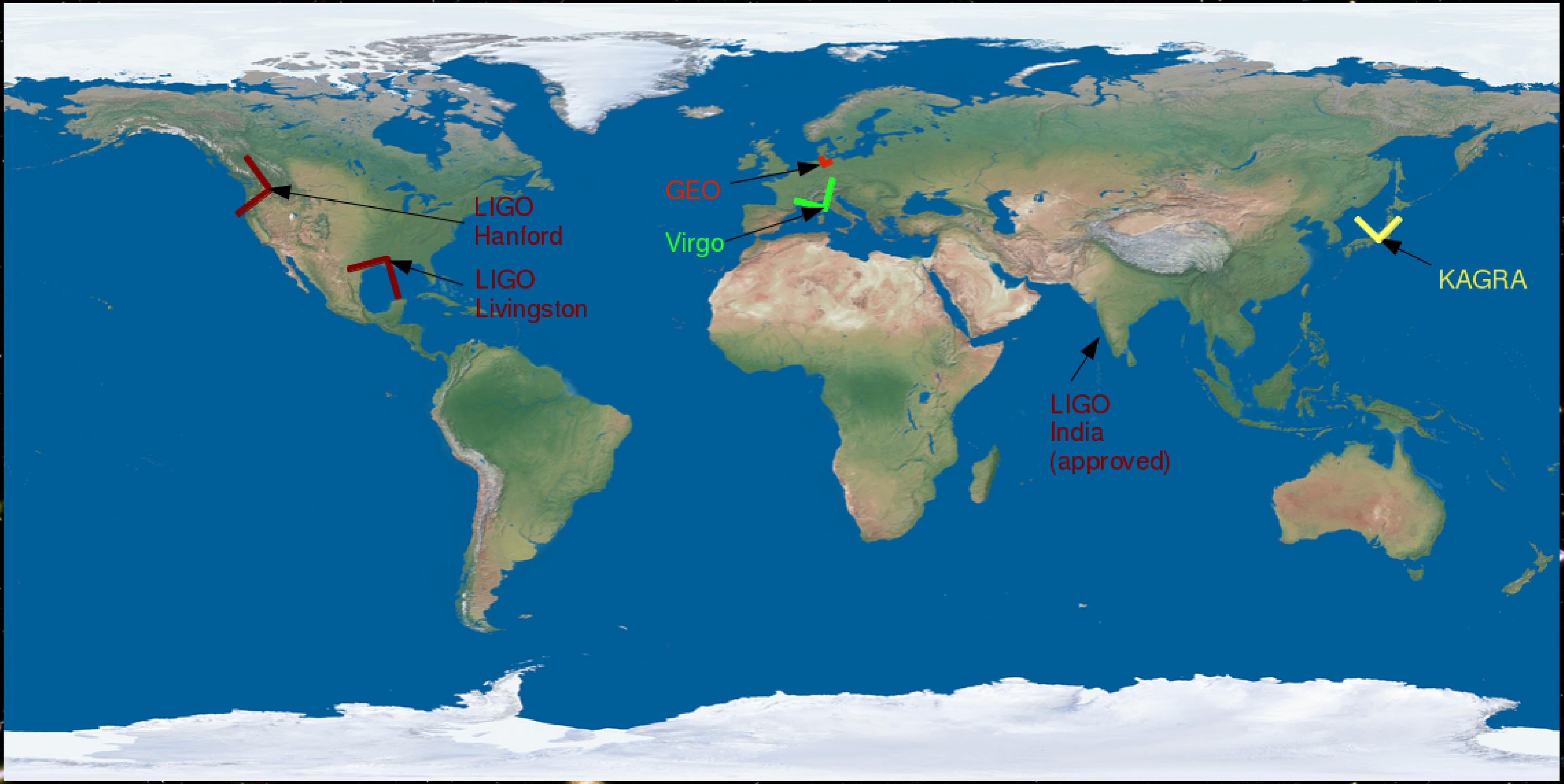
Other potential aLIGO sources

- 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



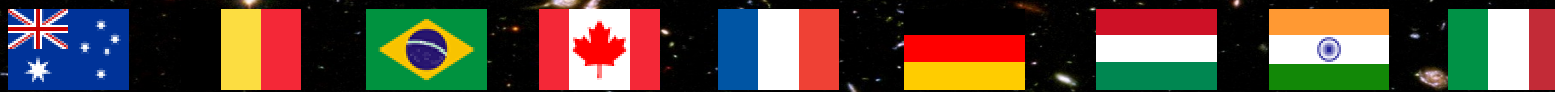
Source: NASA/HST

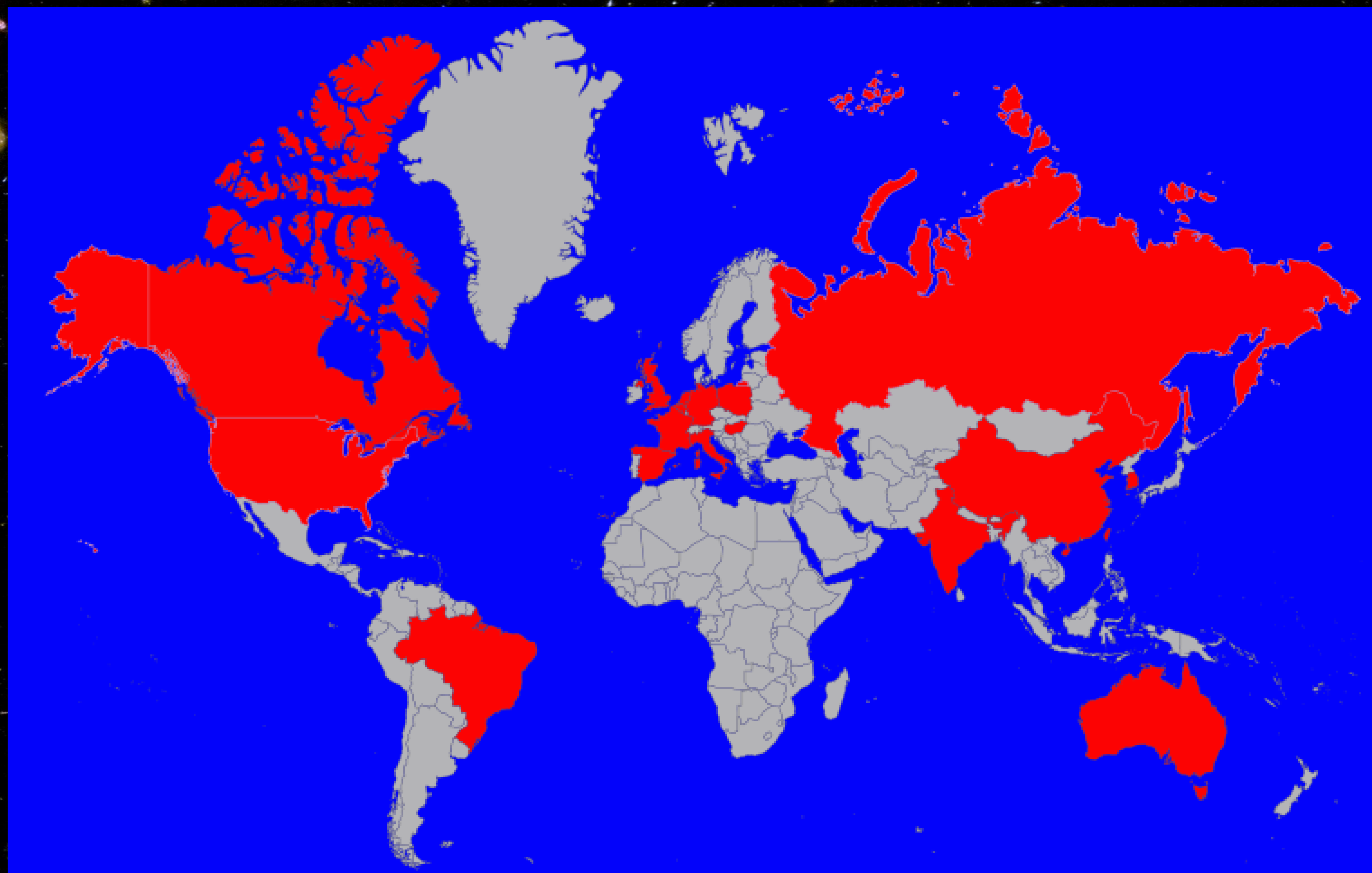
Worldwide network



Source: Virgo/LAPP, T. Patterson

LIGO-Virgo Countries





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

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

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Summary

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

Thank you

References and links

- Abbott et al. *“The basic physics of the binary black hole merger GW150914”* arXiv:1608.01940, Annalen Phys. (2016) 041015
- Abbott et al. *“Binary Black Hole Mergers in the first Advanced LIGO Observing Run”* arXiv: 1606.04856, PRX6 (2016)
- Abbott et al. *“Properties of the Binary Black Hole Merger GW150914”* arXiv: 1602.03840, PRL 116 (2016) 241102
- LIGO Open Science Center: https;//losc.ligo.org