Seminar

GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

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2nd Detection Paper by LIGO

‘GW151226: Observation of Gravitational Waves
from a 22-Solar-Mass Binary Black Hole Coalescence’
Abbott, et al. (LIGO Sci Collab. and Virgo Collab.),
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GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 31 May 2016; published 15 June 2016)

We report the observation of a gravitational-wave signal produced by the coalescence of two stellar-mass black holes. The signal, GW151226, was observed by the twin detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) on December 26, 2015 at 03:38:53 UTC. The signal was initially identified within 70 s by an online matched-filter search targeting binary coalescences. Subsequent off-line analyses recovered GW151226 with a network signal-to-noise ratio of 13 and a significance greater than 5σ. The signal persisted in the LIGO frequency band for approximately 1 s, increasing in frequency and amplitude over about 55 cycles from 35 to 450 Hz, and reached a peak gravitational strain of $3.4^{+0.7}_{-0.9} \times 10^{-22}$. The inferred source-frame initial black hole masses are $14.2^{+8.3}_{-3.7} M_{\odot}$ and $7.5^{+2.3}_{-2.3} M_{\odot}$, and the final black hole mass is $20.8^{+6.1}_{-1.7} M_{\odot}$. We find that at least one of the component black holes has spin greater than 0.2. This source is located at a luminosity distance of 440^{+180}_{-190} Mpc corresponding to a redshift of $0.09^{+0.03}_{-0.04}$. All uncertainties define a 90% credible interval. This second gravitational-wave observation provides improved constraints on stellar populations and on deviations from general relativity.

And also

'Binary Black Hole Mergers
in the first Advanced LIGO Observing Run'
The LIGO Scientific Collaboration and The Virgo Collaboration
ArXiv 1606.04856v2

Binary Black Hole Mergers in the first Advanced LIGO Observing Run

The LIGO Scientific Collaboration and The Virgo Collaboration[a]
(23 JUNE 2016)

The first observational run of the Advanced LIGO detectors, from September 12, 2015 to January 19, 2016, saw the first detections of gravitational waves from binary black hole mergers. In this paper we present full results from a search for binary black hole merger signals with total masses up to $100M_\odot$ and detailed implications from our observations of these systems. Our search, based on general-relativistic models of gravitational wave signals from binary black hole systems, unambiguously identified two signals, GW150914 and GW151226, with a significance of greater than 5σ over the observing period. It also identified a third possible signal, LVT151012, with substantially lower significance, which has a 87% probability of being of astrophysical origin. We provide detailed estimates of the parameters of the observed systems. Both GW150914 and GW151226 provide an unprecedented opportunity to study the two-body motion of a compact-object binary in the large velocity, highly nonlinear regime. We do not observe any deviations from general relativity, and place improved empirical bounds on several high-order post-Newtonian coefficients. From our observations we infer stellar-mass binary black hole merger rates lying in the range 9–240 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$. These observations are beginning to inform astrophysical predictions of binary black hole formation rates, and indicate that future observing runs of the Advanced detector network will yield many more gravitational wave detections.

2^{nd} GW signal in LIGO O1

- With full analysis for LIGO O1, 2^{nd} GW event, named GW151226, was found.
  * Date/Time: Dec. 26^{th}, 2015 03:38:53 UTC
  * SNR 13 (FAR 1/1000 yr)
  * Initial Binary masses : $14.2^{+8.3}_{-3.7}\ M_{\odot}$ and $7.5^{+2.3}_{-2.3}\ M_{\odot}$
  * Final BH mass : $20.8^{+6.1}_{-1.7}\ M_{\odot}$
  * Distance : 440^{+180}_{-190} Mpc
  * At least one BH has spin >0.2

* Signal in 35-450 Hz band for ~1sec with ~55 cycles.
* Peak amplitude : $h \sim 3.4^{+0.7}_{-0.9} \times 10^{-22}$.
* Sky localization accuracy : 1,400 → 850 deg^2

LIGO

- LIGO (Laser Interferometer Gravitational-Wave Observatory) :
  GW observatory with two 4-km laser interferometric antennae placed at Hanford and Livingston sites, separated by about 3,000km from each other.
- Project approved in 1992. Start construction in 1994.
  First obs. run in 2002 (Initial LIGO). Upgrade to aLIGO (Advanced LIGO) from 2008.

Courtesy Caltech/MIT/LIGO Laboratory

LIGO Hanford Observatory (LHO)

LIGO Livingston Observatory (LLO)

LIGO O1 and Search Pipeline

- LIGO O1 (1^{st} Observation Run)
  * Obs. Period : Sept 12^{th}, 2015 – Jan 19^{th} ,2016
  * Total coincident analysis time : 51.5 days.
    → 48.6 days of data after data quality process.
- Data analysis → Matched filtering
  * Coincident window in two detectors : 15msec
    (3,000km separation → 10msec. 5msec for margin).
  * Mass range : $< 100\ M_{\odot}$
  * Two independent pipelines: PyCBC and GstLAL.
    Differ in implementation of matched filtering, use of data quality information, method of background estimation, ⋯

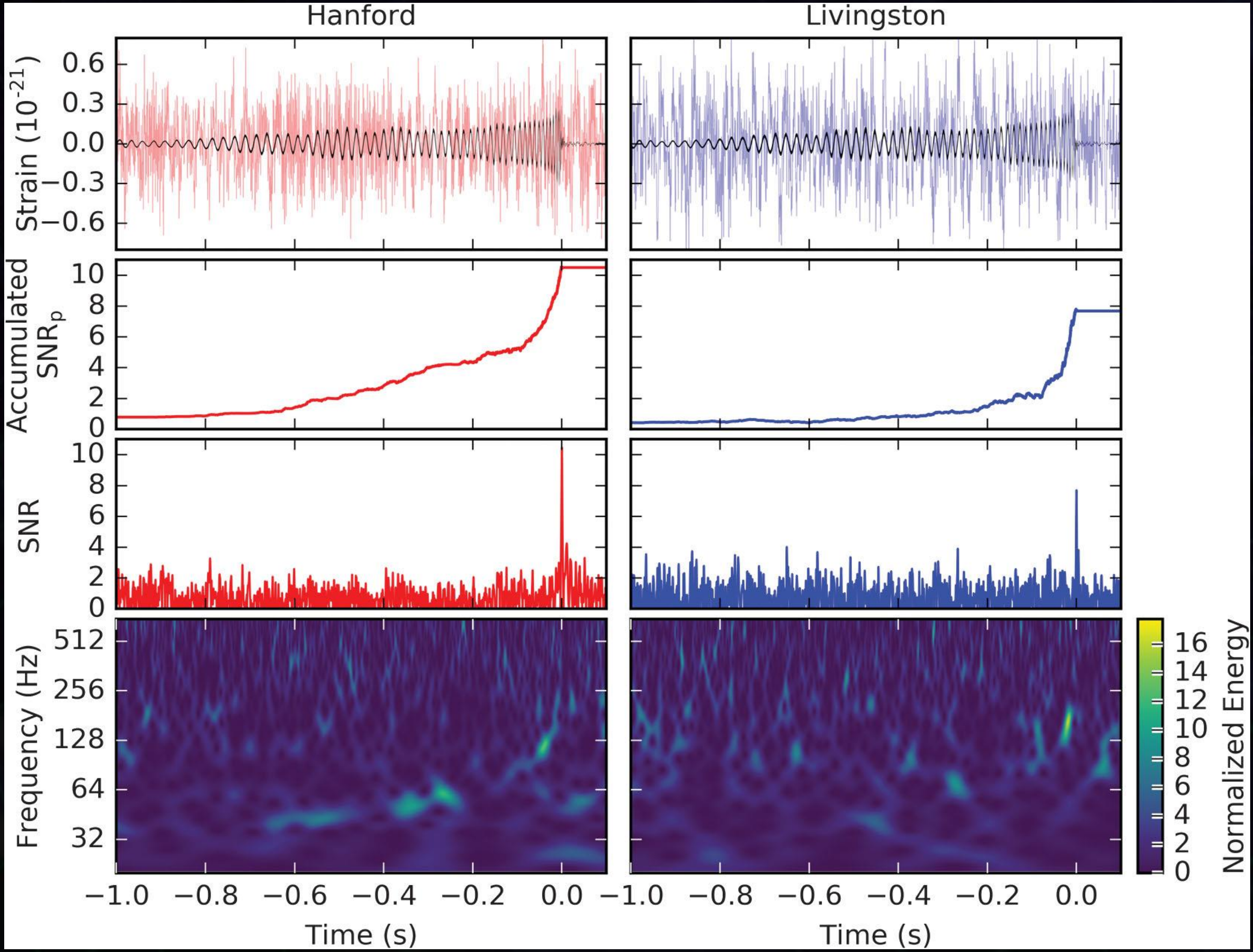
Data and Waveform

Strain amplitude after band pass and line removal

Accumulated SNR

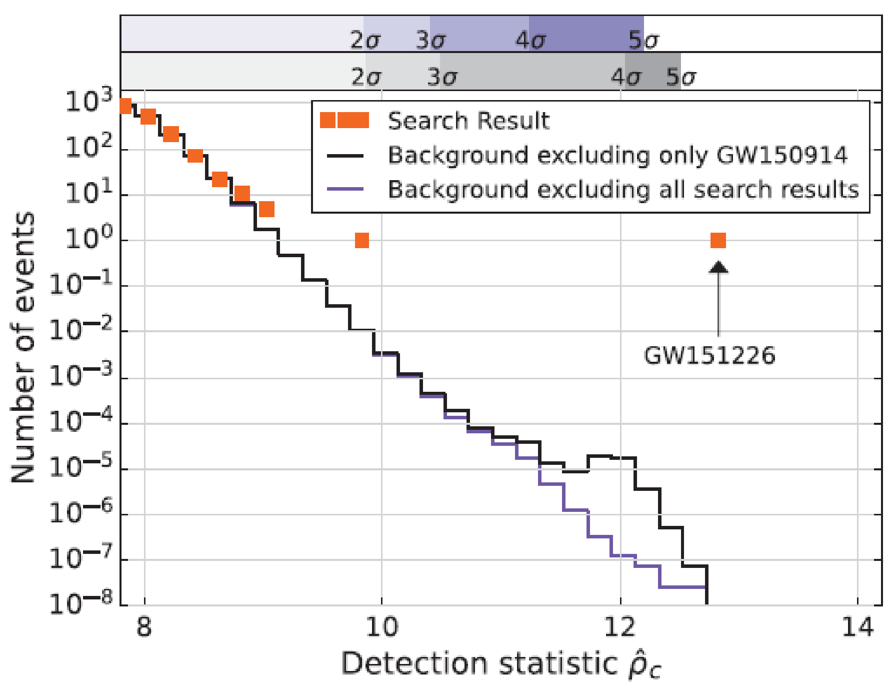
Matched filter output (total SNR)

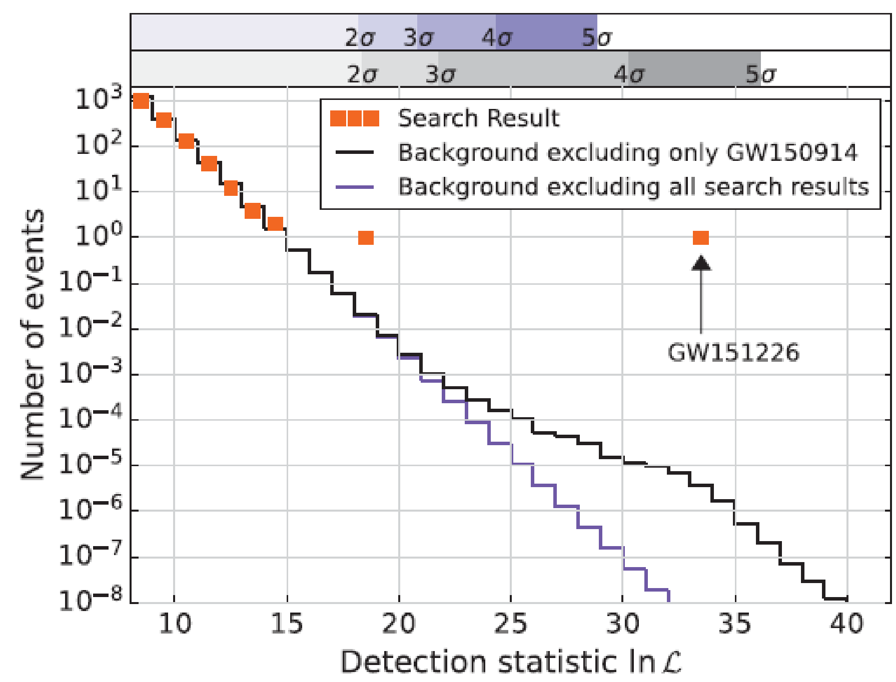
Time-Freq. plane



Search Results

- Both pipeline show >5σ for GW151226.
- Event GW150914 was removed in the background estimation.



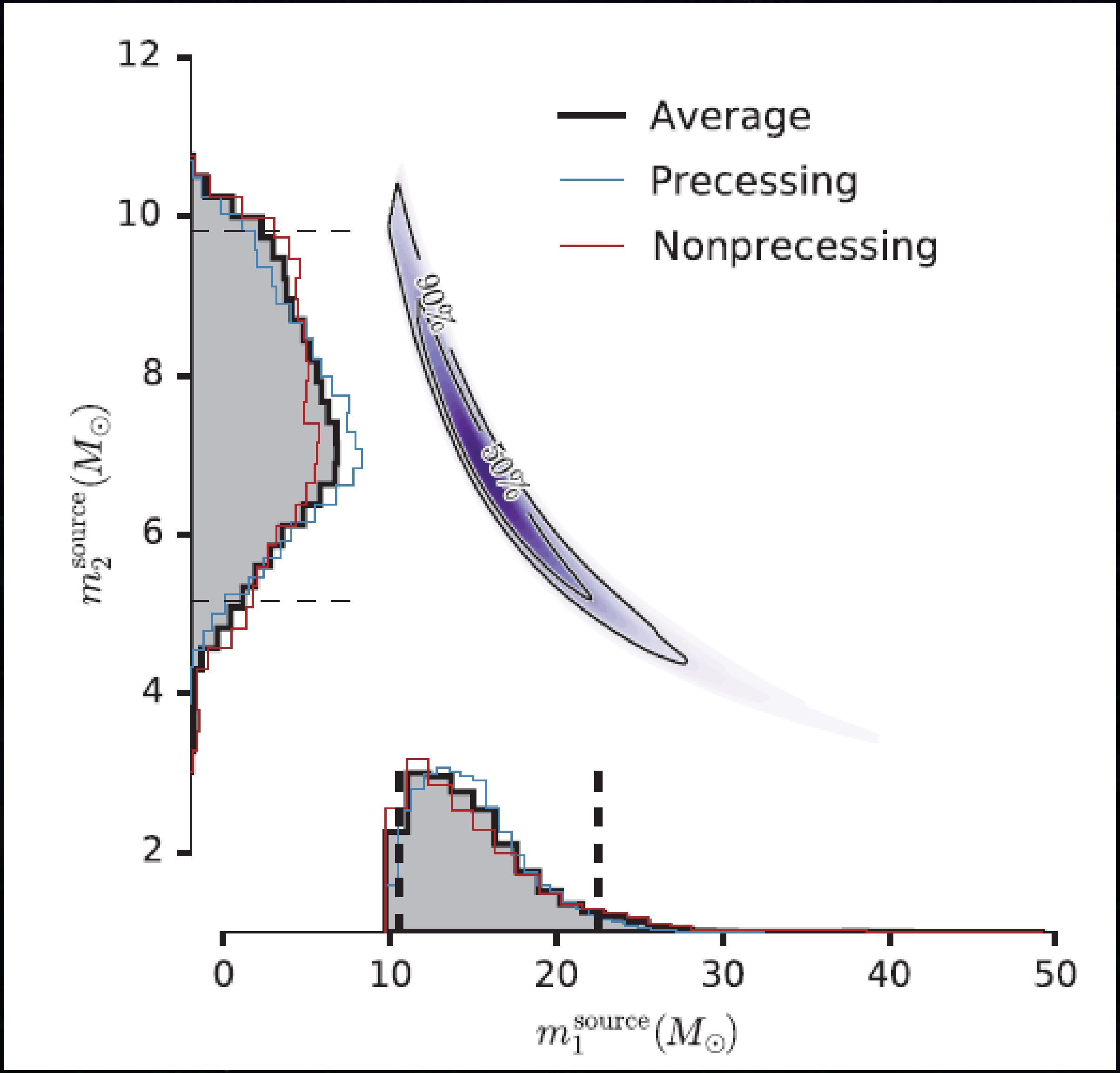


GW151226 Source Parameters

Primary black hole mass	$14.2^{+8.3}_{-3.7} M_\odot$
Secondary black hole mass	$7.5^{+2.3}_{-2.3} M_\odot$
Chirp mass	$8.9^{+0.3}_{-0.3} M_\odot$
Total black hole mass	$21.8^{+5.9}_{-1.7} M_\odot$
Final black hole mass	$20.8^{+6.1}_{-1.7} M_\odot$
Radiated gravitational-wave energy	$1.0^{+0.1}_{-0.2} M_\odot c^2$
Peak luminosity	$3.3^{+0.8}_{-1.6} \times 10^{56}$ erg/s
Final black hole spin	$0.74^{+0.06}_{-0.06}$
Luminosity distance	440^{+180}_{-190} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

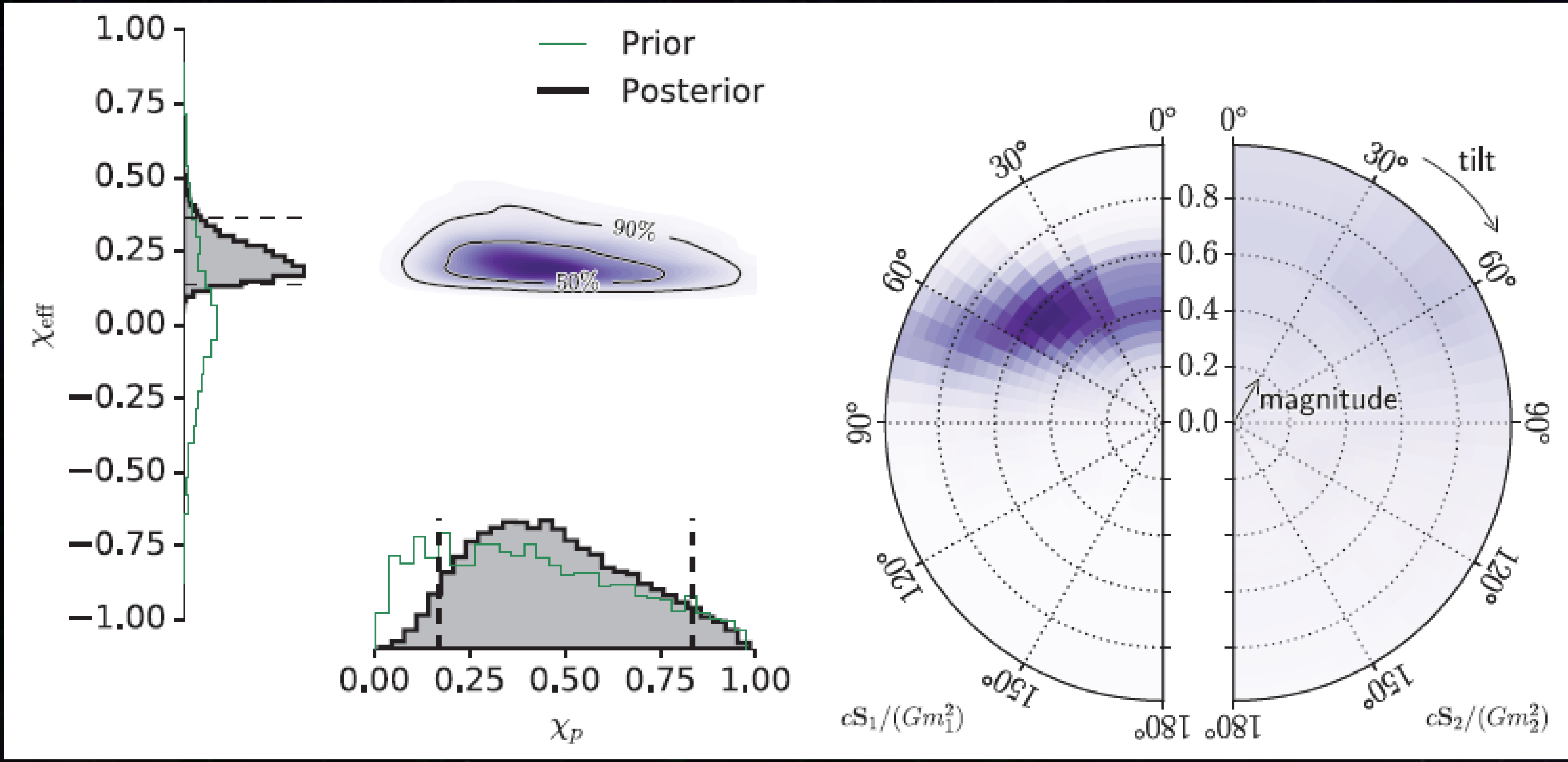
90% credible Intervals

Mass Parameters



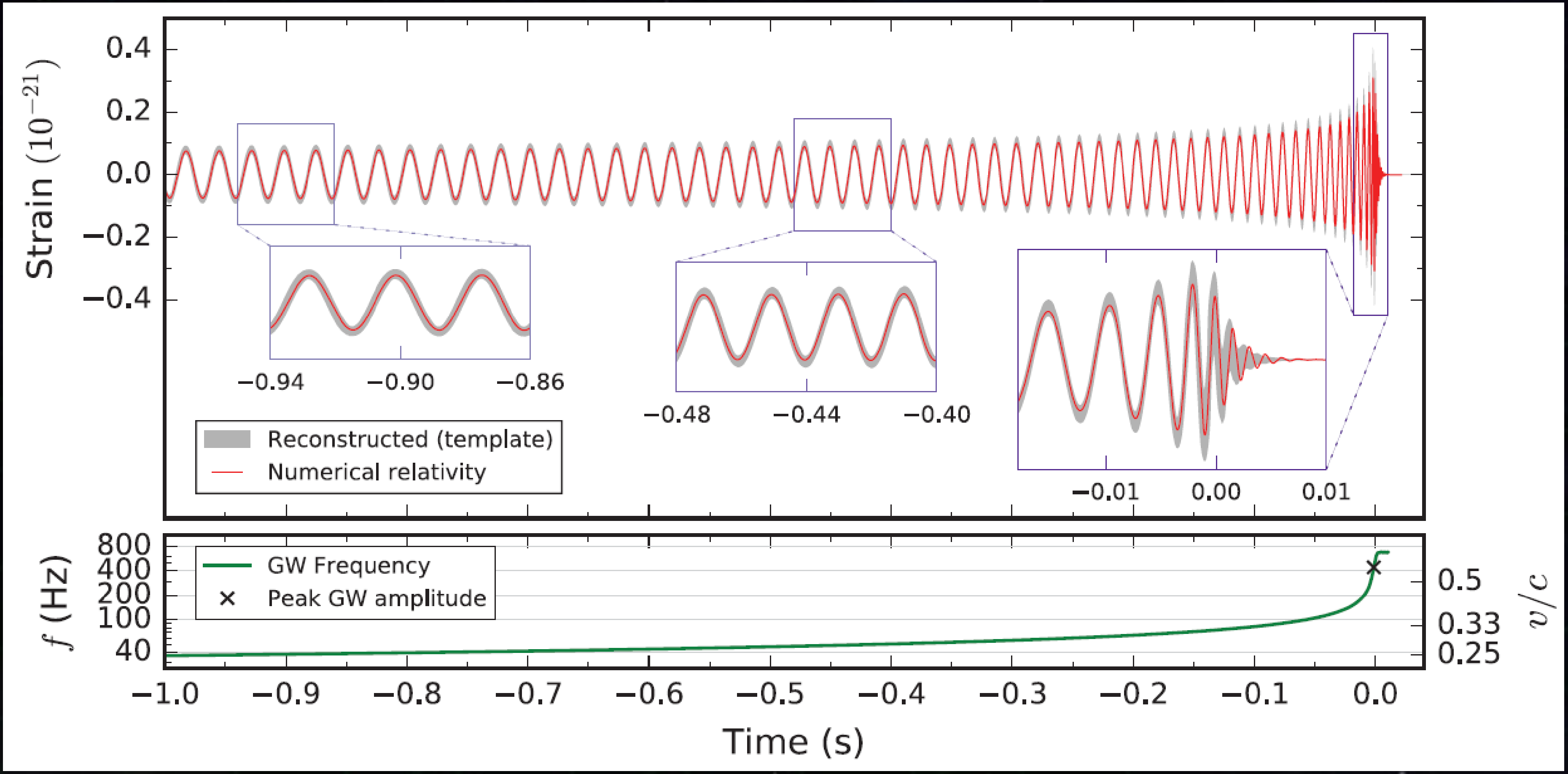
Spin Parameters

- GW151226 has non-zero spin : >0.2 99% CL.
  * Orbit aligned spin : $\chi_{\rm eff}$
  * In-plane spin : $\chi_{\rm p}$



Waveform by GR

- NR Waveform reconstructed from estimated BBH parameters.



GW151226 Features

- Smaller mass than GW150914.
  → Smaller amplitude. Matched filter was critical.
  Longer duration in observation band. Better tests for GR in the inspiral phase.
- At least one BH has spin.
- Masses consistent with values dynamically measured in X-ray binaries
- No constraint on origin of the BBH.

LIGO O1 Events

Parameters

- Chirp mass : $(m_1\, m_2)^{3/5}/M^{1/5}$
- Mass ratio : $q = m_2/m_1 < 1$

- Angular momentum :

$$a_{1,2} = \frac{c}{Gm_{1,2}^2}|\boldsymbol{S}_{1,2}|$$

- Component aligned with orbit

$$\chi_{1,2} = \frac{c}{Gm_{1.2}^2}\boldsymbol{S}_{1,2}\cdot\hat{\boldsymbol{L}}$$

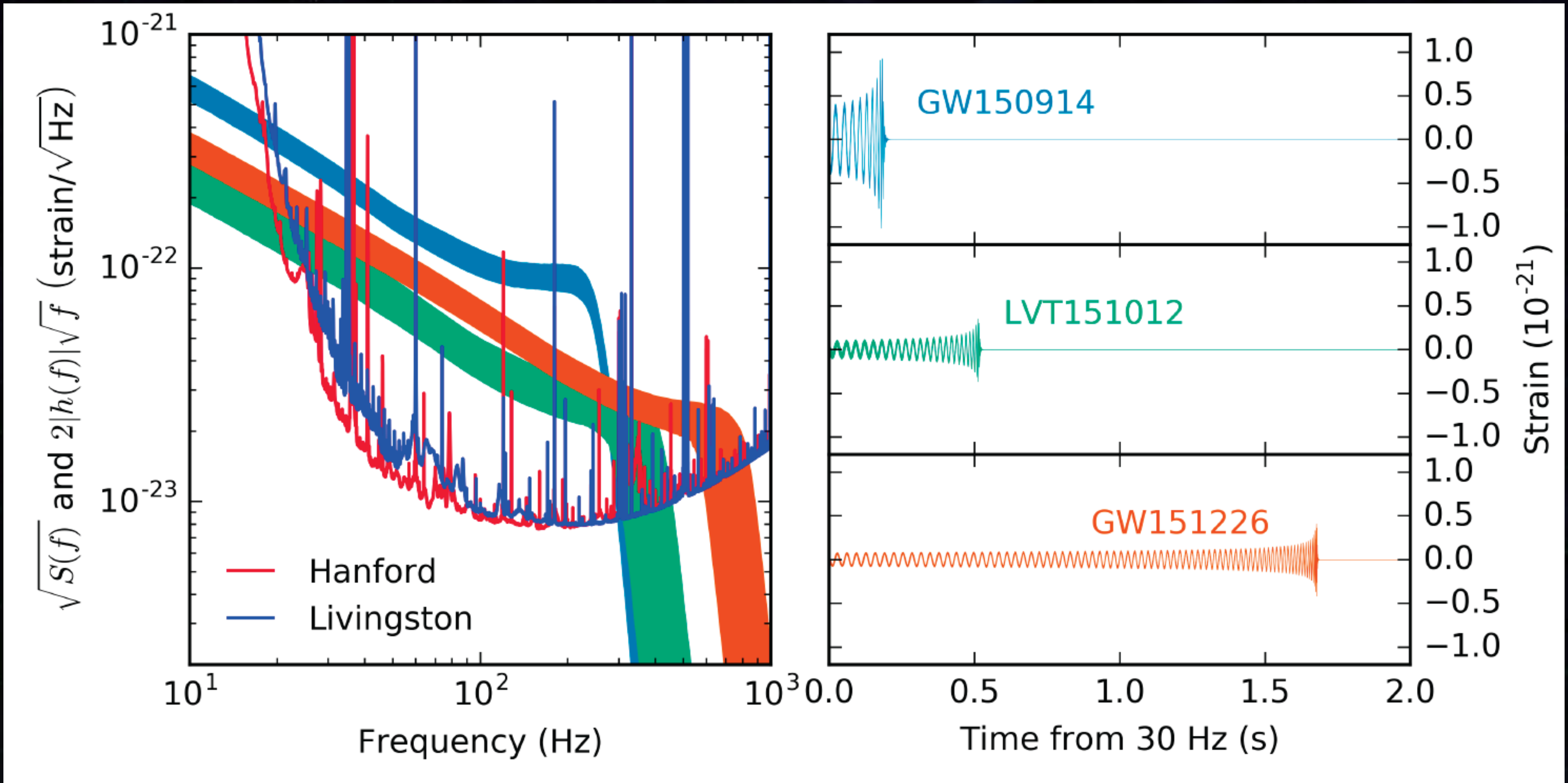
- Effective spin parameter

$$\chi_{\mathrm{eff}} = \frac{m_1\chi_1+m_2\chi_2}{M}$$

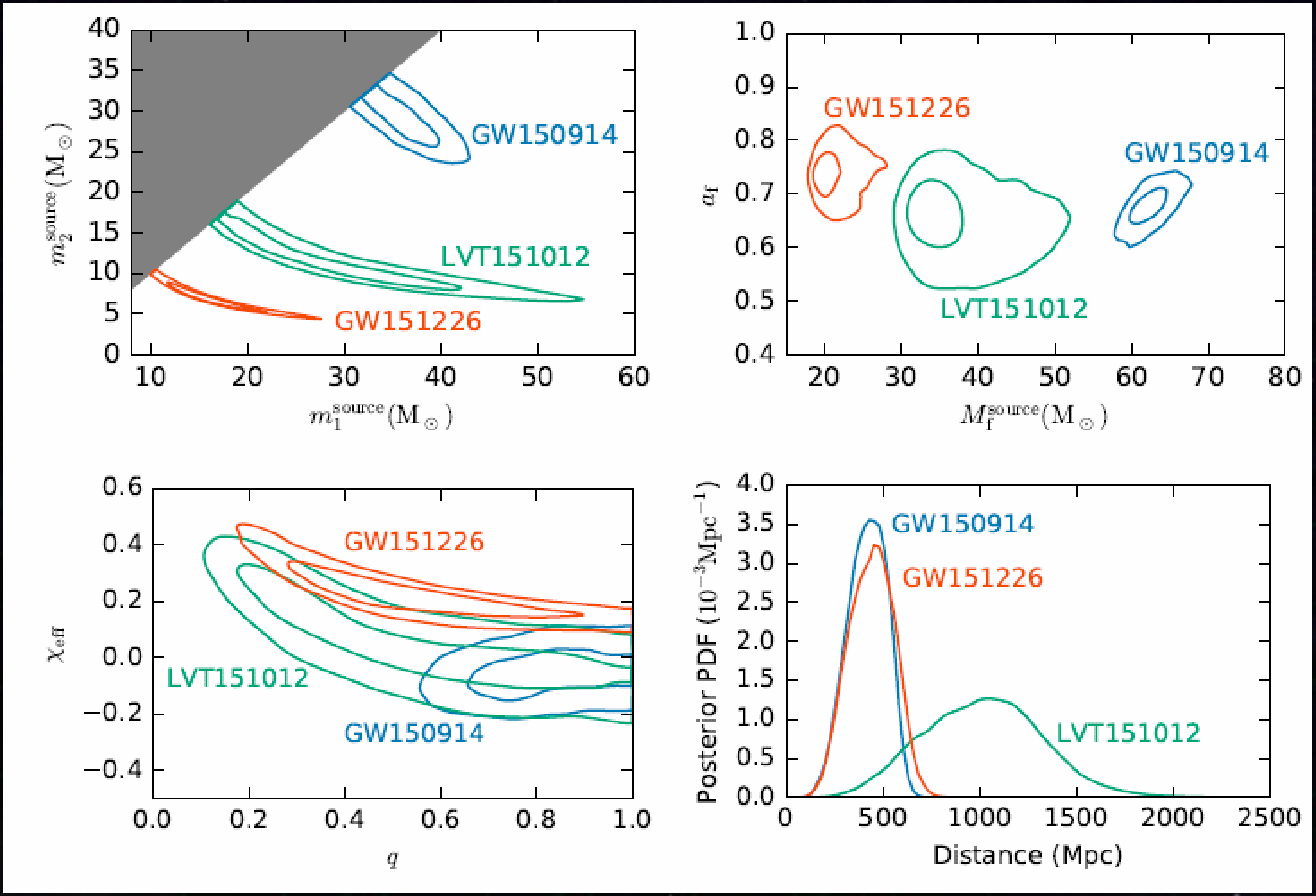
Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0\times10^{-7}$	$< 6.0\times10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathcal{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_f^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_f	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4}\times10^{56}$	$3.3^{+0.8}_{-1.6}\times10^{56}$	$3.1^{+0.8}_{-1.8}\times10^{56}$
Luminosity distance D_L/Mpc	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

LIGO O1 Events

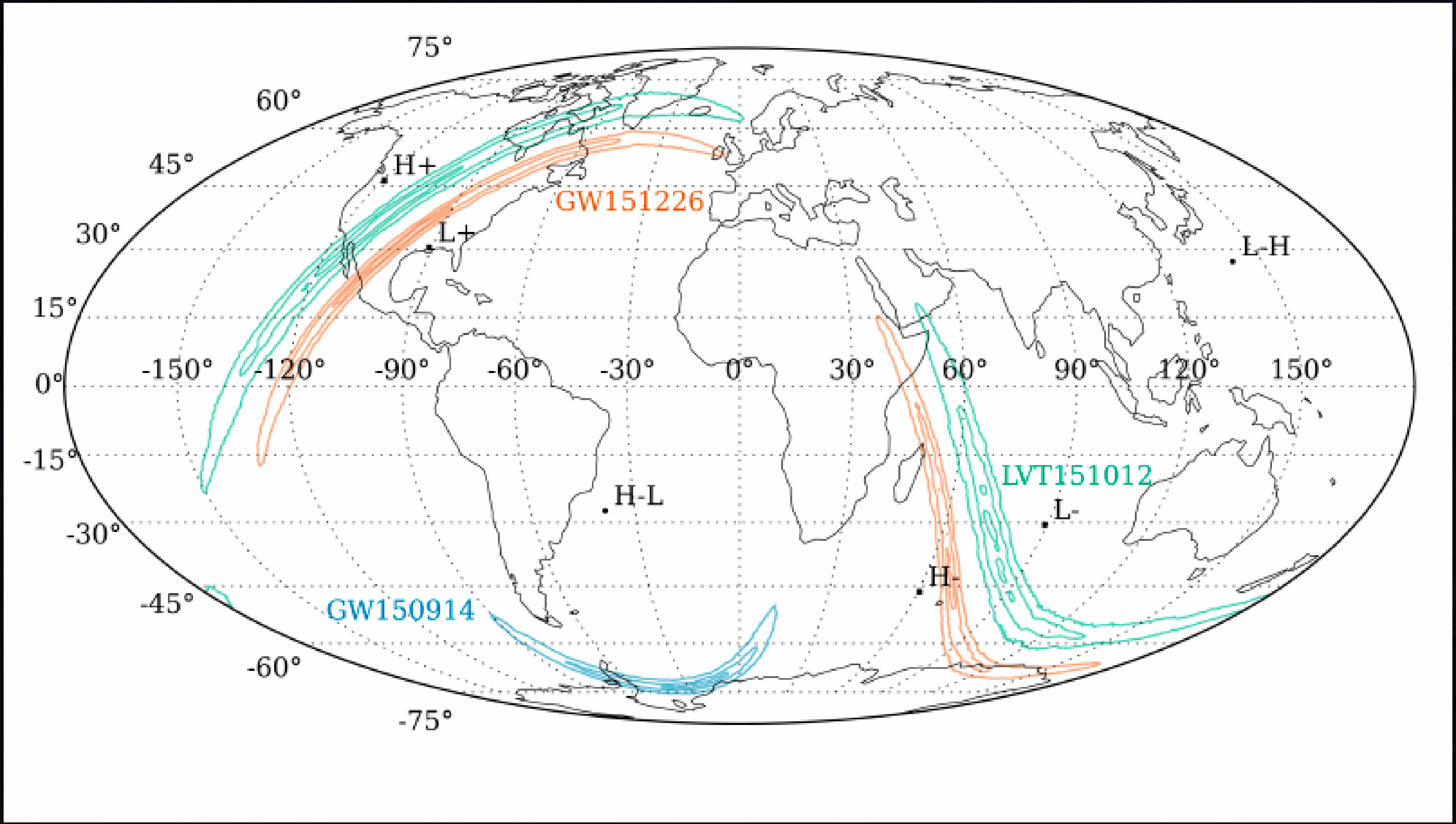
Two events (GW150914, GW151226) and one candidate (LVT151012, 87% CL) found in O1



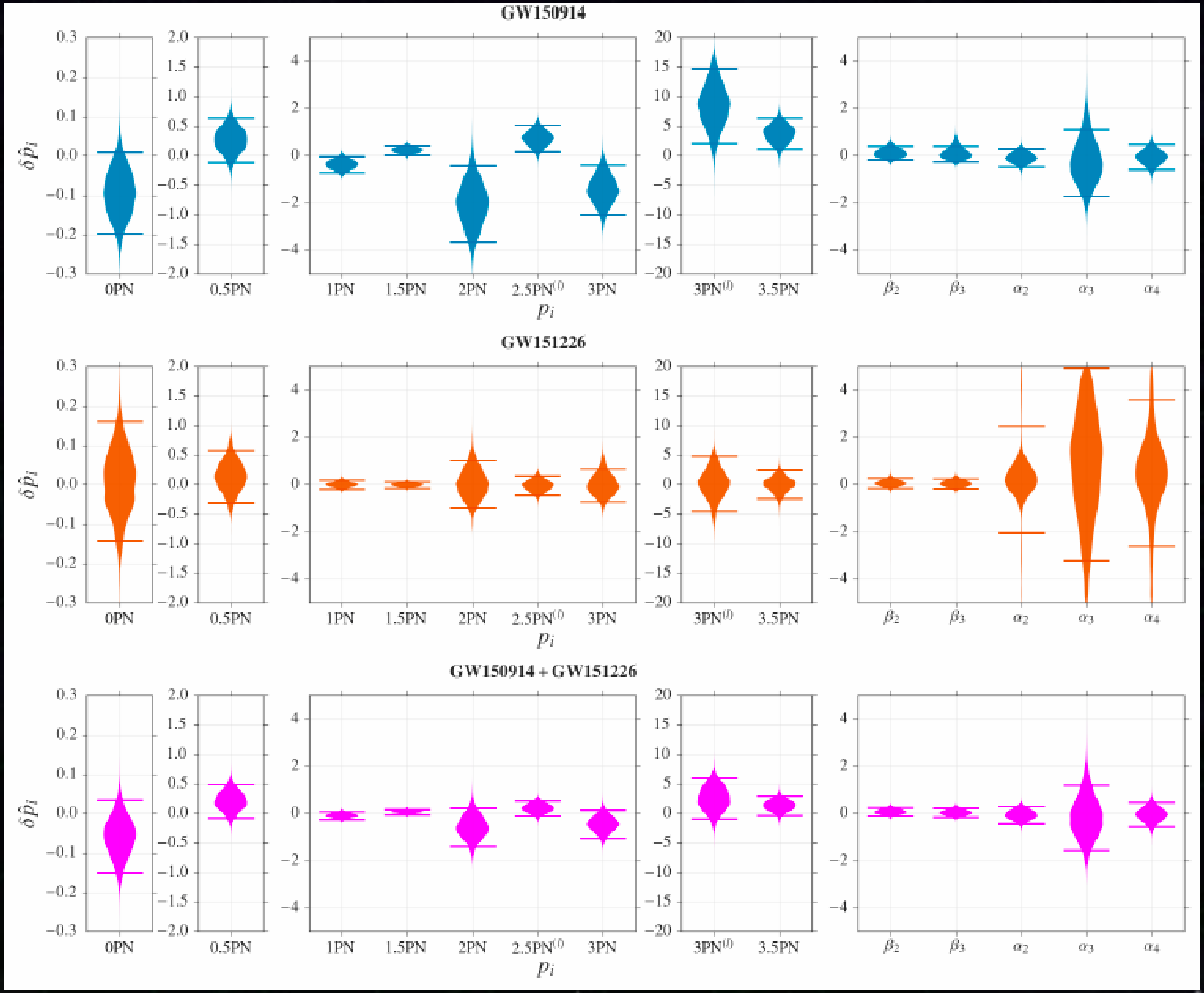
Parameter Estimation Results



Sky Localizations

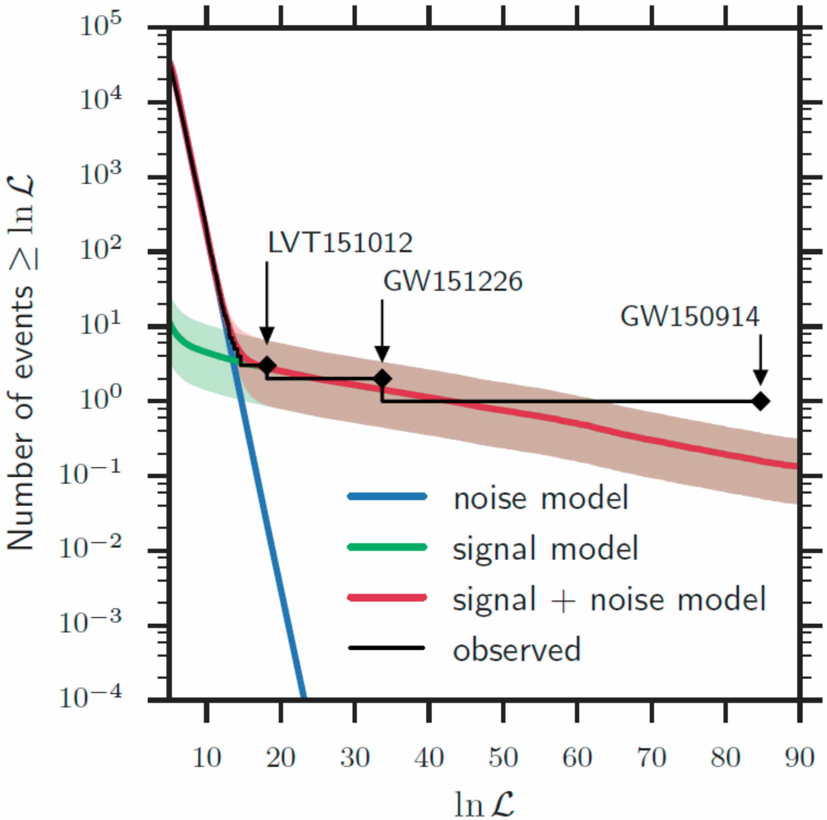


Test of General Relativity



Event Rate

BBH merger rate : $9 - 240\ \mathrm{Gpc^{-3}yr^{-1}}$



Mass distribution	$R/(\mathrm{Gpc^{-3}yr^{-1}})$ PyCBC	GstLAL	Combined
	Event based		
GW150914	$3.2^{+8.3}_{-2.7}$	$3.6^{+9.1}_{-3.0}$	$3.4^{+8.6}_{-2.8}$
LVT151012	$9.2^{+30.3}_{-8.5}$	$9.2^{+31.4}_{-8.5}$	$9.4^{+30.4}_{-8.7}$
GW151226	35^{+92}_{-29}	37^{+94}_{-31}	37^{+92}_{-31}
All	53^{+100}_{-40}	56^{+105}_{-42}	55^{+99}_{-41}
	Astrophysical		
Flat in log mass	31^{+43}_{-21}	30^{+43}_{-21}	30^{+43}_{-21}
Power Law (−2.35)	100^{+136}_{-69}	95^{+138}_{-67}	99^{+138}_{-70}

TABLE II. Rates of BBH mergers based on populations with masses matching the observed events, and astrophysically motivated mass distributions. Rates inferred from the PyCBC and GstLAL analyses independently as well as combined rates are shown. The table shows median values with 90% credible intervals.

End